Journal of Atmospheric and Solar-Terrestrial Physics 161 (2017) 105–117

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Observations of the Weddell Sea Anomaly in the ground-based and space-borne TEC measurements

Irina Zakharenkova[a,b,*], Iurii Cherniak[a,c], Irk Shagimuratov[a]

[a] Kaliningrad Department of IZMIRAN, 41 Pobeda Av., 236010, Kaliningrad, Russia
[b] Institut de Physique du Globe de Paris, 75013, Paris, France
[c] COSMIC Program Office, University Corporation for Atmospheric Research, Boulder, Colorado, USA

ARTICLE INFO

Keywords:
Weddell Sea Anomaly
Swarm
TEC
Topside ionosphere

ABSTRACT

The Weddell Sea Anomaly (WSA) is a summer ionospheric anomaly, which is characterized by a greater nighttime ionospheric density than that in daytime in the region near the Weddell Sea. We investigate the WSA signatures in the ground-based TEC (vertical total electron content) by using GPS and GLONASS measurements of the dense regional GNSS networks in South America. We constructed the high-resolution regional TEC maps for December 2014–January 2015. The WSA effects of the TEC exceed the noontime values are registered starting from 17 LT, it reaches its maximum at 01–05 LT and starts to disappear after 09 LT. Maximal TEC enhancements were as large as a factor of 2.5–3.5 and were registered at 03–04 LT. This effect was mainly localized in the geographical region of 55°S-75°S latitude and 80°W-30°W longitude, close to the Antarctic Peninsula. Further, we examined the WSA occurrence in the topside ionosphere by using GPS measurements from a zenith-looking GPS antenna on board three Swarm satellites to determine topside TEC (above ~500 km altitude) at the topside ionosphere-plasmasphere system. Global maps of the topside TEC indicated that the zone with significant WSA effect in the topside TEC (TEC increase ~2–4 times the noontime level) had a large spatial extent over southern Pacific and Atlantic Ocean. It was observed around 150°W-20°W and between 40°S and 70°S during 23 LT - 06 LT. For the first time, the WSA signatures were shown in the topside TEC data derived from the GPS measurements onboard the Swarm constellation. Independently, two other instruments - FORMOSAT-3/COSMIC radio occultation electron density profiles and in situ measurements by the Langmuir Probe instrument onboard Swarm satellites – were able to confirm: (1) the same location of the WSA zone as revealed in Swarm TEC; (2) the most-pronounced WSA effect, as a maximal electron density exceed over the noontime values, corresponds to altitudes above 400–500 km.

1. Introduction

The Weddell Sea Anomaly (WSA) effect was found first in ionosonde measurements in the 1950s after the International Geophysical Year in 1957 (Bellchambers and Piggott, 1958; Penndorf, 1965) from the Falkland Islands (52°S, 60°W, dip −50.4) to the southern shore of the Weddell Sea (around 75°S, 30°W, dip −64.0). According to the ionosonde observations, during the local summer the ionospheric F2 peak density (NmF2) varied in such a way that the daily peak occurs at local night instead of during daytime hours. The WSA feature only appeared during the southern hemisphere summer, in the months around the December solstice. The observations of the NmF2 maximum displacement to the post-midnight sector during local summer (November–February) for the Argentine Islands ionosonde (65.3° S, 64.3°W) were reported by Wrenn et al. (1987) and then they were compared with model simulations of the Utah State University Time-Dependent Ionospheric Model (TDIM) by Sojka et al. (1988). However, the main constrain of the ground-based facilities (in particular, ionosondes) is that they were able to provide only limited coverage of this area at the Antarctic Peninsula and a few islands nearby. Also a total number of the deployed ionosondes in this region was significantly reduced since International Geophysical Year in 1957. That is why real spatial extent of the WSA was not discovered for several decades. Such limitations of the sparse ground-based instruments could be overcome only by satellite observations.

One decade ago, new LEO (Low Earth Orbit) satellite missions aroused a spate of interest to the WSA phenomenon. Horvath and Essex (2003) and Horvath (2006) used data from the TOPEX/Poseidon satellite to study the WSA appearance in 1998/1999 and 1996/1997 respectively,

---

[*] Corresponding author. Kaliningrad Department of IZMIRAN, 41 Pobeda Av., 236010, Kaliningrad, Russia.
E-mail addresses: zakharenkova@mail.ru (I. Zakharenkova), tcherniak@ukr.net (I. Cherniak), shagimuratov@mail.ru (I. Shagimuratov).

http://dx.doi.org/10.1016/j.jastp.2017.06.014
Received 29 July 2016; Received in revised form 12 May 2017; Accepted 25 June 2017

and they were first to found that it actually extended over the South Pacific as far as 160°W at the time of its formation near dusk in local solar time. The TOPEX mission provided altimeter measurements, which could be converted into the ionospheric TEC (Total Electron Content) for the altitudinal range of 0–1336 km, but only over the ocean surface. Jee et al. (2009) have analyzed more than 13 years of TOPEX TEC data to study seasonal and solar activity variations of the WSA. Next very successful mission was FORMOSAT-3/COSMIC launched in 2006. This mission consists of six identical satellites at six different orbits of 700–800 km altitude and provides unprecedented number of electron density profiles retrieved from the GPS Radio Occultation (RO) experiment. Burns et al. (2008) reported one of the first results of the WSA features observed in the COSMIC data. They extracted and analyzed the ionospheric F2 peak parameters (density, NmF2, and height, hmF2) from RO profiles for April 2006–August 2007 period. They suggested that the WSA was a continuation of the southern, summer equatorial anomaly that had been displaced southward. They also discussed modelling efforts to simulate the WSA using the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) model. These runs did not produce the WSA. He et al. (2009) analyzed the WSA appearance in the ionospheric F2 peak using the global NmF2 and hmF2 maps derived from COSMIC RO profiles for more than two years of observations. They report that the NmF2 change is associated with the hmF2 change, while the latter is correlated closely with the components of the geomagnetic field. Lin et al. (2009) showed first three-dimensional density structure of the WSA in December 2007 using the COSMIC RO profiles. The electron density slices in the altitudinal range of 200–500 km were constructed by data averaging during one-month period. The WSA and the nearby density enhancement region in the southern hemisphere occur over a large area between 30°S and 90°S latitudes and 150°W-30°E longitudes. The WSA feature is most significantly seen at an altitude of 300 km.

Furthermore, it was found that a WSA-like feature with similar electron density enhancement occurs also in the Northern Hemisphere (Horvath and Lovell, 2009), namely at northeast Asia, close to Russian Yakutsk and the Okhotsk Sea. As the midlatitude nighttime (evening) density enhancements were found to exist in both hemispheres (Luan et al., 2008; Thampi et al., 2009; Lin et al., 2010), it was concluded that it is a general midlatitude ionospheric phenomenon and it was also named as “Mid-latitude Summer Nighttime Anomaly” (MSNA). Thampi et al. (2009) highlighted two major features of the MSNA: (1) the electron density is higher during night than daytime and (2) at night, the electron density at mid-latitudes remains higher than lower latitudes. Liu et al. (2010) regarded the MSNA as a phase reversal of the diurnal cycle and found three such regions on the globe, namely at East Asian, Northern Atlantic, and South Pacific (which included the WSA region), by making use of 6 years of in situ electron density measurements at 400 km from the CHAMP satellite. Using the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics/Global Ultraviolet Image (TIMED/GUVI) observations. Zhang et al. (2013) investigated the so-called midlatitude arcs (MLA) as an example of the nightside enhancements of ionospheric electron density at 20°–45° magnetic latitudes in both hemispheres and concluded that MSNA may be a subset of MLA.

From both ionosonde and satellite observations the WSA is considered mainly as the F2 peak phenomenon. However, Horvath and Lovell (2009) analyzed the in situ observations onboard the DMSP (Defense Meteorological Satellite Program) F12 satellite to study the evening/nighttime topside ionosphere during the 1996/1997 southern summer. The constructed maps of the topside ionosphere's plasma density parameters at an altitudinal range of about 850–870 km were able to track a complete nighttime WSA structure. More recently, Slominska et al. (2014) reported about detection of the WSA and MSNA signatures in the in situ data onboard the DEMETER satellite during the years 2005–2010. Though due to a sun-synchronous orbit these observations were limited to 10.5 LT and 22.5 LT time interval, but an altitude of measurements was about 700 km (later decreased to 620 km), i.e. the region greatly above the F2 peak. Further, Liu et al. (2014) revealed the anticorrelation between electron temperature (Te) and electron density in the topside ionosphere along the WSA latitudes, which were observed concurrently by COSMIC, DEMETER and Tatiana-2 satellites at an altitudinal range of 660–830 km. However, a number of papers on the WSA observations in the topside ionosphere is very limited.

Here, we should also note the ground-based GPS TEC measurements. Today ground-based GPS TEC and global ionospheric maps (GIMs) of TEC are one of the most widely used observations for the Earth's ionosphere monitoring, climatology and space weather applications (Jakowski, 1996; Garner et al., 2008). A number of the ground-based receivers within the global and regional networks explosively grows from several hundreds worldwide in the 1990s to more than 6000 stations today. However, there are a few publications on the WSA observations in the ground-based GPS TEC data (Mosert et al., 2011) and there are only few attempts to use GIMs TEC for this purpose as a supportive material (He et al., 2009; Zhang et al., 2013) or as a major data source (Meza et al., 2015).

There are several possible explanations of this fact. First, TEC represents an integral electron content along the related ray path between a ground-based station and GPS satellite, i.e. electron content within an altitudinal range of 0–20,200 km. In case of weak WSA effects in the F2 region peak density, integral nature of the TEC observations could diminish the WSA effect in TEC. Second, the GIMs TEC, produced by several IGS (International GNSS Service) centres, are also based on the ground-based receivers, which are relatively sparse in the Southern Hemisphere, dominated by oceans (e.g., Mannucci et al., 1998). Another important issue of the GIMs TEC is that they are constructed based on a rather limited set of stations (each IGS center specifies their own set of input stations and processes ~150–250 stations worldwide to generate own GIMs product), so only a few IGS stations from the South America continent (most close to the WSA region) are usually processed during generation of the GIMs TEC, for other neighbour grid points the data are interpolated. So, manifestation of the WSA feature in the GIMs TEC depends on the strength of the WSA effects and number of GPS stations used for this GIM generation.

Deployment of denser regional GNSS networks close to the WSA region can provide a new opportunity to test the WSA manifestation in the ground-based TEC observations. On the other side, a lot of modern LEO satellites are equipped with a dual-frequency GPS receiver and a zenith-looking antenna that can be used not only for precise orbit determination (POD) purposes but can also provide new data on the plasma density distribution at the topside ionosphere and plasmasphere (Heise et al., 2002; Zakharenkova and Cherniak, 2015). The aim of this paper is to gain new knowledge about physical mechanisms of the WSA development in a framework of its spatial and altitudinal extent by involving the new space-borne GPS TEC observations and its combination with dense networks of the ground-based GPS measurements. Our study is focused only on the WSA phenomenon, i.e. the Southern Hemisphere manifestation of the MSNA.

2. Database

2.1. Ground-based GPS data

In this study we consider the longitudinal sector of South America. Currently several networks of permanent ground-based stations provide GNSS measurements with an open access. A lot of stations contribute measurements to the International GNSS Service (IGS) and the University NAVSTAR Consortium (UNAVCO) networks and these services have long-term databases since the years 2000s. Rather recently the national networks for continuous GNSS monitoring were deployed in Brazil and Argentina - the Brazilian Network for Continuous Monitoring (RBMC – Rede Brasileira de Monitoramento Continuo dos Sistemas GNSS) and Red Argentina de Monitoreo Satelital Continuo (RAMSAC CORS). It allows us to increase significantly the GNSS data coverage over the southern part of this continent. Fig. 1 presents the geographical location of the available