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IRI-2007 model overestimates electron density during the 23/24 solar minimum

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[1] We compare electron density predictions of the International Reference Ionosphere (IRI-2007) model with in-situ measurements of the satellites CHAMP and GRACE for the years 2000–2009. Orbital-averages of the electron density are considered. During the first half of the period (2000–2004) measurements and collocated model predictions track each other reasonably well at both sampling heights. From 2005 onward the overestimation of the electron density by the model is progressively increasing. Annual averages show that IRI-2007 values are too high by 50% for 2008 and by more than 60% by 2009. An inspection of the latitudinal and local time distributions reveals that the too high predictions primarily occur at low latitudes during daytime hours. From comparison with observations it becomes obvious that IRI-2007 is strongly overestimating the equatorial ion fountain effect during the last deep solar minimum.

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1. Introduction

[2] The ionospheric electron density is a highly variable quantity. Significant changes are observed on various time scales. Among these the solar cycle is an important variation. At fixed height the electron density is modulated by the expansion of the ionosphere (change in F2 peak height) but also by the variation of the electron concentration. Both theses effects vary with the irradiance of solar extreme ultraviolet (EUV). For instance, the solar cycle-dependence of the maximum F region electron density (NmF2) and the related critical frequency (foF2) have been studied among others by *Liu et al.* [2006]. They report an increase of the average NmF2 value from $3 \cdot 10^{11}$ to $2 \cdot 10^{12}$ m^{-3} for solar fluxes F10.7 = 70 to 200 sfu at low latitudes. Similarly, the F region peak height (hmF2) is changing with the solar cycle. According to *Liu et al.* [2006] hmF2 is increasing from about 260 to 330 km for F10.7 = 70 to 200 sfu at the station Wuhan (19.5° MLat) during noon time. The total electron content (TEC) variation over the course of a solar cycle has been investigated, for example, by *Huang and Cheng* [1995]. They find a close relation between electron content and sunspot number, R. Around the ionisation anomaly crest TEC values increase from 30 to 110 TECU for R = 20 to 140 at 16:00 local time in the East Asian region.

[3] Ionospheric models, such as the International Reference Ionosphere (IRI) [e.g., *Bilitza*, 1992, 2003], are expected to reflect these effects. However, there is evidence that some important parameters (NmF2 and hmF2) deviate significantly, in particular at low and equatorial latitudes, from observations [e.g., *Adeniyi et al.*, 2003; *Obrou et al.*, 2003; *Souza et al.*, 2003]. This can strongly influence the electron density, *Ne*, distribution at a certain height level.

[4] *Liu et al.* [2007] have used CHAMP electron density data at 400 km altitude over the period Aug. 2000 to Aug. 2006 for validating the IRI-2001 model [*Bilitza*, 2003]. Particular emphasis was put on the equatorial ionization anomaly (EIA) during daytime and post-sunset hours. They conclude that IRI reproduces the EIA around noon rather well for all levels of solar flux. Conversely, the ion fountain effect around 20:00 LT is too weak in the model, in particular for moderate to strong solar activity. As can be seen by *Liu et al.* [2007, Figure 6], the observed *Ne* profiles across the EIA exhibit higher crest values, which appear at larger distances to the dip-equator, and *Ne* is more depleted above the equator. All this indicates that IRI-2001 underestimates the effect of the vertical plasma drift during post-sunset hours.

[5] The IRI is a purely empirical model based on a large collection of satellite and ground-based observations, and it is expected to give a reasonably accurate description of the ionosphere under quiet geomagnetic conditions. However, the minimum of the solar cycle 23/24 was quite special since it had a record number of days without sun spots [*Livingston and Penn*, 2009]. There is no representative dataset included in IRI that comes from a comparable solar minimum. Therefore the model may not be able to predict the ionospheric conditions correctly during the years 2008 and 2009.

[6] The purpose of this study is thus to test the reliability of IRI, in particular during the recent deep solar minimum. For a direct comparison we make use of measurements from the satellites CHAMP and GRACE. They provide electron density readings over the past decade from two altitudes. This dataset allows for a direct comparison between IRI predictions and observations over the whole range from solar maximum to minimum. Based on these results we perform an assessment of the differences.

2. Data

[7] 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 it has decayed to 310 km. The local time of the orbit changes by 1 hour in 11 day, requiring about 130 day for covering all local times [*Reigber et al.*, 2002]. The Planar Langmuir Probe (PLP) on board the satellite takes in-situ measurements of the electron

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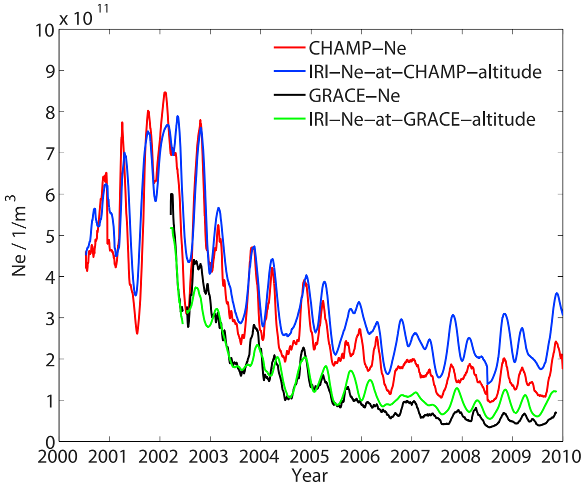

Figure 1. Comparison of CHAMP and GRACE electron density measurements with collocated predictions of the IRI model. Orbital averages are averaged over 31 days.

density every 15 s. The *Ne* readings of the PLP have been verified by comparison against digisonde measurements at Jicamarca [*McNamara et al.*, 2007]. The authors report an average discrepancy between PLP and digisonde recordings of only 4% with a standard deviation of 8.8%. This good agreement adds confidence in the reliability of the CHAMP *Ne* measurements.

[8] 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 these satellites is quite stable over the years. An overview of the orbital evolution of CHAMP and GRACE is given by *Xiong et al.* [2010, Figure 2]. The local time of the orbital plane precesses by 4.5 minutes every day taking the mission 160.5 days to sample all local times [*Tapley et al.*, 2004].

[9] The two GRACE satellites follow each other at a distance of about 220 km. For the determination of the electron density we make use of the K-band ranging (KBR) system, which measures the dual one-way range change between the two satellites. The total electron content (TEC) between the spacecraft can be deduced from the KBR data. When dividing the horizontal TEC by the distance between the spacecraft we get the average electron density. A more detailed description of the electron density retrieval is given by *Xiong et al.* [2010, section 3]. TEC measurements based on radio wave modifications do in principle not require calibration. There is, however, the uncertainty of an arbitrary bias value. By considering long and continuous data series we think, we have constrained the applied bias quiet well.

[10] For comparison electron density predictions have been calculated from the latest model version, IRI-2007 [*Bilitza and Reinisch*, 2007], for each measurement point of the satellite readings. The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). IRI describes monthly averages of the electron density, electron temperature, ion composition (O^+, H^+, N^+, $O2^+$, NO^+, $Cluster^+$), ion temperature and ion drift in the ionospheric altitude range of 50–1500 km.

[11] Comparing to the former IRI models, there are some important changes in the newest version, IRI-2007. Relevant for this study are the two new options for the topside electron density profile. One option is a correction factor for the 2001 model based on over 150,000 topside profiles from Alouette 1, 2, and ISIS 1, 2, and this term varies with altitude, modified dip latitude, and local time [*Bilitza*, 2004]. The other option is the NeQuick topside model that was developed by S. Radicella and his collaborators over the last decade [*Radicella and Leitinger*, 2001; *Coisson et al.*, 2004].

[12] Furthermore there is a much improved model for the topside ion composition. The present IRI model is largely based on a compilation of Russian high-altitude rocket measurements [*Danilov and Yaichnikov*, 1985; *Danilov and Smirnova*, 1995], and on a limited amount of incoherent scatter radar data. Working with the satellite in situ measurements from AE-C, -E, and Intercosmos 24, *Triskova et al.* [2003] have developed a new model for the ion composition in the topside ionosphere.

[13] The inputs for the IRI-2001 and IRI-2007 models are (1) sunspot number, R, (2) global ionospheric index, IG, and (3) the 3-hourly magnetic, a_p index. IG is an ionospheric-effective solar index that is based on foF2 measurements from selected ionosondes and a correlation with the Consultative Committee of International Radio Communications (CCIR) maps [*Liu et al.*, 1983]. For the calculations presented here we have used the version updated on 28 May 2010 (http://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/). Selected options:

foF2: URSI
Ni: DS-95 & TTS-03
Ion drift: not computed
Te: Te topside (Intercosmos)
ESF: not computed
Topside model: NeQuick

3. Comparison Between Model and Observation

[14] For our comparison we made use of all available electron density data from the two considered satellites up to the beginning of 2010. Orbit averages of *Ne* are calculated for each orbit of CHAMP and GRACE. The orbital averages are the basis for further analyses. Each satellite circles the Earth more than 5500 times per year. Collocated IRI *Ne* predictions are generated at the same rate and by considering the actual geophysical conditions. Figure 1 shows the temporal evolution of the four data sets. Here orbital averages have been smooth by a moving boxcar filter over 31 days. This filter length is chosen since IRI predictions are representing monthly averages. Both at CHAMP and GRACE heights we find large intra-annual variations.They reflect primarily the low-latitude seasonal variation of the ionospheric electron density [e.g., *Liu et al.*, 2009]. Rather prominent are the minima around June solstice. Peak densities are obtained during equinox seasons. These seasonal variations are further modulated by the orbit-dependent local time changes of the satellite measurements.

[15] During the solar maximum years and the declining phase of the cycle the modeled *Ne* values track the observations at the two altitudes rather well. However, IRI underestimates somewhat the amplitude of seasonal excur-

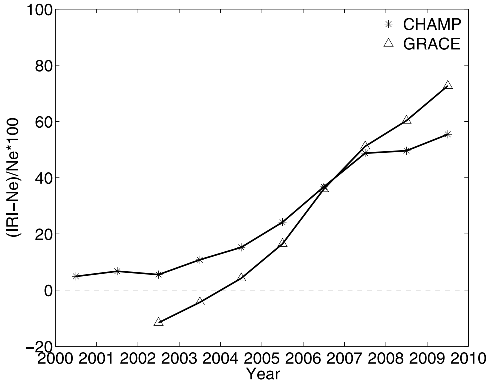

Figure 2. Annual average of the deviation in percent of IRI-2007 electron density estimates from collocated measurements by CHAMP and GRACE.

sions at CHAMP height. GRACE returns systematically higher *Ne* values during fall seasons than the model. After the epoch 2005, however, IRI systematically overestimates the electron density at both altitudes. The differences between the model and measurement curves are increasing with time up to 2010.

[16] In order to obtain a more quantitative estimate of the difference between IRI and satellite date, we calculated annual averages of the relative deviations, Δ, in percent

$$\Delta = \frac{N_{e,IRI} - N_{e,Sat}}{N_{e,Sat}} 100 \qquad (1)$$

where the subscript *Sat* stands either for CHAMP or GRACE.

[17] As can be seen in Figure 2, during the solar maximum years the deviation is small. In case of CHAMP it is in the range of the measurement uncertainty of a few percent [*McNamara et al.*, 2007]. From 2004 onward, however, we observe an increasing difference between the data sets. For 2009 the ratio between *Ne* from IRI and from CHAMP is larger than 1.5. For the altitude of GRACE the model first underestimates the measurements (too small fall peaks), but from 2004 on the deviation rises even faster than at CHAMP location. For the average of 2009 the ratio IRI over GRACE surmounts 1.7. Otherwise the differences at the two altitudes show similar evolutions.

[18] We are interested to find out to which regions or local times these large discrepancies can be attributed. For that reason we went back to the original measurements and binned the data in magnetic latitude versus local time frames. Figure 3 shows in the upper row the electron density distribution as observed by CHAMP during the years 2008 and 2009 separately for the three Lloyd seasons (equinoxes: Mar., Apr., Sep., Oct.; June solstice: May–Aug.; Dec. solstice: Nov.–Feb.). Below collocated IRI densities are plotted. Shown *Ne* values are averages over all longitudes.

[19] It is quite obvious that largest differences between modeled and measured *Ne* appear at low latitudes during daytime. During the post-midnight hours until 06 LT differences are small in all season. The main contribution to the *Ne* overestimation by IRI comes from the daylight hours, in particular from the latitude range ±30° MLat. During post-sunset hours the predicted *Ne* is also somewhat too high at low latitudes. A very similar picture emerges from the model-to-measurement comparison at GRACE altitude (not shown). At this height the relative difference is even higher than at CHAMP. Here the post-sunset hours provide a larger contribution.

[20] Dominant density features in Figure 3 are the two latitude bands representing the equatorial ionization anomaly. The EIA electron density peaks are clearly visible for equinox and December solstice seasons. From the modeled *Ne* we deduce a latitude separation of the peaks of 30.5°,

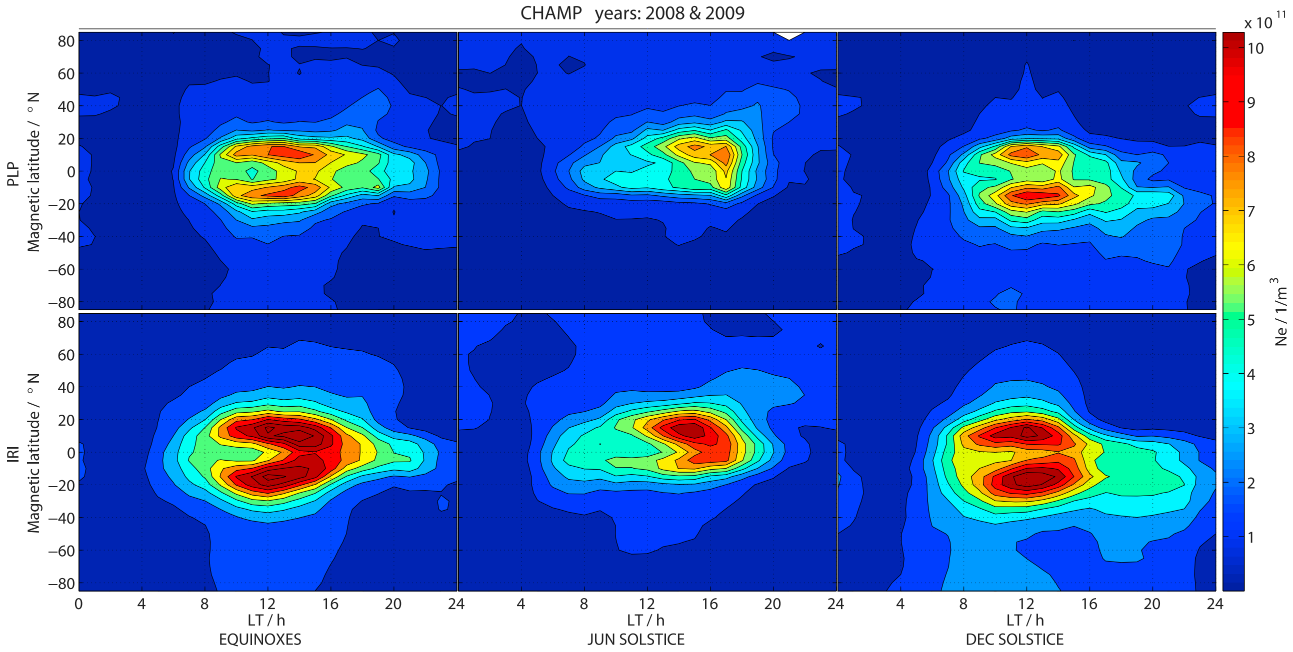

Figure 3. Distribution of electron density versus magnetic latitude and local time (averages over all longitudes) separately for the three Lloyd seasons. (top) CHAMP observations of the years 2008 and 2009, and (bottom) collocated IRI *Ne* predictions.

while from CHAMP measurements the peaks appear to be separated only by 27.5° in latitude. Both these facts imply that IRI is strongly overestimating the equatorial ion fountain effect during the considered solar minimum. This means, more plasma is moved up and it reaches larger heights.

4. Discussion

[21] Based on comparison with CHAMP and GRACE measurements we found that the IRI-2007 model overestimates the electron density by a factor of more than 1.5 in the height range 300 to 500 km during the deep solar minimum of solar cycle 23/24. Conversely, during solar maximum years up to 2004 on average a reasonable agreement of the model at the two altitudes is found. During the minimum years 2008 and 2009 CHAMP was cruising at altitudes of 320–340 km, and GRACE stayed between 450 and 470 km. According to observations by *L. Liu et al.* [2006] the F2 peak height during solar minimum stays below the altitudes of the two spacecraft. One of the new features of IRI-2007 is the improvement in topside electron density. Previous versions tent to overestimate *Ne* above the F2 peak [*Bilitza and Reinisch*, 2007]. We also tried an earlier version of IRI-2007 (updated on 9 Feb. 2009). There we found overestimations of more than a factor of 2 for the year 2009. Obviously the improvements of IRI go in the right direction, but they are not sufficient to account for the special conditions during the recent solar minimum.

[22] By inspecting the latitude and local time distribution of the differences we find that the discrepancy between model and measurements stems primarily from a too strong equatorial ionization anomaly. Furthermore, the distribution of *Ne* suggests that the EIA from IRI peaks at a too large height above the magnetic equator. These two facts can be caused by a too strong vertical plasma drift.

[23] *Stolle et al.* [2008] have studied the L-value dependence of the EIA crests at CHAMP altitude on the prevailing vertical plasma velocity. Their result for L_{crest} obtained over Jicamarca reveals a linear correlation of the form

$$L_{crest} = 1.083 + 1.97 \cdot 10^{-3} v_z \qquad (2)$$

where v_z is the vertical plasma velocity measured in m/s and L_{crest} in Earth radius. We have used the definition of the L-value for dipole geometry

$$L = \frac{r}{R_E} \frac{1}{\cos^2\beta} \qquad (3)$$

where r is the radial distance of the measurement point from the Earth center, R_E = 6371 km is the Earth's radius, and β the magnetic latitude of the EIA crest. From Figure 3 we deduce latitudinal separations of the crests of 30.5° and 27.5° for the IRI and CHAMP results around 12:00 LT. This corresponds to L_{crest} of 1.130 and 1.115 for the model and observation, respectively. With the help of equation (2), we obtain vertical velocities of 25 m/s for IRI and 17 m/s for CHAMP results. For comparison, *Fejer et al.* [2008] obtain from their statistical analysis of ROCSAT-1 plasma drift measurements an average drift velocity of 20.5 m/s over the F10.7 range 100–160 sfu at 12:00 LT. They find almost no solar flux dependence of vertical drift around noon. The reported plasma drift velocity is half way between the values determined in this study. There have to be other causes than just low solar flux level for the small vertical plasma drift deduced from CHAMP observations.

[24] During the recent solar minimum some properties of the ionosphere seem to have changed that cannot simply be parameterized by F10.7 or a_p. In that case IRI, an empirical model, by design cannot reproduce the ionospheric properties correctly. Related problems have been identified by *Emmert et al.* [2010] for the neutral atmosphere when comparing thermospheric mass density measurements with predictions from MSISNRL-00. They report a record low of the thermospheric density during this solar minimum. Largest deviations from the model are observed just below 500 km altitude amounting to more than 20% depletion. For explaining this discrepancy they had to reduce the abundance of atomic oxygen by 12% at 120 km altitude and lower the exospheric temperature by 14K. They propose changes of chemical and dynamical processes in the mesosphere and lower thermosphere as being responsible for the depletion of O at the base of the thermosphere. We suggest that also the ionosphere has experienced fundamental modifications during the deep minimum. An indication for that may be the weak recovery of electron density at the end of 2009 when the solar flux has already started to rise again. This fact contributes significantly to the huge difference in *Ne* between IRI and satellite observations in 2009. It will be interesting to watch the evolution during the coming months and years. This may help to find out what kind of modification is required to adapt the IRI model to the new conditions.

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