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Comparison of IRI-2012 with JASON-1 TEC and incoherent scatter radar observations during the 2008–2009 solar minimum period

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ABSTRACT

The 2008–2009 solar minimum period was unprecedentedly deep and extended. We compare the IRI-2012 with global TEC data from JASON-1 satellite and with electron density profiles observed from incoherent scatter radars (ISRs) at middle and high latitudes for this solar minimum period. Global daily mean TECs are calculated from JASON-1 TECs to compare with the corresponding IRI TECs during the 2008–2009 period. It is found that IRI underestimates the global daily mean TEC by about 20–50%. The comparison of global TEC maps further reveals that IRI overall underestimates TEC for the whole globe except for the low-latitude region around the equatorial anomaly, regardless of season. The underestimation is particularly strong in the nighttime winter hemisphere where the ionosphere seems to almost disappear in IRI. In the daytime equatorial region, however, the overestimation of IRI is mainly due to the misrepresentation of the equatorial anomaly in IRI. Further comparison with ISR electron density profiles confirms the significant underestimation of IRI at night in the winter hemisphere.

1. Introduction

The International Reference Ionosphere (IRI) is the most widely used standard model for the ionospheric specifications. It is an international joint project of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). The IRI, as a data-driven empirical model, provides the total electron content (TEC) for a given location, time, and date as well as the height profiles of electron density, electron temperature, and ion composition (Bilitza and Reinisch, 2008; Bilitza et al., 2014 and references therein).

The 2008–2009 solar minimum period was unusual in terms of solar EUV and its duration. The level of solar EUV was extremely low and the duration of low solar activity was longer than any previous minimum periods (Russell et al., 2010; Solomon et al., 2010; Chen et al., 2011). The anomalous characteristics in solar EUV level lead to the unique state of the ionosphere as well as the thermosphere during the last solar minimum period (Liu et al., 2011; Emmert et al., 2010; Solomon et al., 2010, 2011, 2013; Jee et al., 2014).

A number of studies have evaluated how the IRI estimates the ionosphere during the unusual solar minimum period (Lühr and Xiong, 2010; Klenzing et al., 2011; Bilitza et al., 2012; Lee and Reinisch, 2012; Araujo-Pradere et al., 2013; Yue et al., 2013; Zakharenkova et al., 2013; Themens et al., 2014; Zakharenkova et al., 2015). Most of these studies seem to indicate that the IRI is not capable of correctly reproducing the ionosphere during this period. For example, Klenzing et al. (2011) compared the IRI-2007 with ion density profiles observed from C/NOFS satellite near the magnetic dip equator for the December solstice of 2008. They found that the IRI overestimates the ion density at 400–850 km altitude in the afternoon and post-sunset local time sector. Lühr and Xiong (2010) compared the IRI-2007 with electron densities observed from CHAMP and GRACE satellites for 2008 and 2009. They found that the IRI on average overestimates the electron density at 400–500 km altitude by about 50% and 60% for 2008 and 2009, respectively. By using ionosonde and C/NOFS satellite data, Bilitza et al. (2012) further investigated the limitations of IRI-2007 for the topside ionosphere, reported by Lühr and Xiong (2010), during the last solar minimum period. Based on the results of the comparisons with data for NmF2 and topside electron density at 400–500 km altitude, they investigated the possible causes for the IRI overestimation of the topside density despite the good agreement of IRI NmF2 with ionosonde observations. Most recently, Themens et al. (2014) evaluated the performance of IRI-2007 within the polar cap using the ionosonde measurements at four Canadian High Arctic Ionospheric Network (CHAIN) stations during the solar minimum period between 2008 and 2010. Their results showed that the IRI significantly underestimates nighttime NmF2 in the polar cap for most seasonal conditions except for summer period.

Most of previous evaluation studies of the IRI during the 2008–

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2009 solar minimum period were performed in the specific regions of altitude or latitude and longitude in which only a certain type of observations are available from satellites or ground-based instruments. In this study, we use the JASON-1 TEC data for the global ionosphere and the measurements of electron density profiles obtained from the incoherent scatter radars at middle and high latitudes, in order to see how IRI-2012 performs for the global ionospheric TEC and the height profiles of electron density during the solar minimum period.

2. Data and model

2.1. JASON-1 TEC data

JASON-1 is the satellite mission developed jointly by the Centre National d'Etudes Spatiales (CNES), France and the National Aeronautics and Space Administration (NASA), USA and launched in December 2001, as the TOPEX/Poseidon follow-on mission to monitor the surface of the global ocean (Ping et al., 2004). The precise sea surface height measurement requires the removal of the ionospheric delay imposed on the altimeter, which results in, as a by-product of the satellite mission, the TEC measurements of the ionosphere between the sea surface and the satellite orbit altitude of about 1336 km (Fu et al., 1994; Imel, 1994). As in the TOPEX satellite, the TEC data from JASON-1 satellite provides a measurement of the ionospheric vertical TEC almost every second but only over the ocean with 66° inclination.

TEC data from the Global Positioning System (GPS) is the most widely utilized TEC measurement for the ionosphere due to the unprecedented temporal and spatial coverages of the observation. However, there are fundamental limitations in the GPS TEC data due to the characteristics of the measurement. First, apart from the instrumental biases of GPS satellites and ground-receivers, the GPS TEC measurement initially produces slant TECs along the line-of-sight path between the satellites and receivers and the slant TECs need to be converted to vertical TECs, typically based on the assumption of a thin shell model of the ionospheric electron content situated at a certain altitude. This procedure undoubtedly introduces errors in the resulting vertical TECs, especially when the horizontal gradient of the ionospheric density is large as in the regions of the equatorial anomaly and auroral oval or at dusk sector (Mannucci et al., 1998). The another aspect of the GPS TEC measurement is that it includes not only the ionospheric electron contents but also the plasmaspheric electron content within the satellite orbit altitude of 20,200 km. The plasmaspheric contribution to GPS TEC cannot be ignored, especially at night and it can even reach as much as the ionospheric contribution in the early morning sector (Yizengaw et al., 2008; Jee et al., 2010; Lee et al., 2013).

On the other hand, the TOPEX and JASON (T/J) TEC measurements provide the most direct estimate of the ionospheric vertical TEC between the ground and the satellite orbit of about 1336 km over the global oceans, without any additional procedures for the vertical TEC. Furthermore, the altitude range for T/J TEC is hardly affected by plasmaspheric processes. In principle, therefore, it is supposed to produce the most direct and accurate TEC measurement of the ionosphere. Most of validation studies for T/J TEC measurements have been performed by comparisons with TEC measurements from GPS and DORIS (Doppler orbitography and radiopositioning integrated by satellite) and TEC models based on these data (Imel, 1994; Ho et al., 1997; Codrescu et al., 2001; Ping et al., 2004; Zhao et al., 2004; Brunini et al., 2005; Azpilicueta and Brunini, 2009; Yasyukevich et al., 2010).

DORIS TEC is measured by a receiver onboard the TOPEX satellite, which produces the slant TEC between the satellite and a global set of DORIS beacons spread around the Earth. This TEC is basically similar to GPS TEC except that it has the same altitude range as T/J TEC measurements. Ideally, DORIS TEC would be the most favorable independent data to validate T/J TEC. However, DORIS TEC measurements involve more complex preprocessing steps to derive the vertical TECs from DORIS phase measurements than GPS TEC observation (Imel, 1994; Zlotnicki, 1994; Dettmering et al., 2014). In particular, Zlotnicki (1994) demonstrated in their analysis of the altimetric corrections in TOPEX that the ionospheric correction by the TOPEX dual-frequency altimeter is superior to the DORIS correction.

In the comparison of T/J TEC with GPS TEC, they mostly utilized the global TEC models such as the Global Ionosphere Map (GIM) which should have additional model uncertainties in addition to all the limitations of GPS TEC measurement. Furthermore, the GPS TEC-driven models show the worst performance in the oceans where the GPS receivers are scarce. Note that the T/J TEC measurements exist only over the oceans. Using GPS TECs from the regional receiver network with high spatial resolution in Japan, Ping et al. (2004) reported that the bias between JASON-1 and GPS TECs is not significant, less than 1 TECU. Although a number of previous study indicated that there seems to be a systematic bias of a few TECUs in the T/J TEC measurements (Ho et al., 1997; Codrescu et al., 2001; Brunini et al., 2005), most of these studies is only showing that there are a few TECU differences between the measurements, but their results do not necessarily prove which measurement is more accurate than the other measurements. Since there are no known issues in the T/J TEC determination and no previous studies clearly demonstrating that the T/J TECs have a bias, based on the comparison with valid independent observations for the ionospheric TEC, we use the T/J TEC data as a ground truth to evaluate the IRI model (Yasyukevich et al., 2010).

For this study, the 1-s TEC data were averaged for about 18 s, which corresponds to about 1° of the satellite orbit, to reduce the observational random errors (Imel, 1994; Zlotnicki, 1994). For each 18-s data points, the corresponding geomagnetic coordinates are computed by adopting quasi-dipole coordinates (Richmond, 1995). For global TEC map, we bin the data in magnetic latitude (MLAT) versus magnetic local time (MLT) coordinate and the binning resolution for MLAT and MLT is $2° \times 15$ min. We also used three seasonal bins: equinox (day of year: 50–110 and 234–294), December solstice (day of year: 1–50 and 295–366), and June solstice (day of year: 111–233) for the seasonal variations of the ionosphere.

2.2. ISR electron density profiles

To further investigate the results of the IRI evaluation for the global ionosphere, we used electron density profiles observed by three incoherent scatter radars (ISRs) located at middle and high latitudes: Millstone Hill (42.6°N, 288.5°E, invariant latitude = 55°); European Incoherent Scatter Tromsø UHF radar (EISCAT: 69.6°N, 19.2°E, invariant latitude = 66°); EISCAT Svalbard radar (ESR: 78.2°N, 16.0°E, invariant latitude = 75°). Table 1 shows the numbers of days available from three radars for three seasonal cases. Since the electron density profiles from ISRs are produced with an

Table 1
Numbers of days for which the ISR data are available for three seasonal cases.

	Millstone Hill	EISCAT (Tromsø)	ESR (Svalbard)
Equinox	40	62	24
Dec. Sol.	50	113	75
Jun. Sol	47	86	41
Total	117	248	174