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RESEARCH ARTICLE

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Key Points:

- The MSNA can well be interpreted as tidal features
- The WSA could be explained by tidal components D0, DW2, and SPW1
 The east-west differences of
- ionosphere can be explained by DE1

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The Midlatitude Summer Night Anomaly as observed by CHAMP and GRACE: Interpreted as tidal features

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Abstract This paper presents a description of the Midlatitude Summer Night Anomaly (MSNA) in terms of solar tidal signatures, based on in situ observations from CHAMP (CHAllenging Minisatellite Payload) and GRACE (Gravity Recovery and Climate Experiment) during the solar minimum years 2008 and 2009. Our analysis is focusing on 40° to 60° magnetic latitude ranges in both hemispheres, where the reversed diurnal variations of the electron density are strongest. The results revealed that in the Southern Hemisphere the longitudinally symmetric tide D0 is particularly strong during December solstice. The well-known Weddell Sea Anomaly is caused by a simultaneous constructive interference of three components D0, DW2, and SPW1. During June solstice the eastward propagating tide DE1 is the strongest in the Northern Hemisphere, which causes a wave-2 longitudinal pattern. The two crests of the wave-2 pattern at nighttime correspond well with the MSNA feature in the Northern Hemisphere. The MSNA feature over the USA continent is particularly strong, which can be explained by the combined contributions of the components DE1, D0, and DW2. The diurnally varying difference in electron density between the USA East and West Coast can also be explained by the phase propagation of the DE1. A similar effect has also been observed in the Asian region. The peak electron densities of the tidal component D0 appear around 0700 LT and 2000 LT in the Southern and Northern Hemispheres, respectively. The time shift suggests that the two hemispheres move in antiphase up and down. The planetary wave SPW1 exhibits an electron density crest near longitude sectors where the dip equator reaches far into the summer hemisphere.

1. Introduction

In recent years, more and more studies are focusing on the longitudinal modulation of the ionosphere by tidal effects originating from the lower atmosphere. These tides are often excited by latent heat release in tropospheric deep convective tropical clouds and propagate vertically upward. Therefore, tidal effects in the ionosphere have attained more attention in the equatorial and low-latitude regions, where prominent longitudinal wave patterns have been found in ionospheric quantities such as the equatorial ionization anomaly (EIA), Equatorial Electrojet, vertical plasma drift, and total electron content (TEC) [England et al., 2006; Lühr et al., 2008; Kil et al., 2007; Scherliess et al., 2008; Lühr et al., 2012]. The magnitudes of these tidal components vary differently with season, causing the ionospheric quantities to show longitudinal patterns with varying wave numbers over the course of a year. Best known are the wave number-4 (WN4) patterns during the months around August and wave number-3 (WN3) pattern around solstice seasons, corresponding to the diurnal DE3 and DE2 nonmigrating tides, respectively [Immel et al., 2006; Wan et al., 2010; Lühr et al., 2008, 2012]. For the labeling of the tidal components we use the common convention. The first letter D, S, or T stands for diurnal, semidiurnal or terdiurnal; the second letter E or W for eastward or westward propagating and the final number quantifies the azimuthal wave number. D0 represents a wave that is increasing and decreasing simultaneously at all longitudes at a diurnal period. Stationary planetary waves are labeled SPWs and the number at the end quantifies the maxima around the globe. The phase of the tides defines the time when the wave crest passes the 0° longitude meridian. In case of SPWs the longitude of the wave maximum is given. Model simulations revealed that nonlinear interaction between the migrating tides and DE3/DE2, can lead to large stationary planetary waves SPW4/SPW3, with amplitudes almost equal to DE3/DE2 [Oberheide et al., 2011; Pancheva et al., 2012]. The importance of the SPW4/SPW3 contribution to WN4/WN3 patterns in the EIA has also been reported by Xiong and Lühr [2013], by using in situ electron density observations from CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE).

In this paper we present evidence of nonmigrating tidal signatures in the midlatitude ionosphere, especially its role for the Midlatitude Summer Nighttime Anomaly (MSNA). The term MSNA is now used to describe the anomalous electron density pattern during local summer in both hemispheres [*Thampi et al.*, 2009, 2011; *Lin et al.*, 2010]. The classic example in the Southern Hemisphere is the Weddell Sea Anomaly (WSA), which is located near the Weddell Sea region and shows larger electron density at nighttime than at daytime during local summer. It was first recorded by an ionosonde in the 1950s [e.g., *Bellchambers and Piggott*, 1958; *Penndorf*, 1965] and further detailed in recent years by using satellite observations [e.g., *Horvath and Essex*, 2003; *Burns et al.*, 2008; *Lin et al.*, 2009; *He et al.*, 2009]. Analog WSA-like features in the Northern Hemisphere have also been widely reported based on various observations [e.g., *Chan and Colin*, 1969; *Rishbeth and Mendillo*, 2001; *Liu et al.*, 2007; *Lin et al.*, 2009; *Thampi et al.*, 2009].

Several potential mechanisms have been proposed by many scientists who attempted to explain the MSNA phenomenon. Rishbeth [1967, 1968] revealed that the equatorward wind prevailing at nighttime could drive the plasma along field lines upward. When the upward drift starts before the solar photo-ionization ceases (usually occurs in local summer), the plasma is pushed to higher altitudes where the recombination is very slow and the plasma can exist for a longer time. Later, this wind mechanism has been interpreted as a combine result of solar photo-ionization, thermospheric wind, and the local magnetic field configuration [Dudeney and Piggott, 1978; He et al., 2009]. Some other mechanisms such as the transportation of plasma from the dayside ionosphere and the downward flux from the plasmasphere have also been proposed [Burns et al., 2008]. Instead of focusing only on the nighttime electron density enhancement, but considering the typical diurnal cycle including both daytime and nighttime, Liu et al. [2010] reported that the MSNA features can be regarded as part of a phase reversal in midlatitude F region electron density with larger densities during nighttime than at daytime. This kind of phase reversal can be found in three distinct regions on the globe, which are the East Asian region centered around (53°N, 150°E), the Northern Atlantic region centered around (45°N, 50°W) and the South Pacific region centered around (60°S, 110°W). By employing a three-dimensional physics-based ionosphere model, SAMI3, coupled with the Thermosphere lonosphere Electrodynamics General Circulation Model (TIEGCM) and the Global Scale Wave Model, Chen et al. [2013] revealed that the standing diurnal oscillation component (D0) dominates the vertical neutral wind causing the southern MSNA feature. This tide manifests itself as a diurnal eastward propagating wave-1 pattern in satellite observations.

To compliment the observations and model simulations of the MSNA, we add here an investigation from the tidal perspective and on global scale. We use the in situ electron density measurements from CHAMP and GRACE during the recent solar minimum (2008–2009), as waves propagating upward from the lower atmosphere reach the thermosphere during those years more easily with clear signature and measurable amplitudes. In section 2, we first introduce the data and processing approach. Then we try to derive tidal spectra by fitting synthetic signals to our observations in section 3. Finally, we will discuss the results in the context of previous publications.

2. Data Sets and Processing Approach

The CHAMP satellite was launched on 15 July 2000 into a circular, near-polar orbit (inclination: 87.3°) with on initial altitude of 456 km. By the end of 2009 the orbit has decayed to 310 km. The local time of the orbital plane changes by 1 h in 11 days, requiring about 131 days for covering all local times [*Reigber et al.*, 2002]. The Planar Langmuir Probe (PLP) on board the satellite was taking measurements of the electron density and temperature every 15 s. The PLP electron density readings have been validated by comparison against digisonde measurements at Jicamarca [*McNamara et al.*, 2007].

GRACE, comprising two spacecraft GRACE-A and GRACE-B, was launched on 17 March 2002 into a near-circular, polar orbit (inclination: 89°) with an initial altitude of about 490 km. The altitude of the two spacecraft is quite stable over the years, which stays around 440 km at the end of 2013. The local time of the orbital plane precesses by 4.5 min every day taking the mission 161 days to sample all local times [*Tapley et al.*, 2004]. The two spacecraft follow each other at a distance of about 170–220 km. The total electron content (TEC) between the two spacecraft can be deduced from the K Band Ranging (KBR) data. When dividing the horizontal TEC by the distance between the spacecraft, the averaged electron density can be derived [*Xiong et al.*, 2010; *Lühr and Xiong*, 2010]. The GRACE electron density data have been validated by Incoherent Scatter Radar observations from European Incoherent Scatter Scientific Association (EISCAT), Millstone



Figure 1. The global distribution of ΔNe from CHAMP observations around (top) 1000 LT and (bottom) 2200 LT during (left) December solstice season 2008 and (right) June solstice season 2009. ΔNe means the longitudinal mean value of *Ne* has been subtracted.

Hill, and Arecibo (C. Xiong et al., Validation of GRACE electron densities by incoherent scatter radar data and estimation of plasma scale height in the topside ionosphere, submitted to *Advances in Space Research*, under review, 2014).

2.1. Processing Approach

Harmonic longitudinal structures observed by near-polar orbiting satellites can be caused by a multitude of tidal components. A general mathematical formulation of the relation between longitudinal patterns in satellite observations and the nonmigrating tidal description in the Earth-fixed frame is given by *Forbes et al.* [2006] and *Häusler and Lühr* [2009] in their section 2. To suppress the migrating tides, the longitudinal mean value has to be subtracted hour by hour. These mean-free data are further processed by the one-dimensional Fourier transform which will bring forth the sum of observed tidal signatures for each wave number. Spectra for wave number patterns from 1 to 4 have been analyzed. By interpreting the amplitudes and phase characteristics the six most prominent tidal components have been determined. Later, we use this set of selected tides for reproducing the observations.

3. Results

3.1. MSNA

As we described above, the MSNA is most prominent during local summer. Therefore, two time intervals have been selected, which are 131 days and 161 days to cover all 24 local time hours for CHAMP and GRACE, respectively, centered on 21 December 2008 as well as 21 June 2009. To see the global distribution of the electron density, the data are first sorted into geographic latitude (1°) and longitude (15°) bins.

Figure 1 depicts the CHAMP electron density observations around 1000 LT (top) and around 2200 LT (bottom) during December 2008 solstice season (left) and June 2009 solstice season (right). ΔNe means the longitudinal mean value of *Ne* has been subtracted for each latitude bin. We can see that ΔNe shows familiar EIA structure at equatorial and low-latitude regions around 1000 LT during both solstice seasons. A wave-3 and wave-4 longitudinal modulation is discernible in the equatorial region during December and June solstices, respectively.



Figure 2. The local time versus longitudinal distribution of ΔNe within the latitude ranges $\pm 40^{\circ} - \pm 60^{\circ}$ MLAT for the (left) Southern and (right) Northern Hemispheres during local summer from (top) CHAMP and (bottom) GRACE observations. White lines indicate the wave crests of the dominant tidal components.

At southern midlatitude regions, ΔNe is mostly negative between 30°W and 150°W around 1000 LT, while mostly positive in the same longitude sector around 2200 LT during December solstice 2008. The prominent positive ΔNe feature around 2200 LT corresponds to the WSA structure. As is known that the normal diurnal cycle of the midlatitude *F* region electron density consists of a midday maximum and a midnight minimum. Comparing the ΔNe values between 30°W and 150°W at the two local times, it seems there is an inverse diurnal variation. While ΔNe is found to be mostly positive around 1000 LT and negative around 2200 LT between 30°E and 150°E, which seems to follow the normal diurnal variation of the midlatitude *F* region electron density. When taking all longitudes into account, we can consider this diurnal variation as a wave-1 longitudinal modulation of the midlatitude region during the southern summer months.

Similarly, longitudinal modulation of ΔNe can also be found at northern midlatitudes during June solstice 2009 but here with a pattern of wave number-2. Clearly wave-2 peaks can be found between 90°W–150°W and 30°E–90°E between 40°N and 60°N around 1000 LT. While around 2200 LT, ΔNe shows a minimum between 90°W and 120°W, and the secondary minimum can also be found between 30°E and 90°E. Compared to 1000 LT, the enhanced ΔNe around 30°W and 150°E longitude sectors correspond to the northern MSNA, as reported by *Liu et al.* [2010].

3.2. Nonmigrating Tides in the Midlatitude Ionosphere During Local Summer

As we discussed above, the longitudinal wave structures observed by near-polar orbiting satellites can be caused by many different tidal components. By analyzing the propagating phase of the wave in local time, the different tidal components can be separated. Here we focus on midlatitudes therefore the data between $\pm 40^{\circ}$ and $\pm 60^{\circ}$ magnetic latitude (MLAT) has been selected for further investigation in the two hemispheres. Then ΔNe is averaged over the considered latitude range for each local time hour. Figure 2 presents the local time versus longitudinal distribution of the latitudinally averaged ΔNe for the Southern (left) and Northern (right) Hemisphere during local summer. Both observations from CHAMP (top) and GRACE (bottom) show clear longitudinal wave-1 and wave-2 patterns in the Southern and



Figure 3. The local time versus longitudinal distribution of (top) synthetic tidal signals and (bottom) residuals from CHAMP observations during (left) Southern and (right) Northern summer season.

Northern Hemisphere, respectively. Compared to the CHAMP observations, the ΔNe distribution is somewhat smoother at GRACE altitude but otherwise varies similar.

For determining the relevant tidal components we first apply a Fourier transform to the ΔNe values at all longitudes. Spectra for wave number patterns from 1 to 4 have been analyzed separately for the Southern and

 Table 1. Amplitudes and Phases of the Six

 Most Prominent Tidal Components Responsible for the Modulation of the Midlatitude

 Ionosphere During Local Summer

	Local Summer (2008–2009)		
Tides	Amplitude (10 ¹⁰ m ⁻³)	Phase (h)	
Northern Hemisphere			
SPW2	0.41	17.92°E	
DE1	2.23	2.35	
D0	1.37	19.65	
DW2	1.17	12.36	
SW1	0.80	8.17	
TW1	0.58	6.78	
DW1	4.00	19.30	
	Southern Hemisphere		
SPW1	2.25	39.26°W	
DE1	1.84	9.46	
D0	6.36	6.62	
DW2	2.92	15.50	
SW1	1.93	11.40	
TW2	1.42	7.48	
DW1	6.60	20.80	

Northern Hemispheres. By interpreting the amplitudes and phase characteristics the six most prominent tidal components have been determined independently for the two hemispheres. In a next step we use the six most prominent tidal components to construct tidal spectra of ΔNe for the two hemispheres. Overall this procedure follows the approach as used by *Xiong* and Lühr [2013] for the investigation of the equatorial ionization anomaly. Taking CHAMP observation for example, Figure 3 presents the synthetic signals (top) and residuals (bottom) for the southern (left) and northern (right) local summer season. The residuals are defined as the observations minus the synthetic signal. For the two hemispheres the residuals are quite randomly scattered, implying that the selected tidal components sufficiently well represent the observations. The amplitudes and phases of the six dominant tidal components are list in Table 1.

We can see that the dominant tidal components D0 and DE1 (indicated by white solid and dash-dotted lines in Figure 2) contribute to the wave-1 and wave-2 pattern in the Southern and Northern Hemispheres, respectively. The constructive interference of the westward propagating tidal component DW2



Figure 4. The local time versus longitudinal distribution of ΔNe from (top) CHAMP, (middle) synthetic tidal signals, and (bottom) residuals during (left) southern and (right) northern winter season.

(indicated by white-dashed lines in Figure 2) with D0 results in the ΔNe peaks at 30°E around 1100 LT and at 90°W around 2300 LT in the Southern Hemisphere. While in the Northern Hemisphere, the ΔNe peaks at 180°E around 0400 LT, at 30°E around 0900 LT and at 90°W around 1900 LT imply a constructive interference of the westward tidal component DW2 with the eastward tide DE1. When comparing the two hemispheres, four common tidal components, D0, DE1, DW2, and SW1 have been founded, which may imply common sources for the tides in the two hemispheres during local summer season. However, when comparing phases, the eastward tilted components DE1 and D0 are out of phase in the two hemispheres, while in case of the westward propagating tides there is a systematic delay by about 3 h in the Southern Hemisphere.

3.3. Nonmigrating Tides of the Midlatitude Ionosphere During Local Winter

We further looked at the midlatitude ionosphere during local winter season. Figure 4 presents the local time versus longitudinal distribution of the latitudinal averaged ΔNe from CHAMP observation (top), as well as the synthetic signals (middle) and residuals signals (bottom), during southern (left) and northern (right) local winter. Similar to local summer the longitudinal wave-1 and wave-2 patterns with smaller magnitude of ΔNe still exist in the Southern and Northern Hemispheres, respectively. But a reversed phase can be found

Table 2. Same as Table 1 but for LocalWinter in Both Hemispheres

Tides	Local Winter (2008–200 Amplitude (10 ¹⁰ m ⁻³)	9) Phase (h)	
indes	Northern Hemisphere	Thuse (II)	
Northern Hemisphere			
SPW1	0.93	67.78°W	
SPW2	0.58	111.00°E	
DE1	0.75	1.86	
D0	0.63	20.22	
DW3	0.40	19.87	
SW1	0.22	4.74	
DW1	1.80	15.70	
Southern Hemisphere			
SPW1	1.82	136.88°E	
SPW2	0.28	14.70°E	
D0	1.25	7.00	
DW2	0.45	14.02	
DW3	0.27	21.55	
SW1	0.51	10.50	
DW1	2.20	15.40	

around noon. To check this quantitatively again, a Fourier transform is applied to ΔNe data at all longitudes. The six most prominent tidal components for the two hemispheres during local winter have been listed in Table 2. Different from that during local summer, D0 and DE1 become the secondary tidal components in the Southern and Northern Hemispheres, while the planetary stationary wave SPW1 takes the leading role in both hemispheres. The five common tidal components, SPW1, SPW2, D0, DW3, and SW1 may imply also common sources in the two hemispheres during local winter season.

An inspection of the phases reveals that the individual tidal components appear at practically the same phases in the summer and winter seasons. This is valid for both hemispheres. An exception makes the prominent planetary wave SPW1 in the Southern Hemisphere. Its wave crest appears in the region of the Weddell Sea Anomaly around December solstice but 180 in longitude further east during the June solstice months (c.f. Tables 1 and 2 and Figure 4).

4. Discussion

The analysis presented above has provided for the first time all the nonmigrating tidal signatures related to the Midlatitude Summer Night Anomaly (MSNA). The in situ observations of CHAMP and GRACE revealed that the ionospheric electron density at midlatitude regions exhibit prominent longitudinal wave-1 and wave-2 patterns during local summer in the Southern and Northern Hemisphere, respectively.

4.1. Comparison With MSNA

The regions of the Weddell Sea Anomaly and the MSNA in the Northern Hemisphere have been intensively studied [e.g., *Bellchambers and Piggott*, 1958; *Penndorf*, 1965; *Burns et al.*, 2008; *He et al.*, 2009; *Thampi et al.*, 2009; *Lin et al.*, 2009, 2010]. These papers focused mainly on the nighttime enhancement in these regions during local summer. From a perspective of diurnal variation, *Liu et al.* [2010] regarded the MSNA as a phase reversal of the diurnal cycle. They found three such regions on the globe which they termed as at East Asian, Northern Atlantic, and South Pacific. The Weddell Sea Anomaly is part of the South Pacific region. Compared to our results, as depicted in Figure 2, the first two regions correspond well with the longitudinal wave-2 pattern in the Northern Hemisphere, with peak electron density centered at 75°W and 150°E during night-time. The third region, South Pacific, corresponds well with the longitudinal wave-1 pattern in the Southern Hemisphere, with peak electron density centered at 90°W during nighttime.

The typical diurnal cycle of the midlatitude *F* region electron density usually shows midday maximum and midnight minimum. From Figure 2, we can see that the electron density in the longitude sectors $90^{\circ}W-135^{\circ}W$ and $0^{\circ}E-90^{\circ}E$ follows the typical diurnal cycle in the Northern Hemisphere, and such a region can also be found at longitudes $0^{\circ}E-150^{\circ}E$ in the Southern Hemisphere. From a global perspective both the normal diurnal cycle and the phase reversed diurnal cycle of electron density variations can be explained by the longitudinal wave-1 and wave-2 tidal patterns of the Southern and Northern Hemisphere during local summer, respectively (see Figure 2).

4.2. The Ionospheric East-West Differences in North American and Far East Regions

Zhang et al. [2011] reported about an East-West Coast difference in TEC over the continental USA. They found that the Total Electron Content (TEC) in the evening is higher on the East Coast ($60^{\circ}W-80^{\circ}W$) than on the West Coast ($110^{\circ}W-130^{\circ}W$), and a vice versa TEC relation in the morning. A similar east-west difference of the ionosphere with smoother variations has later been reported by *Zhao et al.* [2013] in the Far East region. They found the *F* region electron density at 70°E to be larger than that at 140°E around noon hours and a reversal around night hours. From a global view, *Xu et al.* [2013] reported that such east-west differences of the midlatitude TEC can be found in North America, South America, and Oceania. These authors regarded the longitudinal differences in the ionosphere at midlatitudes as caused by the longitudinal

variations of magnetic declination combined with the effect of the thermospheric zonal winds. These winds are thought to push the plasma up or down along field lines.

In our CHAMP and GRACE observations during June solstice, depicted in Figures 1 and 2, there is one prominent peak on the eastward wave-2 pattern in the Northern Hemisphere over the USA East Coast during late evening hours. A comparable peak in electron density appears around December solstice at noon (see Figure 4) over the USA West Coast (90°W–120°W). These electron density features reflecting the coastal difference described by *Zhang et al.* [2011] fit well into our tidal picture. Similarly for the Far East anomaly, on the eastern leg of our wave-2 crest we find a maximum near 60°E around noon and another maximum near 150°E shortly before midnight. This is again consistent with the report of *Zhao et al.* [2013]. Also, during local winter, as depicted in our Figure 4, the wave-2 tidal component in the Northern Hemisphere causes east-west differences in the ionosphere at the affected longitude ranges. This is consistent with results of *Xu et al.* [2013] that the east-west differences depend mainly on local time but less on season or level of solar activity. Therefore, we prefer to explain the reported east-west differences at midlatitudes as tidal signatures.

4.3. The Model Simulations

The eastward propagating wave-1 pattern of the southern MSNA has also been investigated by *Chen et al.* [2013]. The SAMI3 model, combined with TIEGCM and the Global Scale Wave model can well simulate the mesospheric and lower thermospheric tidal effects related to the development of the southern MSNA. They found that the tidal component D0 dominates the vertical neutral wind manifesting the southern MSNA. This is in combination with the stationary planetary wave SPW1, which is a secondary tidal component in this region. Our data confirm, as listed in Table 1, D0 is the dominant tidal component during southern summer, with an amplitude almost equal to the migrating tidal component, DW1. We also observe a significant planetary wave SPW1. Therefore, we confirm part of the model simulations as reported by *Chen et al.* [2013]. Our observations reveal, however, a prominent role of the westward propagating nonmigrating tide DW2, which is not taken into account by their model. It is actually the constructive interference of the tidal components D0 and DW2 and SPW1 in the region of the WSA that creates the large density enhancement at nighttime (see guiding lines in Figure 2).

Also, in the Northern Hemisphere we can related all the reported electron density anomalies with combined effects of tidal components, here in particular DE1 and DW2 contribute. Very prominent are the density peaks over the continental USA during the two solstice seasons (see Figures 2 and 4, right). According to our analysis they are the result of constructive interferences of D0, DE1, DW2, and SPW1. In several studies the evening high-density regions over the USA have been identified as source region of repeated polar patch events [e.g., *Foster et al.*, 2005; *Noja et al.*, 2013]. Similarly, the Eastern Asia anomalies can also be related to crossing points of DE1 with DW2 (see Figure 2).

By model simulation, *Jones et al.* [2013] reported that at low latitude and midlatitude the migrating and nonmigrating tides could be generated in situ through ion-neutral interactions due to the longitude dependent ionosphere imposed by the magnetic field configuration. Their simulated results showed that the primary diurnal tides excited in situ include DE1, D0, and DW2 at 500 km (350 km) under solar maximum (minimum) conditions. Smaller amplitude semidiurnal nonmigrating tidal components are SE1, S0, SW1, and SW3. Comparing to our Tables 1 and 2, the tidal components DE1, D0, DW2, and SW1 are also found to be very prominent in our electron density observations.

4.4. Characteristics of Tidal Waves

As we know, nonmigrating tides can be excited by asymmetries at Earth surface [*Hagan and Forbes*, 2003], nonlinear interactions between the migrating tides and planetary waves [*Hagan and Roble*, 2001], and by the nondipolar geomagnetic field configuration [*Wu et al.*, 2012]. The nonlinear interaction between migrating wave DW1 and the stationary planetary wave SPW1 can generate the diurnal D0 and DW2 components. In general, the migrating wave, DW1, propagating upward from the lower atmosphere, is forced primarily by diurnal solar insolation of the stratosphere and troposphere [*Chen et al.*, 2013] and influenced by the background zonal mean winds. Part of DW1 in the upper thermosphere can also be attributed to an in situ response to the EUV solar radiation absorption [*Hagan et al.*, 2009]. In case of midlatitude ionospheric tidal signatures that we are describing here, such a wave coupling mechanism does not seem to be responsible. The phase changes with season and between hemispheres of the major tidal components do not match.

The dominant tidal component, in particular in the Southern Hemisphere is D0. It represents an increase and decrease occurring simultaneously at all longitudes. From Tables 1 and 2 we can deduce, that maximum densities are obtained at about 0700 LT in the Southern Hemisphere during both solstices and around 2000 LT in the Northern Hemisphere. This suggests an antisymmetric rising and lowering of the F_2 layer in the two hemispheres.

Another prominent component is the stationary planetary wave, SPW1. Its wave crest appears at June solstice in the East Asian, Australian sector (Northern Hemisphere: 125°E, Southern Hemisphere: 137°E), but during December solstice it is found over the east coasts of the Americas (Northern Hemisphere: 68°W, Southern Hemisphere: 39°W). These are both the sectors where the magnetic equator reaches far into the summer hemisphere. The displacement of the dip equator influences obviously the electron density even at midlatitudes.

The third tidal component, DW2, passes the Greenwich meridian around 1400 LT in the two hemispheres and during both solstices (see Table 1 and 2). This may suggest an in situ excitation by solar EUV absorption.

The eastward propagating nonmigrating tide DE1 is in our case primarily a northern hemispheric feature. We have presently no immediate explanation for the generation mechanism of DE1. An application of an electron dynamic ionospheric model in combination with a global scale wave model could be helpful for disclosing the processes responsible for that tidal component.

5. Summary

Here we have presented a description of the Midlatitude Summer Night Anomaly (MSNA) in terms of solar tidal signatures. Our analysis is focusing on 40° to 60° MLAT ranges in both hemispheres. This is the region where the reversed diurnal variations of the electron density are strongest. The study is based on in situ observations of the satellites CHAMP and GRACE from the solar minimum years 2008 and 2009.

A number of important results were obtained:

- 1. In the Southern Hemisphere the longitudinally symmetric tide D0 is particularly strong during December solstice. There are also other prominent tidal components, e.g., DW2 and the stationary planetary wave SPW1. The well-known Weddell Sea electron density anomaly is caused by a simultaneous constructive interference of the three components D0, DW2, and SPW1.
- 2. During June solstice the eastward propagating tide DE1 is the strongest in the Northern Hemisphere. This tide causes a wave-2 longitudinal pattern. As a consequence reversed phase diurnal electron density variations appear at two regions over the USA and East Asia. The MSNA feature over continental USA is particularly strong. Here we have the combined contributions of the components DE1, D0, and DW2.
- 3. The diurnally varying difference in electron density between the USA East and West Coast can also be explained by the phase propagation of the DE1. A similar effect has been observed in the Asian region. This can be related to the propagation of the second wave crest of the DE1. We prefer the tidal explanation over earlier studies suggesting the zonal wind in combination with the magnetic field declination as cause for the varying coastal differences. This seems to influence also the electron density at midlatitudes.
- 4. The prominent tidal component D0 represents a synchronous rise and sink of the F_2 layer at all longitudes. We observe peak electron densities in the Southern Hemisphere around 0700 LT and peak densities in the north at about 2000 LT. The time difference suggests that the two hemisphere move in antiphase up and down. The planetary wave SPW1 exhibits an electron density crest near sectors where the dip equator reaches far into the summer hemisphere.

Here we presented tidal features of the midlatitude ionosphere where well-known anomalies occur. For a better understanding of the tidal generation mechanisms one should consider all latitudes. The global view of tidal signatures in the topside ionosphere will be the topic of a follow-up paper.

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