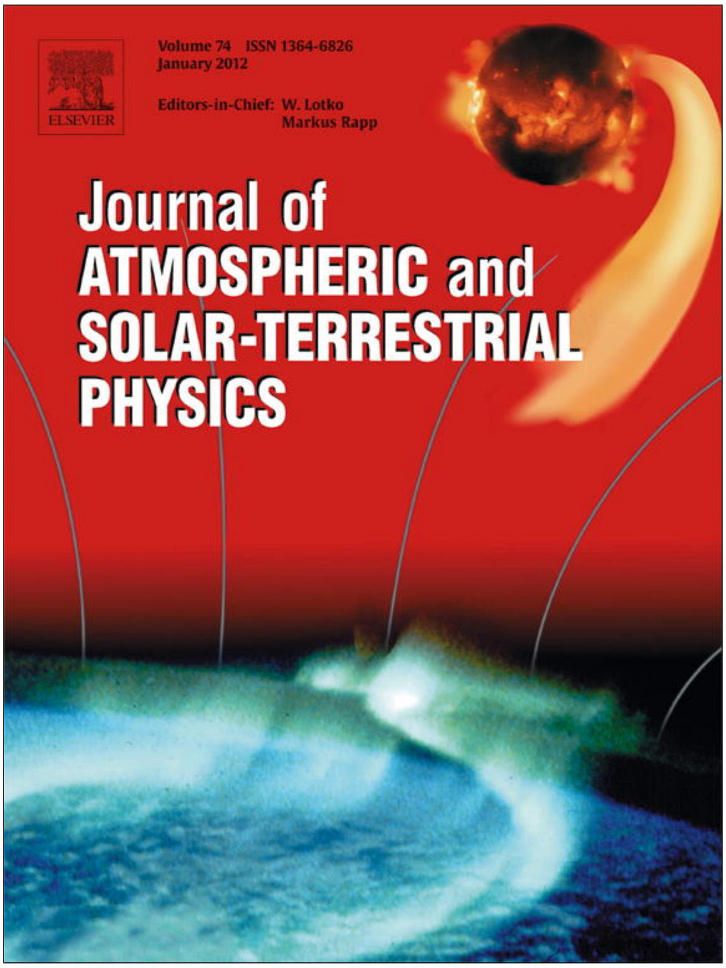
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Measurements and IRI model predictions during the recent solar minimum

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ABSTRACT

Cycle 23 was exceptional in that it lasted almost two years longer than its predecessors and in that it ended in an extended minimum period that proved all predictions wrong. Comparisons of the International Reference Ionosphere (IRI) with CHAMP and GRACE in-situ measurements of electron density during the minimum have revealed significant discrepancies at 400–500 km altitude (Lühr and Xiong, 2010). Our study investigates the causes for these discrepancies with the help of ionosonde and Planar Langmuir Probe (PLP) data from the Communications/Navigation Outage Forecasting System (C/NOFS) satellite. Our C/NOFS comparisons confirm the earlier CHAMP and GRACE results. But the ionosonde measurements of the F-peak plasma frequency (foF2) show generally good agreement throughout the whole solar cycle. At mid-latitude stations yearly averages of the data-model difference are within 10% and at low latitudes stations within 20%. The 60–70% differences found at 400–500 km altitude are not seen at the F peak. We will discuss how these seemingly contradicting results from the ionosonde and insitu data-model comparisons can be explained and which parameters need to be corrected in the IRI model.

1. Introduction

The recent solar cycle minimum, the minimum between cycles 23 and 24, was quite unusual. It lasted longer and reached lower than previous solar minima as is shown in Fig. 1. The duration of cycle 23 exceeded prior cycles by almost 2 years and the yearly solar radio flux (F10.7A) was about 5% lower than in previous cycles. In fact the sun exhibited 265 spotless days a record not reach since 1913. A number of articles have discussed the exceptional status of this minimum as documented in record lows in solar irradiance and solar wind and as a consequence a record high influx of cosmic rays. Examining satellite drag data Emmert et al. (2010) found the lowest thermospheric densities since the beginning of the space age. Solomon et al. (2010, 2011) showed that this very low densities can be explained by the anomalously low solar EUV fluxes observed by SOHO/SEM and TIMED/SEE. Liu et al. (2011) found that the 1-year moving mean of the F2 plasmas frequency, foF2, was lower than during previous cycle with the largest differences during daytime reaching 0.5–1.2 MHz. They note that these low values can be explained in terms of the observed decline in EUV irradiance. But many ionospheric models rely on the solar radio flux (F10.7) to represent solar forcing of the ionospheric plasma. Chen et al. (2011) showed that the decrease in solar EUV irradiance from the cycle 22/23 minimum to the 23/24 minimum was much larger (15%) than the decline in F10.7 (5%). The widely used F10.7 index is therefore not a good indicator for EUV variations during the cycle 23/24 minimum period.

C/NOFS-CINDI measurements have shown that the ionosphere significantly contracted during this period with the H^+ to O^+ transition height (Heelis et al., 2009) and the topside ion temperature (Coley et al., 2010) being much lower than the predictions by the International Reference Ionosphere (IRI). With IRI being the international standard for ionospheric parameters, there were a number of studies investigating the performance of IRI during these unusual minimum conditions. IRI is an empirical model and was developed with a large volume of the available ionospheric observations from ground and space (Bilitza and Reinisch, 2008). It was therefore expected that IRI would have some problems representing the ionosphere during the 23/24 minimum because no prior data were available for IRI modeling taken under similar conditions. In addition to the work with C/NOFS-CIDNI data an important study was undertaken by Lühr and Xiong (2010) using CHAMP and GRACE insitu measurements of electron density. These measurements at 350–450 km and 490 km, respectively, showed that IRI overestimated the measured densities by about 50% in 2009 and by about 60% in 2008. Our study is intends to investigate the causes for this discrepancy with ionosonde data and with insitu measurements from the C/NOFS-PLP instrument.

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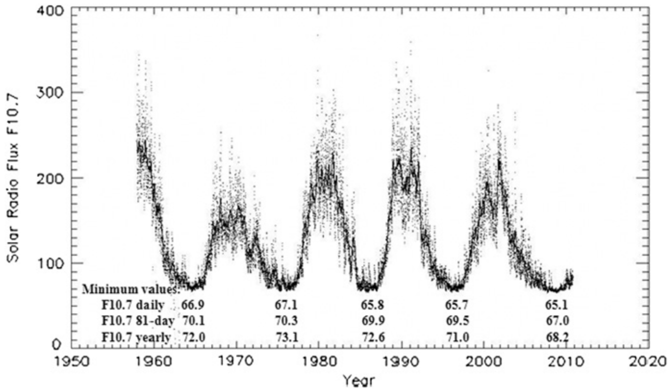

Fig. 1. Daily solar photon flux at 10.7 cm wavelength (F10.7) over the last solar cycles. The numbers at the bottom list the cycle minima at different levels of averaging. The last minimum is the deepest for all three levels of averaging. The length of the last cycle is about two years longer than previous cycles.

Table 1
Ionosonde station coordinates.

Station	Geodetic latitude	Geodetic longitude	Dip in 1980/90	Dip in 2010
Rome/Italy	41.8	12.5	57.3	57.6
L'Ebre/Spain	40.8	0.5	56.0	55.7
El Arensillo/Spain	37.1	353.3	51.8	50.9
Kwajalein/RMI[a]	9.4	167.4	7.9	8.3
São Luís/Brazil	−2.3	316.0	2.3	−4.6
Cachoeira Paulista/Brazil	−22.5	315.0	−28.9	−34.3
Ascension Island/BOT[b]	−7.9	345.6	−34.7	−38.7

[a] Republic of the Marshall Islands.
[b] British Overseas Territory.

2. Data and model used

The ionosonde stations used in this study and their coordinates are listed in Table 1. Our compilation includes 4 middle latitude stations (Rome, L'Ebre, El Arensillo, Ascension Island), one station at the magnetic equator (São Luís), and two stations at the flanks of the anomaly (Kwajalein, Cachoeira Paulista). All of the stations are operating Digisondes with the exception of Rome where the in-house developed AIS-INGV ionosonde is operated. We selected stations with long data records so that we would be able to compare foF2 during the current solar cycle with several prior cycles. Most of the data were retrieved with the help of the SPIDR system of NOAA's National Geophysical Data Center (NGDC). Data from the Brazilian stations were analyzed by Jonas Rodrigues de Souza who is a co-author of this paper.

The Communication/Navigation Outage Forecast system (C/NOFS) satellite is an Air Force mission with some of the instruments supported by NASA (De La Beaujardière et al., 2004). C/NOFS was launched on April 16, 2008 into a low-inclination (13°) orbit with a perigee near 400 km and an apogee near 850 km. The orbit is such that it takes 65 days for the perigee to precess through all local times. C/NOFS carried 6 instruments into space: (1) the Ion Velocity Meter (IVM), (2) the Neutral Wind Meter (NWM), (3) the Planar Langmuir Probe (PLP), (4) a GPS dual-frequency receiver (CORISS), (5) a radio beacon (CERTO), and (6) the Vector Electric Field Instrument (VEFI). The IVM and NWM are part of the Coupled Ion-Neutral Dynamics Investigation (CINDI) that is supported by NASA. For our study we rely on PLP measurements of the electron density from launch to present.

The satellite and ionosonde data will be compared with predictions of the International Reference Ionosphere (IRI) model (Bilitza and Reinisch, 2008). IRI is a widely used empirical standard for the representation of ionospheric densities and temperatures that was initiated in the late sixties by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) (Rawer et al., 1978). Our ionosonde comparison is focused on the plasma frequency foF2 that is routinely monitored by the ionosondes and that is proportional to the F2 peak density, NmF2. IRI offers two options for the plasma frequency foF2, the CCIR (1966) model and the URSI model (Rush et al.,1989). Both models will be used in our comparison.

3. Ionosonde comparison

In this section we compare ionosonde measurements of foF2 with predictions of the IRI model starting from 2011 and going back in time until 1980 or how ever far back data were available from the particular station. This will allow us not only to evaluate the performance of IRI during the recent solar minimum but also will let us compare with prior minima. In Fig. 2 we compare 30 years of data from three European stations representing middle Northern latitude conditions. These are the ionosondes located in Rome, Italy and the two Spanish stations l'Ebre and El Arenosillo (see Table 1). The parameter shown is the relative difference between the ionosonde measurements and the IRI/CCIR model defined as

$$PD = (foF2_{IRI} - foF2_{ionosonde})/foF2_{ionosonde} \quad (1)$$

The panels on the left side are for the daytime period LT = 10:00–14:00 and that on the right for the nighttime period LT = 22:00–2:00. The first row is for station Rome, the second for l'Ebre and the third for El Arenosillo. The data are given with an hourly resolution and cover the period from 980 to 2011 with data gaps where no data were available from NGDC/SPIDR.

For all three stations neither the daytime data nor the nighttime data show the increase in PD from 0.2 (20%) in 2006 to 0.6 (60%) in 2009 that Lühr and Xiong (2010) had found with CHAMP and GRACE density measurements in the altitude range 400–500 km. The PD values and PD variability for the cycle 23/24 minimum (2008/2009) is not significantly different from the rest of the 30 year time period. The F region peak is expected at a height level of about 200 km and is therefore below the altitude range of the satellite study.

Before we investigate the implications of these results for IRI in Section 5, we want to first discuss a few of the variation patterns seen in Fig. 2. For all three stations the daytime data are within 20–30% of the model predictions and the nighttime data within 30–40% for the whole 30 year time period. This agrees well with other studies of the percentage variability around the monthly mean (Bilitza et al., 2004). At nighttime, PD values are larger than during daytime because the absolute densities are much smaller than during daytime. While the data are mostly scattered evenly around the optimal fit case (PD = 0) we do recognize a small solar cycle signal in the data with the distribution shifted towards the negative side during solar minimum. This means that IRI slightly underestimates the foF2 values during solar minimum. It is a very small effect, best seen for the Rome data, but it is worth mentioning because it is opposite to the trend found by Lühr and Xiong (2010) at 400 and 500 km. Closer inspection also reveals a seasonal variation in the variability. During daytime the largest scatter is found during winter. This agrees with expectations because the absolute foF2 values are lowest in winter and therefore the relative change is much larger in winter than in the other seasons. During nighttime the data indicate that IRI underestimates summer values and

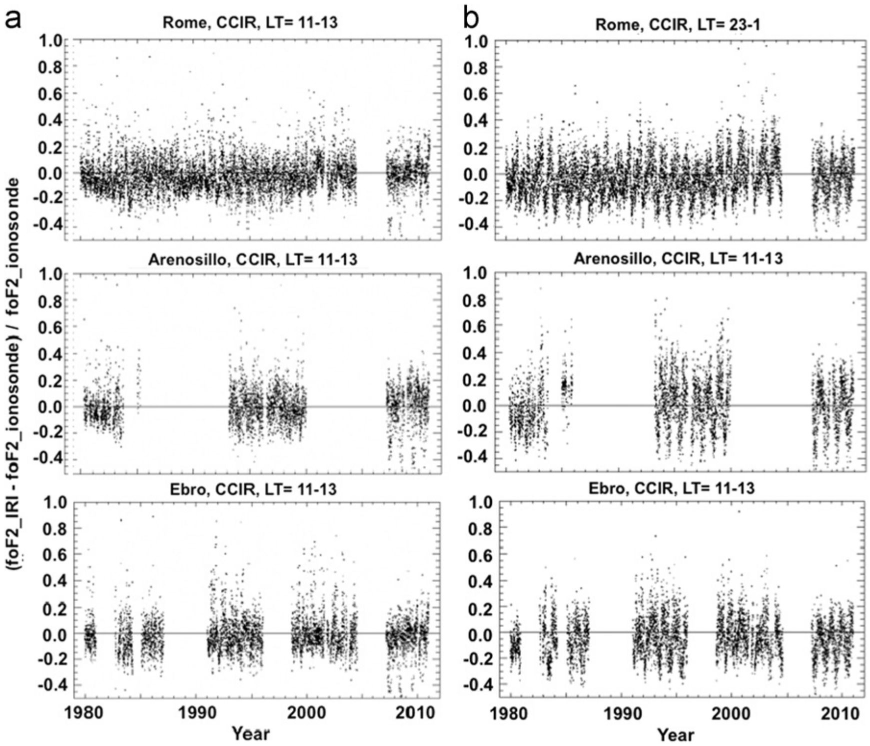

Fig. 2. (a and b) Scatter plots of the relative difference between IRI/CCIR and ionosonde measurements of foF2 for the Local Time period LT=11:00–13:00 (a, left column) and LT=23:00–1:00 (b, right column) for ionosonde stations at Rome, Italy (1st row), Ebro, Spain (2nd row), and Arenosillo, Spain (3rd row) over the time period from 1980 to 2011.

overestimates winter values. Although not the focus of this study this discrepancy in the representation of the annual variation, most clearly seen during nighttime, is important for future improvements of the IRI model.

To get a better understanding of the overall results of our comparisons we have calculated yearly averages. These are plotted in Fig. 3 which is organized in the same way as Fig. 2, except that we have not only included the PD averages computed with the IRI/CCIR option for foF2 but also with the IRI/URSI option. With just a few exceptions the yearly averages of the data-model differences for day and night are within 10% for the 30 year time period, which is a remarkable result by itself. The plot also shows again that nothing exceptional is happening during the 2008/2009 minimum in terms of IRI's predictive capabilities. We do see the IRI underestimation during solar minimum that was mentioned in the previous paragraph but the effect is very small. Concerning the CCIR and URSI foF2 options, our results slightly favor the CCIR model which is expected because the CCIR model is recommended for locations on the continents whereas URSI is the recommended choice for the ocean areas (Rush et al., 1989).

So far we have dealt with ionosonde stations from Northern middle latitudes. In Figs. 4–7 the relative differences PD are plotted for four ionosonde stations that are at low latitudes or in the Southern hemisphere. Kwajalein Island (Fig. 4) and Cachoeira Paulista (Fig. 6) are stations located on the flanks of the Equatorial Ionization Anomaly (EIA), São Luís (Fig. 7) is near the magnetic equator, and Ascension Island is at Southern mid-latitudes. The data are shown in separate figures because different time periods are covered by the different data sets. The starting year for available data is 2005 for Kwajalein Island, 2001 for Ascension Island, 1991 for Cachoeira Paulista, and 1995 for São Luís. Again we do not see a steep increase towards the recent solar minimum but a rather consistent variation behavior throughout the solar cycle. The day-to-day variability is largest at the stations near the anomaly flank (Kwajalein Island and Cachoeira Paulista) reaching up to 35–40% and it is lowest (about 20%) at the magnetic equator station (São Luís) and the Southern mid-latitude station (Ascension Island). As was the case for the Northern mid-latitude stations, we find that the yearly averages are within 10% with just a few exceptions. This is remarkable because foF2 in the EIA region is highly variable and can change largely from day-to-day. The Kwajalein nighttime data indicate shortcomings in the representation of annual variations in IRI similar to what we had observed with the mid-latitude data in Fig. 2. During nighttime the Ascension Island data consistently exceed the IRI values resulting in mostly negative PD values. Further analysis is required to investigate this special behavior, however this is not the topic of the present study.

4. Comparison with C/NOFS PLP data

Because we find that ionosonde foF2 data do agree well with IRI throughout the recent solar minimum contrary to what Lühr and Xiong (2010) had found with satellite in situ measurements in the region above the F peak, we decided to continue our investigation with a more recent data set of satellite in situ measurements. We are using the data from the Planar Langmuir Probe (PLP) instrument on the Communication/Navigation Outage Forecast system (C/NOFS) satellite. The data shown in Fig. 8 show the average PLP and IRI values for the altitude range 400–500 km and the Local Time range 10:00–14:00. The averages are taken over the 65-day LT repeat cycles. Starting from launch to mid-2010 we obtain 12 such repeat cycles and averages, and these are plotted in Fig. 8. The number of 1-second data points in each of the 65-day bins is in the 100,000 s (see the list of M values in Figs. 8 and 9). IRI averages are computed for the exact same conditions as the satellite data and averaged in the same way as the satellite data. IRI closely follows the annual and semi-annual variation seen in the C/NOFS data with peaks during the equinoxes and higher values in winter than in summer the

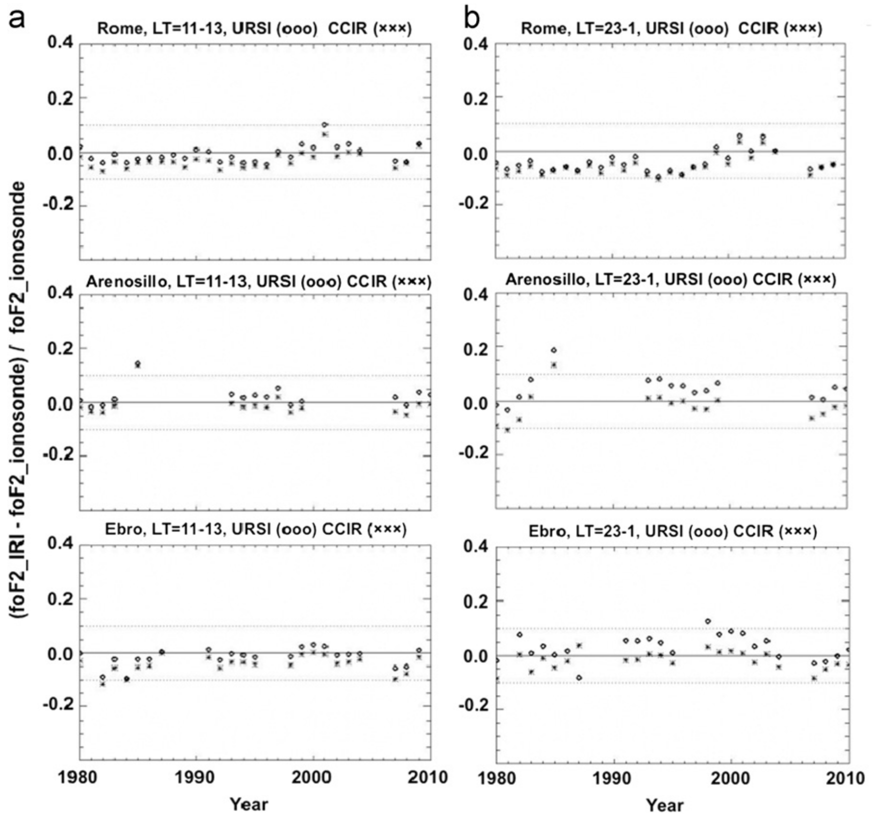

Fig. 3. (a and b) Yearly averages of the relative difference between IRI and ionosonde measurements of foF2 for the Local Time period LT=11:00–13:00 (a, left column) and LT=23:00–1:00 (b, right column) for the ionosonde stations at Rome, Italy (1st row), Ebro, Spain (2nd row), and Arenosillo, Spain (3rd row) over the time period from 1980 to 2011.

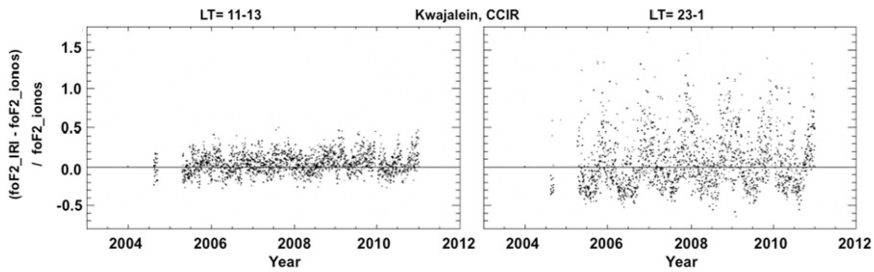

Fig. 4. (a and b) Scatter plots of the relative difference (PD) between IRI and ionosonde measurements of foF2 for the Local Time period LT=11:00–13:00 (a, left panel) and LT=23:00–1:00 (b, right panel) for the ionosonde station at Kwajalein, Republic of Marshall Islands over the time period 2004–2011.

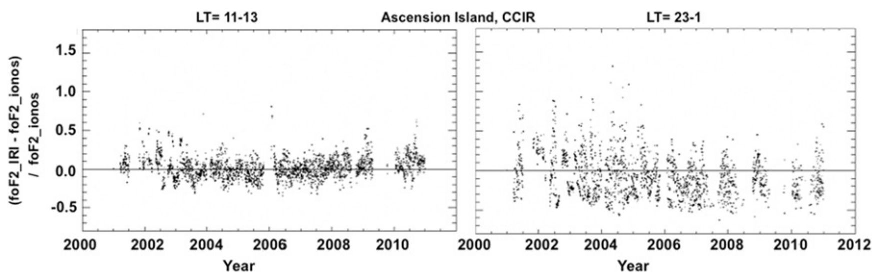

Fig. 5. (a and b) Scatter plots of the relative difference (PD) between IRI and ionosonde measurements of foF2 for the Local Time period LT=11:00–13:00 (a, left panel) and LT=23:00–1:00 (b, right panel) for the ionosonde station at Ascension Island, British Overseas Territory over the time period 2001–2011.

well-known winter anomaly (WA). Both data and model also show an increasing trend with the increasing solar activity after the solar minimum was reached at the end of 2008. A similar trend is also seen with the nighttime data in Fig. 9 which also show the WA behavior for both model and data averages. The data and model overlap within their standard deviation ranges, but the IRI averages are systematically higher than the observations. The numbers on the left side of Figs. 8 and 9 list the model-data ratio for each one of the 12 cycles. During noon (Fig. 8) the ratio varies from 1.22 to 2.13 with an overall average of 1.74.

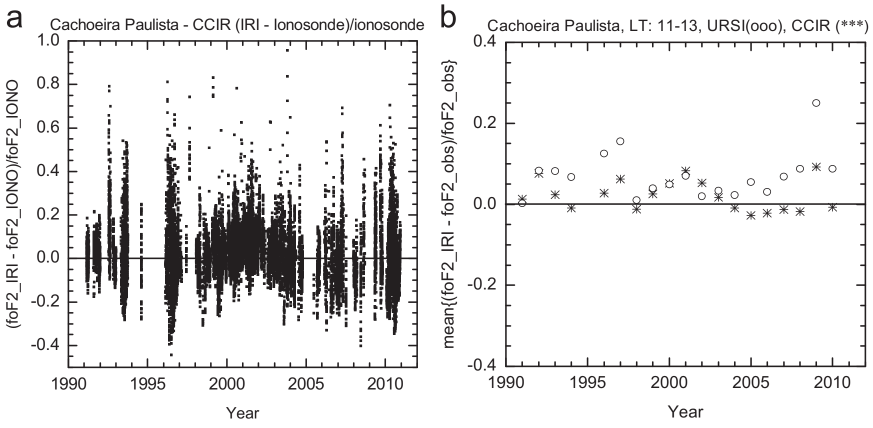

Fig. 6. (a and b) Scatter plot (a, left panel) of the relative difference (PD) between IRI and ionosonde measurements of foF2 for the Local Time period LT = 11:00–13:00 for the ionosonde station at Cachoeira Paulista, Brazil (near anomaly crest) over the time period 1990–2011. The panel on the right shows the yearly averages of PD for the two IRI foF2 options (CCIR and URSI maps).

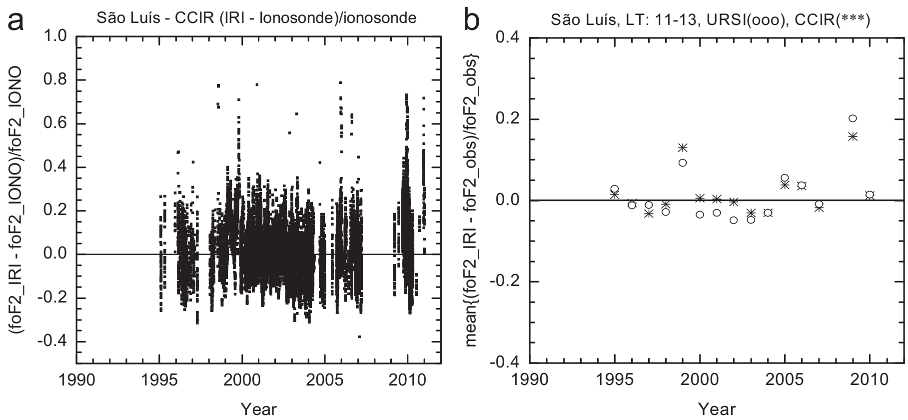

Fig. 7. (a and b) Scatter plot (a, left panel) of the relative difference (PD) between IRI and ionosonde measurements of foF2 for the Local Time period LT = 11:00–13:00 for the ionosonde station at São Luís, Brazil (near magnetic equator) over the time period from 1995 to 2011. The panel on the right shows the yearly averages of PD for the two IRI foF2 options (CCIR and URSI maps).

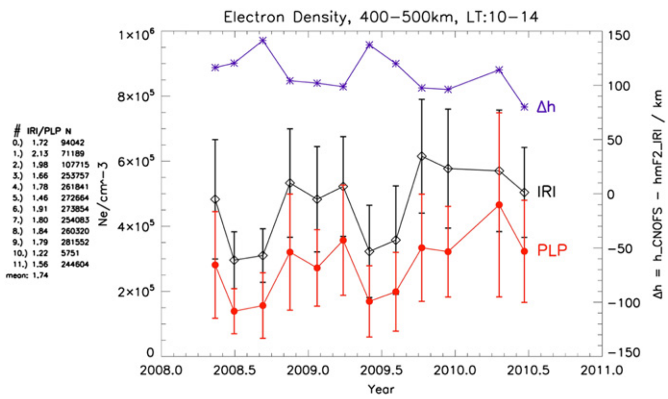

Fig. 8. Electron density averages and standard deviations computed from C/NOFS PLP data (●) and with the IRI model (◇) for the altitude range 400–500 km and the Local Time (LT) interval 10:00–14:00 from satellite launch to mid-2010. Averaging is done over all data points available within a 65-day LT-repeat cycle. The uppermost curve (×) shows the average difference between the satellite altitude (h_CNOFS) and the IRI-predicted height of the F-peak (hmF2_IRI). The table on the left lists the ratio IRI vs. PLP density and the total number of data points in each one of the considered 65-day periods.

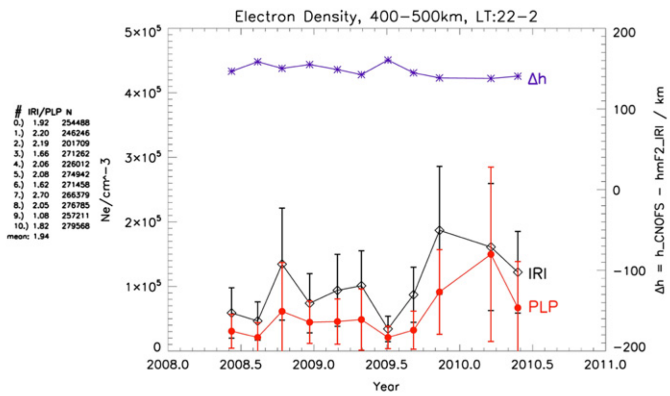

Fig. 9. Electron density averages and standard deviations computed from C/NOFS PLP data (●) and with the IRI model (◇) for the altitude range 400–500 km and the Local Time (LT) interval 22:00–2:00 from satellite launch to mid-2010. Averaging is done over all data points available within a 65-day LT-repeat cycle. The uppermost curve (×) shows the average difference between the satellite altitude (h_CNOFS) and the IRI-predicted height of the F-peak (hmF2_IRI). The table on the left lists the ratio IRI vs. PLP density and the total number of data points in each one of the considered 65-day periods.

This corresponds to a percentage difference between model and data of 74% and is similar to what Lühr and Xiong (2010) had found with CHAMP and GRACE data.

For nighttime the ratio is even larger with an average difference of 94%. In fact these numbers are higher than the 60–65% that Lühr and Xiong (2010) had found. But their percentages were based on orbit averages covering all latitudes because both CHAMP and GRACE are in high-inclination (polar) orbits, whereas C/NOFS is in a low-inclination orbit covering only equatorial and low latitudes up to 13°. As Lühr and Xiong (2010) noted the data-model discrepancies are highest in the Equatorial Ionization Anomaly (EIA) region and since C/NOFS only samples this region it is not surprising that it generates higher percentage differences than the other two satellites. For day and night the ratio shows an overall decrease with increasing mission time and thus a better data-model agreement as we move away from the solar minimum.

There is a third curve in Figs. 8 and 9 and that shows the average altitude difference from the C/NOFS satellite down to the IRI-predicted height of the F peak, hmF2. This parameter will be important in the context of discussing the causes of the data-model differences in the next section. We find that on average the satellite is about 100 km above the IRI F peak during daytime and about 150 km during nighttime. This reflects the fact that at low latitudes IRI predicts lower hmF2 values at night than during daytime.

5. Discussion

How is it possible that we find good agreement between IRI and observations at the F-peak but large discrepancies at about 100–150 km above the peak? To answer this question we have to understand the way the electron density profile is described in the IRI model. In IRI the topside electron density profile is normalized to the F-peak density (NmF2) and height (hmF2). The absolute value of electron density found at a fixed height is therefore determined by the models for NmF2 and hmF2 and by the model for the parameters that determine the topside profile shape. In our ionosonde comparison in Section 3 we have shown that there is good agreement between observations and model for NmF2. The problem therefore must lie with either hmF2 or the topside shape parameters or a combination of the two. The focus of this study is hmF2, the topside shape parameters will be the topic of a follow-on investigation.

In IRI the correlation between hmF2 and the propagation factor M(3000)F2 is used to model the F2-peak height. This is done because M(3000)F2 can be relatively easily measured with an ionosonde from the ground and a long data record and also global models exist for this parameter. The same is not true for hmF2 which requires scaling and inverting of the ionogram which has only recently become part of the routine operations with the advent of the modern digisondes. M(3000)F2 is defined as *MUF/foF2* where the maximal usable frequency (*MUF*) is the highest frequency at which a radio wave can propagate from a given point over a distance of 3000 km. Shimaizaki's (1955) early work had shown a close anti-correlation between hmF2 and M(3000)F2. Later studies found that additional terms had to be added describing the effect of the ionization below the F2 peak (Dudeney, 1978) and the variation with solar activity (Bilitza et al., 1979). IRI uses the Bilitza et al. (1979) formula and the CCIR (1966) M(3000)F2 model. This M(3000)F2 model uses the same special spherical harmonics representation as the widely used CCIR foF2 model but to a lesser order. It uses only about half the amount of coefficients as the foF2 model and therefore lacks in the description of smaller scale longitudinal, latitudinal and temporal variations of hmF2. One well-known shortcoming is the omission of the evening spike in hmF2 at low latitudes.

In Fig. 10 we illustrate how a change in IRI hmF2 (Fig. 10a) or in topside profile shape (Fig. 10b) could lead to a good agreement with the CHAMP measurements without changing the IRI F2-peak density (NmF2). In this paper we focus on the change in hmF2. By lowering the IRI hmF2 value the profile is shifted downward resulting in lower densities at the satellite orbit altitude. Lower hmF2 values during this solar minimum are in fact expected because of the unusually low neutral temperatures and densities (Emmert et al., 2010) resulting from the very low and extended minimum in solar EUV fluxes. Using the IRI topside profile, we have calculated the decrease in IRI hmF2 (ΔhmF2) required to get a 70% density reduction at an altitude of 450 km at low latitudes. We have done this exercise for magnetic latitudes from -20° to 20° in steps of 5° for noon and midnight for different seasons in the minimum years 2008 and 2009. For these conditions the required ΔhmF2 varies from 59 to 66 km.

Araujo-Pradere et al. (in press) have looked at ionosonde hmF2 measurements during the recent minimum and how well they compare to IRI predictions. They find that IRI overestimated the values deduced from ionograms but only by 10–20 km much lower than what our analysis required. But their study was based on data from middle latitudes stations. We have used data from the two Brazilian stations Cachoeira Paulista and Sao Luis to investigate the model-data discrepancies for hmF2 in the low latitude region. The results are shown in Figs. 11 and 12. While IRI overestimates hmF2 measured at Sao Luis by about 40 km it underestimates the Cachoeira Paulista measurements by about the same amount. Near the magnetic equator (Sao Luis) we therefore are close to the required hmF2 correction that would lead to a better agreement of IRI with the satellite electron densities. But at Cachoeira Paulista, a station at the edge of the EIA region, hmF2 would have to be shifted upward and therefore lead to even larger discrepancies

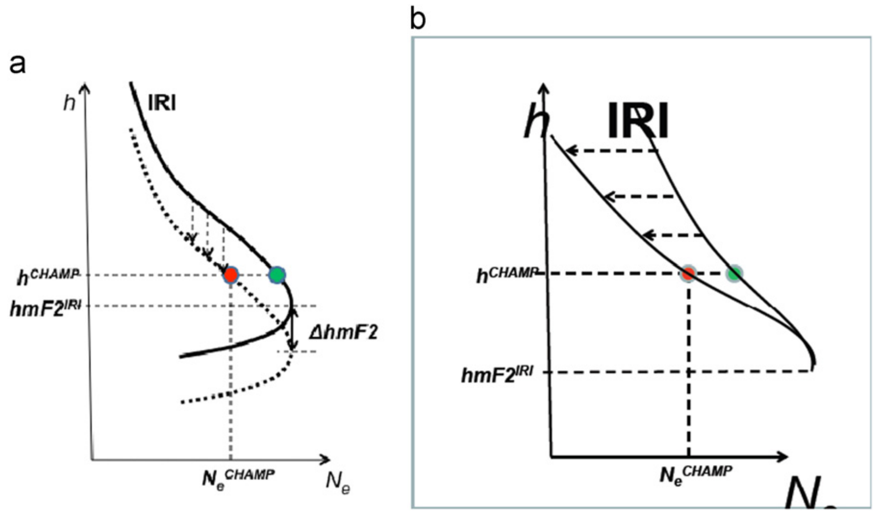

Fig. 10. (a and b) Illustration of the change in IRI F2-peak height hmF2 (a, on right) or in IRI topside profile shape (b, on left) that would be required to bring agreement of the IRI density with the CHAMP measurement.

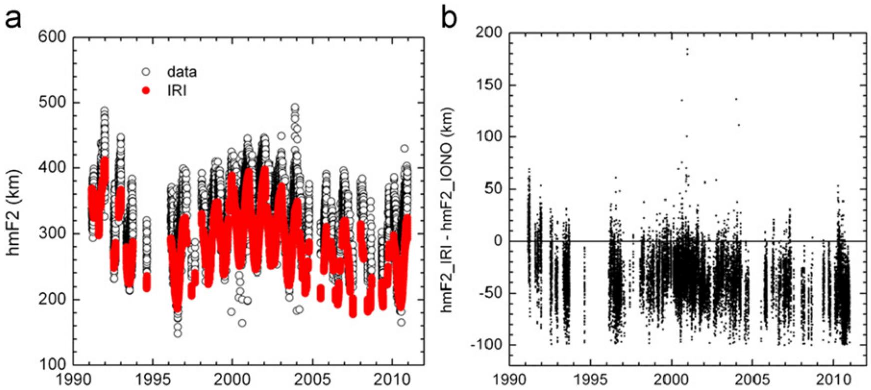

Fig. 11. (a and b) The panel a on the left shows the F2-peak height (hmF2) as measured by the ionosonde at Cachoeira Paulista, Brazil (open circles) and as predicted by IRI (red circles) during noon (LT:11–13) from 1991 to 2011. Panel b on the right shows the difference between the modeled and measured hmF2.

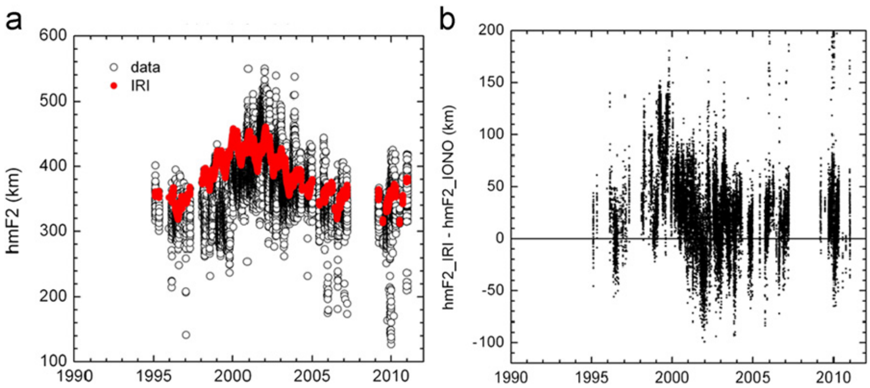

Fig. 12. (a and b) The panel a on the left shows the F2-peak height (hmF2) as measured by the ionosonde at Sao Luis, Brazil (open circles) and as predicted by IRI (red circles) during noon (LT:11–13) from 1991 to 2011. Panel b on the right shows the difference between the modeled and measured hmF2.

with the satellite measurements. For both stations the best agreement is found during solar maximum and discrepancies increase towards solar minimum indicating a systematic misrepresentation of solar activities trends in the IRI hmF2 model.

6. Summary and conclusions

We have investigated possible causes for the shortcomings of the International Reference Ionosphere (IRI) model during the last solar minimum as reported by Lühr and Xiong (2010) with CHAMP and GRACE data and by Heelis et al. (2009) and Klenzing et al. (2011) with C/NOFS data. Our study finds that IRI predicts quite well the F-peak density, NmF2. Comparisons with middle and low latitude ionosonde measurements of NmF2 over several decades show good agreement with yearly average differences of less than 10% at middle latitudes and less than 20% at low latitudes. Our comparisons with C/NOFS PLP measurements confirm the earlier results of Lühr and Xiong (2010) with a 60–70% discrepancies during the minimum in the altitude range 400–500 km. Since the peak density NmF2 is well represented by IRI the cause for such a large discrepancy must lie with the IRI description of the F-peak height, hmF2, and of the shape of the topside profile. As an empirical model IRI is based on a large volume of past ground and space data. It represents conditions that have been observed during prior solar cycle minima. The model-data discrepancy is also an indication for the very special state the ionosphere was in during the most recent solar minimum and the uniqueness of this minimum compared to prior minima.

In this study we only investigate the impact of the hmF2 model. Record low neutral densities have been reported for this minimum (Emmert et al., 2010) and this could possibly lead to very low values of hmF2 thus explaining a potential misrepresentation in the current IRI model. Our exercise of leaving the IRI topside profile shape unchanged and then estimating the change in peak height that would be required to achieve a 60–70% reduction of the IRI electron density in the altitude range 400–500 km, produced hmF2 reductions of about 60–70 km. Studies by Araujo-Pradere et al. (in press) with ionosonde data from the middle latitude stations Millstone Hill and Grahamstown found that IRI did indeed overestimates hmF2 measurements but only by about 10–20 km. But Lühr and Xiong (2010) had already found that most of their orbit-averaged discrepancy was accumulated at low latitudes. We have compared IRI hmF2 predictions with the measurements at the two Brazilian low latitudes stations Sao Luis and Cachoeira Paulista. We indeed find that at the magnetic equator (Sao Luis) the IRI overestimation of hmF2 is double that at middle latitudes. However, we also find that at the edge of the Equatorial Anomaly (Cachoeira Paulista) region IRI predictions are lower than what is measured and therefore would lead to even larger discrepancies at 400–500 km altitudes.

Further study is required with more data from different stations to fully evaluate this problem and to start developing improvements for the IRI hmF2 model. But it is worth pointing out that one important difference between the NmF2 and hmF2

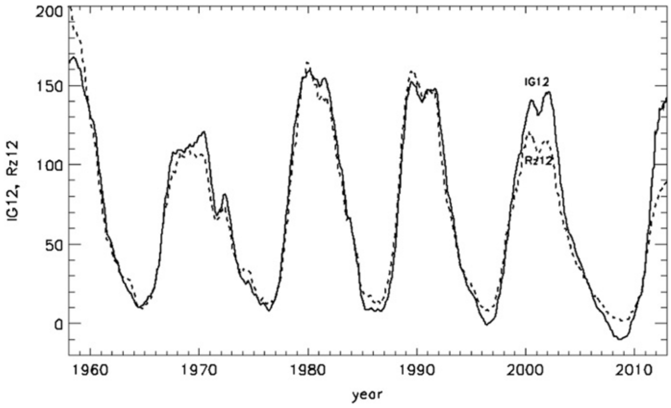

Fig. 13. Sunspot number Rz12 (broken curve) and ionosphere-effective solar index IG12 (solid curve) from 1958 to present. The values shown are the 12-months running mean of the index.

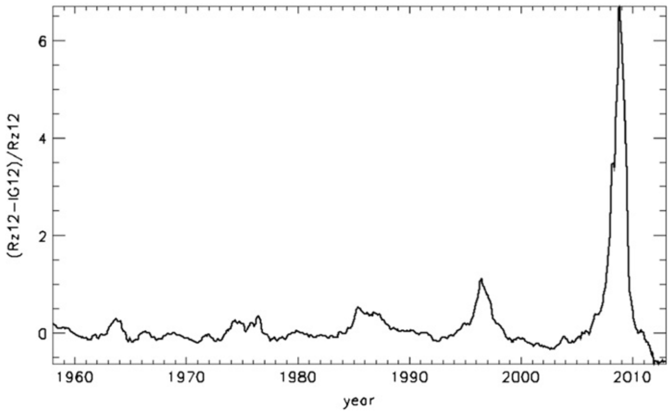

Fig. 14. Percentage difference between the Rz12 and IG12 indices from Fig. 13.

models is the reliance on different indices for describing the solar influence. While the IRI foF2/NmF2 model use a ionosphere-effective solar index that is based on ionosonde measurements, the IG12 index, the IRI hmF2 relies on the sunspot number Rz12. A comparison between these two indices over the last six solar cycles in Fig. 13 illustrates the insufficiencies of the sunspot number in describing the solar cycle changes observed in the F-region ionosphere with the most pronounced differences during the solar minima and maxima. The percentage differences between these two indices in Fig. 14 show the largest differences during the cycle minima and highlight the very special conditions during the most recent minimum. The percentage difference between the two indices is a factor of 4 higher during this minimum than during the previous minimum. In fact this representation seems to indicate an increasing trend in the percentage difference over the last few minima. It does show that sunspot number is not a good index for describing ionospheric conditions during the solar cycle minimum and definitely not during the most recent solar minimum. The next step therefore should be to develop an hmF2 model for IRI that depends on IG12 and not Rz12 for its description of variations with the solar cycle.

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