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Investigating the Accuracy of IRI Model for the Ionospheric TEC parameter during Strong, Severe and Great Geomagnetic Storms from 2000-2013

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Abstract

Several efforts have been made to study the behavior of Total Electron Content (TEC) with many types of geomagnetic storm, the purpose of this research is to study the disturbances of the ionosphere through the TEC parameter during strong, severe and great geomagnetic storms and the validity of International Reference Ionosphere IRI model during these kinds of storms. TEC data selected for years 2000-2013 (descending solar cycle 23 to ascending cycle 24), as available from koyota Japan wdc. To find out the type of geomagnetic storms the Disturbance storm time (Dst) index was selected for the years (2000-2013) from the same website. Data from UK WDC have been taken for the solar indices sunspots number (SSN), radio flux (F10.7) and ionosphere index parameter (IG12). The predicted TEC are calculated from IRI model. From data analysis, it is found that there are (132) events happened in the tested years for the strong, severe and great geomagnetic storms, a largest number of solar storms appeared in years 2000 to 2005 at solar maximum from solar cycle 23 and the number of storms increases with increasing the SSN. In general, there is a good proportionality between disturbance storm time index (Dst) and the total electron contents, the values of TEC in daytime greater than nighttime, but there is anomaly when the storm continued for several hours from the day, there is a highly a broad increasing in TEC started from sunrise to sunset. Also two peaks or more appeared when two types of storms occurred remaining for one event or the storm remains for more than one day. Finally there is approximately sharp peak at noon, when the storm started in early morning. Concerning the validity of the IRI model during strong, great, and severe geomagnetic storm shows that there is a weak correlation between the observed and predicted TEC values, so that the model must be corrected during major storms.

Keywords: TEC, Geomagnetic storm, IRI model.

التحقيق في دقة الانموذج النظري IRI في تنبأ المحتوى الالكتروني TEC خلال العواصف الجيومغناطيسية القوية والشديدة والكبيرة منذ عام ٢٠٠٠

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الخلاصة

العديد من الجهود بذلت لمعرفة سلوك او تصرف المحتوى الالكتروني TEC مع نوع العاصفة، الغرض من هذا البحث هو دراسة الاضطرابات التي تحدث في طبقة الايونوسفير من خلال العامل TEC اثناء الانواع

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الثلاثة من العواصف الجيومغناطيسية القوية والشديدة والكبيرة،وكذلك دراسة صلاحية الانموذج IRI أثناء هذه الانواع من العواصف. تم اختيار البيانات للمحتوى الالكتروني للأعوام ٢٠٠٠-٢٠١٣ (تنازل الدورة الشمسية ٢٣ وتصاعد الدورة ٢٤) والمتاحة من الموقع كيوتو اليابانية ولمعرفة نوع العواصف المغناطيسية الأرضية تم الاستعانة ببيانات المؤشر لاضطرابات العواصف (DST) ولنفس السنوات المختارة في هذه الدراسة والتي أخذت من نفس الموقع الياباني. أخذت البيانات من المملكة المتحدة WDC للنشاط الشمسي والمتمثل بعدد البقع الشمسية (SSN)، والتدفق الراديوي (F10.7) ومؤشر الغلاف الجوي المتأين (IG12).ولقد حسبت القيم المتوقعة للمحتوى الالكتروني من الموديل النظري IRI وتم مقارنتها بالقيم المرصودة. من خلال تحليل البيانات، وجد أن هناك (١٣٢) عاصفة جيومغناطيسية قوية وشديدة وكبيرة حدثت اثناء السنوات المختارة في هذه الدراسة. ويبدو أن أكبر عدد من العواصف الشمسية حدثت خلال السنوات من عام ٢٠٠٠ لغاية عام ٢٠٠٥ من الدورة الشمسية ٢٣ اي عند النشاط الشمسي العالي. وبصورة عامة تبين ان قيم TEC في النهار اعلى من قيمها في الليل، ولكن هنالك شذوذ في الاحداث التي تستمر فيها العاصفة ليوم كامل تقريبا تبقى قيم TEC كبيرة ليلا ونهارا وكذلك ظهور قمتين او اكثر نتيجة لظهور نوعين مختلفين من العواصف، كما يمكن ان نلاحظ ظهور قمة حادة في منتصف النهار في حالة العواصف التي تكون في بداية الصباح. كما تظهر الدراسة أن هناك ارتباطا عظيما بين مؤشر (DST) وTEC ولوحظ بأن عدد العواصف يزداد مع زيادة عدد البقع الشمسية SSN. يمكن ان نلاحظ التغيرات الفصلية التي تحدث اثناء ظهور العواصف مع الاضطرابات في النشاط الشمسي وكشفت الدراسة بأنه في عام ٢٠٠٠ عندما يكون النشاط الشمسي عالي حدوث عواصف في كل شهر تقريبا اي لكل اشهر السنة، ولكن عندما يكون النشاط الشمسي واطئ للسنوات ٢٠٠٧-٢٠١٠ لا توجد عواصف على الاطلاق. بخصوص كفاءة الانموذج IRI خلال العواصف الجيومغناطيسية القوية والحادة والكبيرة وجد أن هنالك عدم ترابط بين القيم الملاحظة والقيم المتنبأ بها للمحتوى الالكتروني لذلك تم تصحيح النموذج النظري ليتوافق مع الارصادات خلال انواع العواصف المختارة.

Introduction

The topside ionosphere is the region which extends from the altitude of the F layer peak to about 2000 km and more, where plasma distributions are controlled by the plasma transport process, and field-aligned plasma flows play an important role in determining the plasma density profiles [1]. The radiation from the Sun and Earth's atmosphere form a system which is driven by the transfer of energy from the solar radiation to the constituent particles of Earth's atmosphere. Other factors such as season, position in the solar cycle, and geomagnetic activity also significantly affect on the behavior of the ionosphere [2]. As the ionosphere owes its existence to the Sun as the main ionizations energy source, the ionosphere naturally varies with time of day, season and geographic position [3]. Ionospheric disturbances can be resulted from solar disturbances or geomagnetic field disturbances. The ionospheric disturbances are associated directly or indirectly with the events on the Sun as well as the geomagnetic disturbances are also caused by events initiated from the Sun; however, these events rather affect the outer most geomagnetic field line (also called the magnetopause) and compress the geomagnetic field causing the geomagnetic disturbances [4]. Variations of the total electron content (TEC) of the ionosphere are mainly associated with major geomagnetic storms occurring with the arrival of coronal mass ejections (CMEs) to the Earth environment.

Geomagnetic Storm

The geomagnetic storm has adverse effect on the ground as well the space based technological systems, which are becoming integral parts of human life. The response of atmospheric constituents to the storm mainly, depends on the intensity of storm, time of occurrence, duration of storm, season and longitude. The geomagnetic storm can be either positive or negative depending on the increase or decrease in electron density. The state of geomagnetic storm is determined by the local time at which a storm starts. It is very well established that storm commencing in the day time results in the positive phase and that in night results the negative phase. The equator ward neutral wind alone or together with PPEF (prompt penetration of Electric field) can produce positive storm [5]. During magnetic disturbed conditions, the prompt penetration of magnetospheric electric fields (PPEF) mainly occurs during initial phase with IMF Bz reversal from northward to southward and during recovery phase with IMF Bz reversal from southward to northward. There are two principal sources for the variation in the low- and mid-latitude ionospheric electric field during geomagnetic storms, (1) prompt penetration of electric fields associated with magnetospheric convection and (2) the neutral wind disturbance dynamo [6].

The effect of ring current is very less during the quiet time. However ring current shows large disturbances in Dst index at the time of storm. The variation in current is responsible for the decrease of horizontal component of earth's magnetic field Bz. The Dst index defines the effectiveness of geomagnetic storm. The negative value of Dst index indicates the commencement of the storm. The intensity of storm depends on the value of Dst index. As the Dst index becomes more and more negative the storm also becomes stronger and stronger. Dst is expressed in nanoteslas (nT) and is based on the average value of the horizontal component of the Earth's magnetic field measured hourly at four near-equatorial geomagnetic observatories [7]. The minimum Dst value reached is often used to classify the strength of a geomagnetic storms as in table-1 below.

Table 1- Geomagnetic storm classification [8].

Dst value	Storm type
Minimum Dst below -20 nT	Weak storm
Minimum Dst below -50 nT	Moderate storm
Minimum Dst below -100 nT	Strong storm
Minimum Dst below -200 nT	Severe storm
Minimum Dst below -320 nT	Great storm

The Earth's ionosphere exhibits considerable diurnal, seasonal, and geographical variations with the solar disturbances and geomagnetic storms. It can cause serious problems in many radio applications such as radio communications, navigation and space weather. Since 1999, studies began to link the change of Total Electronic Content (TEC) with geomagnetic storms [9].

Previous studies

Baran, et al. (2001) analyses the spatial and temporal TEC changes through time series at selected sites and maps for different sectors of northern hemisphere in comparison with the quiet TEC variations, during November 1997 Storm [10]. Later Ezuqer, et al. (2004) studied the behavior of the Vertical Total Electron Content (VTEC) obtained from GPS signals, received during the high solar activity year 1999 at American sector for different latitudes and longitudes, the result showed that the VTEC variability during daylight hours is about 30٪ of median or less and for night time hours is greater than 30٪ [11]. Bhuyan and Borah, (2007) measured TEC simultaneously using GPS at Indian sector during 2003–2004. The results revealed that the IRI TEC is greater than those measured at about all local times [12]. Stankov (2009) studied TEC changes during the geomagnetic storms intensity, season, and latitude of the latest solar activity cycle using (GNSS) and European IGS (International GNSS Service) stations. The result was that the storm-time behavior of TEC shows amplitudes that tend to increase during more intense storms [13]. Sethi, et al. (2010) analyzed values of (TEC) measured by ATS-6 are used to assess the latest available IRI-2007 model during solar minimum over Indian sector covering equatorial to low-mid- latitudes stations. The study revealed that during all seasons and at all locations the TEC predicted by NeQuick and IRI01-corr options provided in the IRI-2007 model shows much better agreement with the TEC observations as compared to those generated by IRI-2001.option. TEC predicted using NeQuick option found to be little more closely to the observation except at equatorial station during daytime, while IRI-2001 option highly over estimates the TEC in all seasons and time [14]. Sura E (2012), which is found that there is a good correlation between the predicted and observed TEC values during no storm and moderate, but there is a bad correlation during strong and higher storm [15]. Adebiyi S.J., et al. in (2014) found that A strong seasonal anomaly and clear equinoctial asymmetry in TEC response to the storms were observed [16]. The last study made by Lopez-Montes et al. in (2015), they found that large geomagnetic storms produce significant ionospheric disturbances at mid latitudes over Mexico. Large ionospheric disturbances are observed (positive phase), probably associated with the PPEFs and equatorward neutral wind. In addition, some events produced negative ionospheric storms (negative phase), probably due to changes in the neutral composition. found that large geomagnetic storms produce significant ionospheric disturbances at mid latitudes over Mexico. Large ionospheric disturbances are observed (positive phase), robably associated with the PPEFs and equatorward neutral wind. In addition, some events produced negative ionospheric storms (negative phase), probably due to changes in the neutral composition [17].

The major purpose of this paper is to study the diurnal variation of ionospheric TEC during strong, severe and great geomagnetic storms for long time period 2000-2013, then to reveal the validity of IRI model during these kinds of storms.

Data Selection

In this research, the data of observed the total electron content parameter (TEC obs.) in (TECU) selected for years from 2000 - 2013 (during the descending phase of solar cycle 23 and ascending cycle 24), as available from the site World Data Center for Geomagnetism, Kyoto from Japanese GPS with coordinates (longitude 133^o E, latitude 33^o N), and height 600km except year 2001 there is no data. The solar indices sunspots number (SSN), radio flux (F10.7) and ionosphere index parameters (IG12) have been taken from the European website (http://www.ukssdc. ac.uk/wdcc1/data_menu.html) for the same years selected in this research. Also the Dst index have been taken for the period 2000-2013 from the Japanese website (http://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html). The predict TEC are calculated from IRI model (http://omniweb.gsfc.nasa. gov/vitmo/iri_vitmo.html).

Data Analysis

To find out the type of geomagnetic storms the Disturbance storm time index (Dst) was studied for the years selected in this research. Figure-1 reveals the monthly variation of disturbances storm time index Dst for years from 2000 to 2013. According to table 1 represented above, considered (Dst < -100 Strong storm, Dst < -200 Severe storm, and Dst < -320 nT Great storm). From figure 1 it is found that there are 132 events for great, serve, and strong geomagnetic storms are happened in years 2000-2013, which are chosen to study the validation of IRI model during these three kinds of storms, also Figures-2 and -3 represent the behavior of solar activity through the solar indices sunspot number (SSN) and solar flux ($F_{10.7}$) for the same years selected respectively.

Figures 4 –7 represent the daily variation of observed TEC (Obs.) comparing with predicted values of TEC calculated from IRI model with Dst index variation during geomagnetic storm through years chosen 2000-2013 respectively.

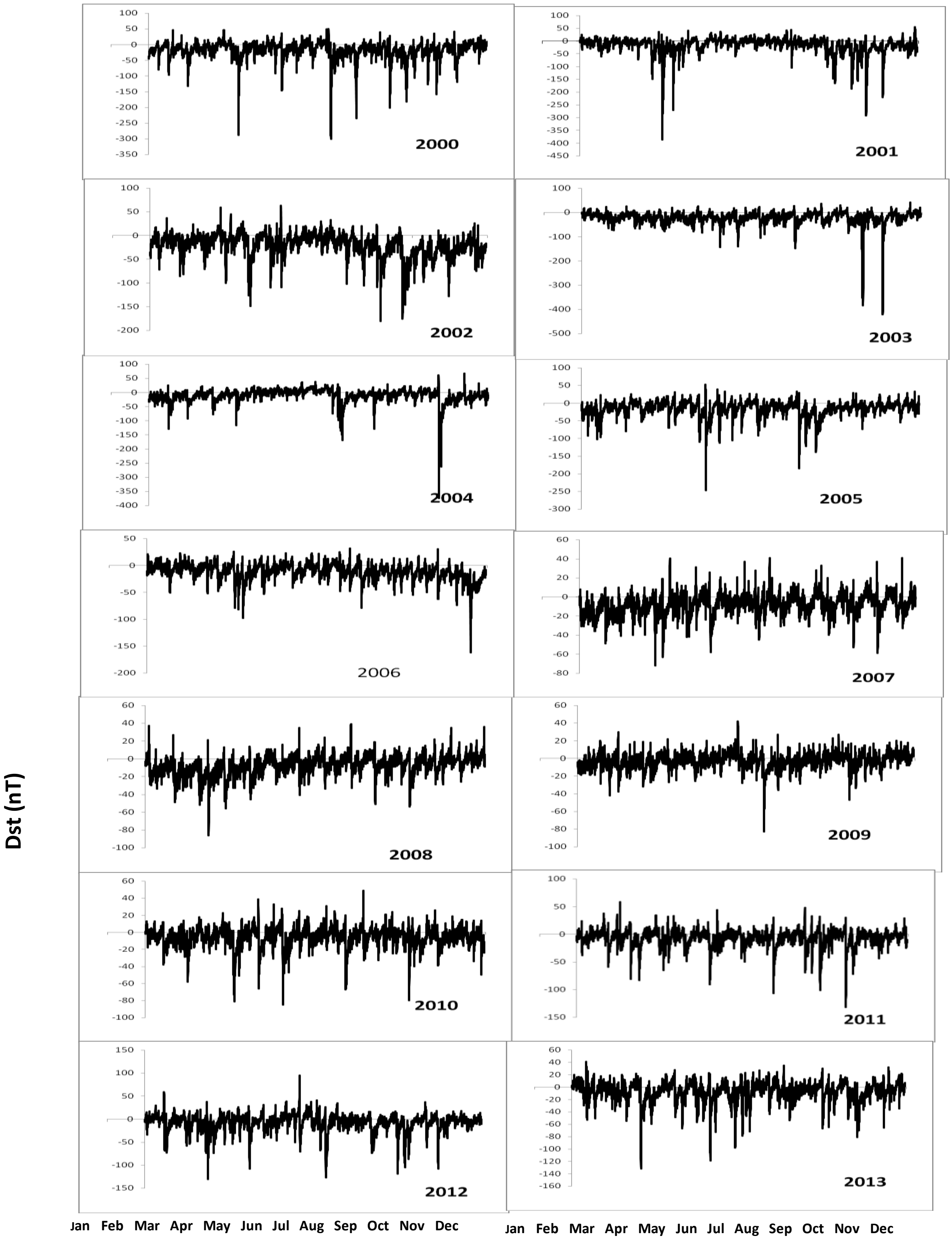

Figure 1- Daily variations of Disturbance storm time index values (DST) for years 2000-2013

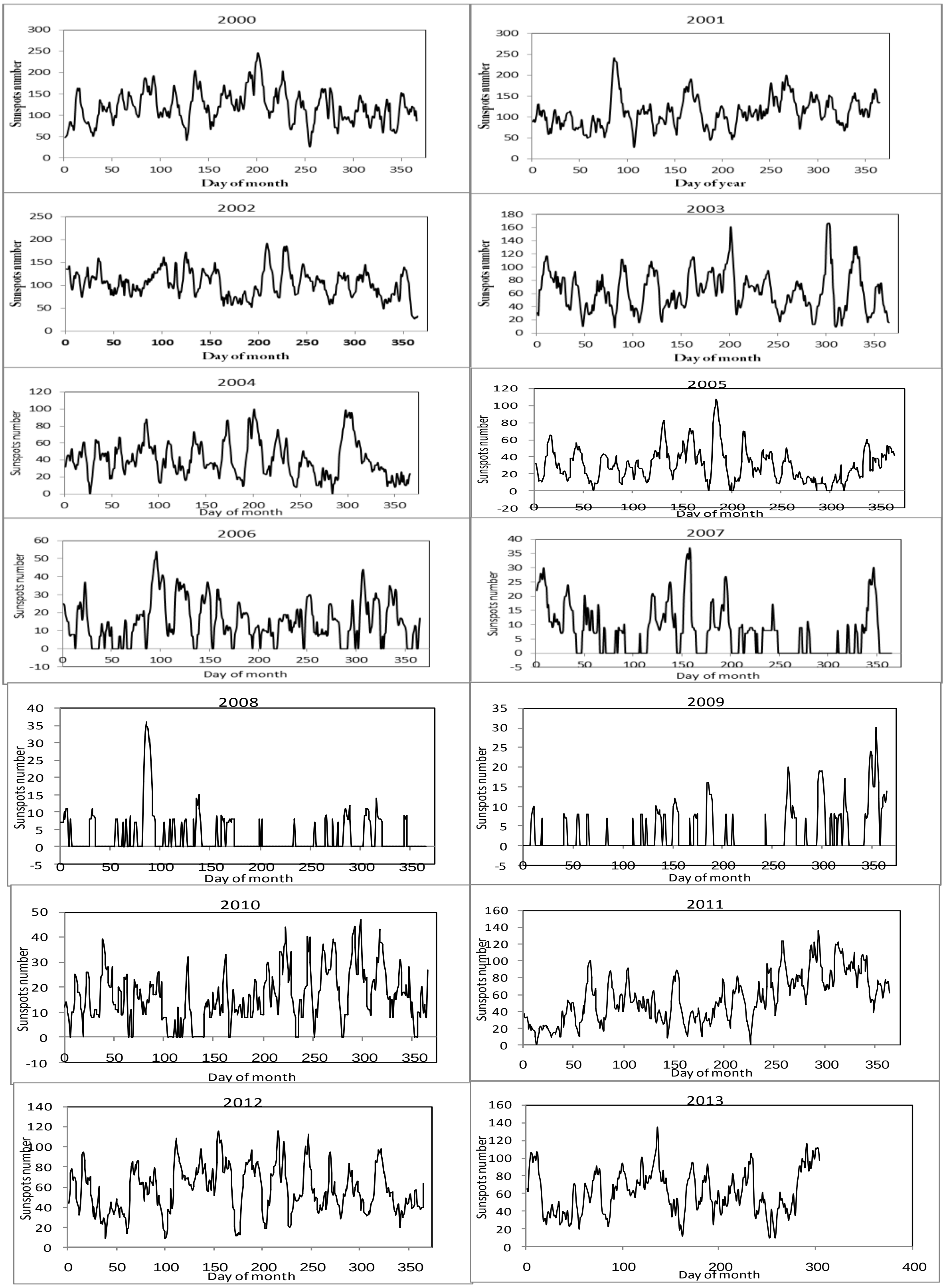

Figure 2- The daily variation of the sunspot number from 2000 to 2013.

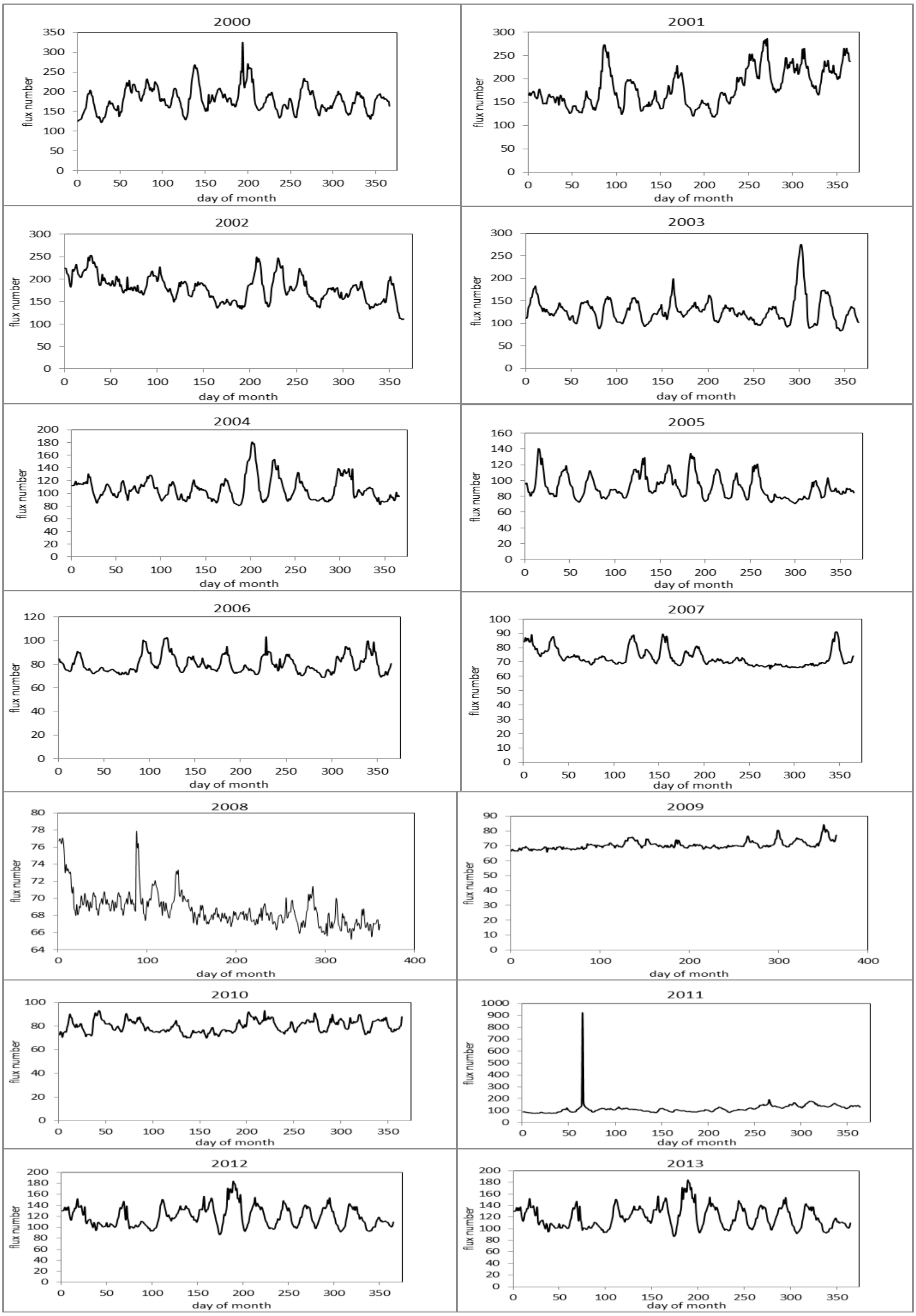

Figure 3- The daily variation of the solar radio flux F10.7 from 2000 to 2013.

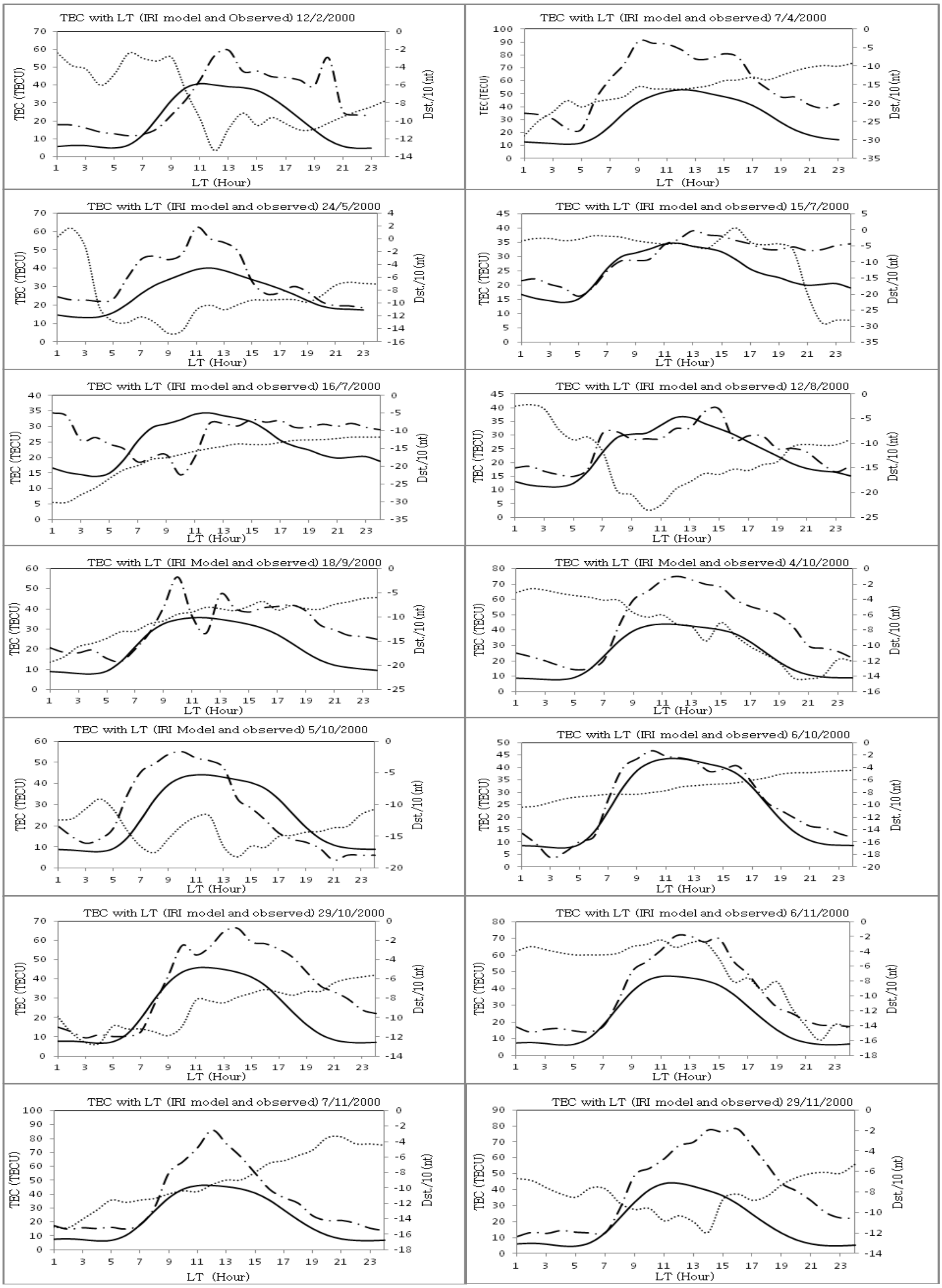

Figure 4- Daily variation of TEC comparing with IRI and Dst for year 2000 (____ IRI Model − · − · − observed, ····· Dst).

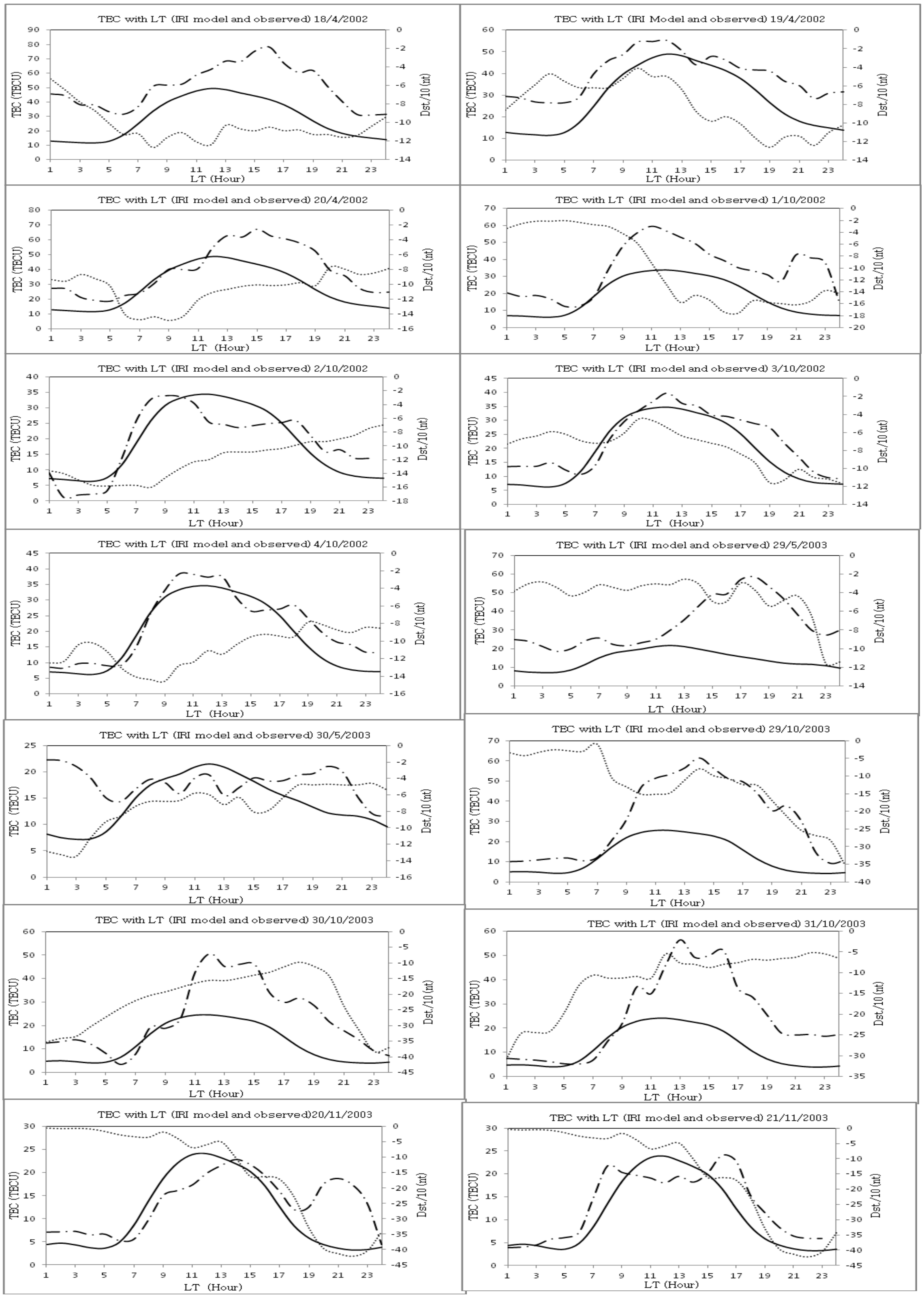

Figure 5- Daily variation of TEC comparing with IRI and Dst for year 2002 and 2003 (____ IRI Model −・−・− observed, ····· Dst).

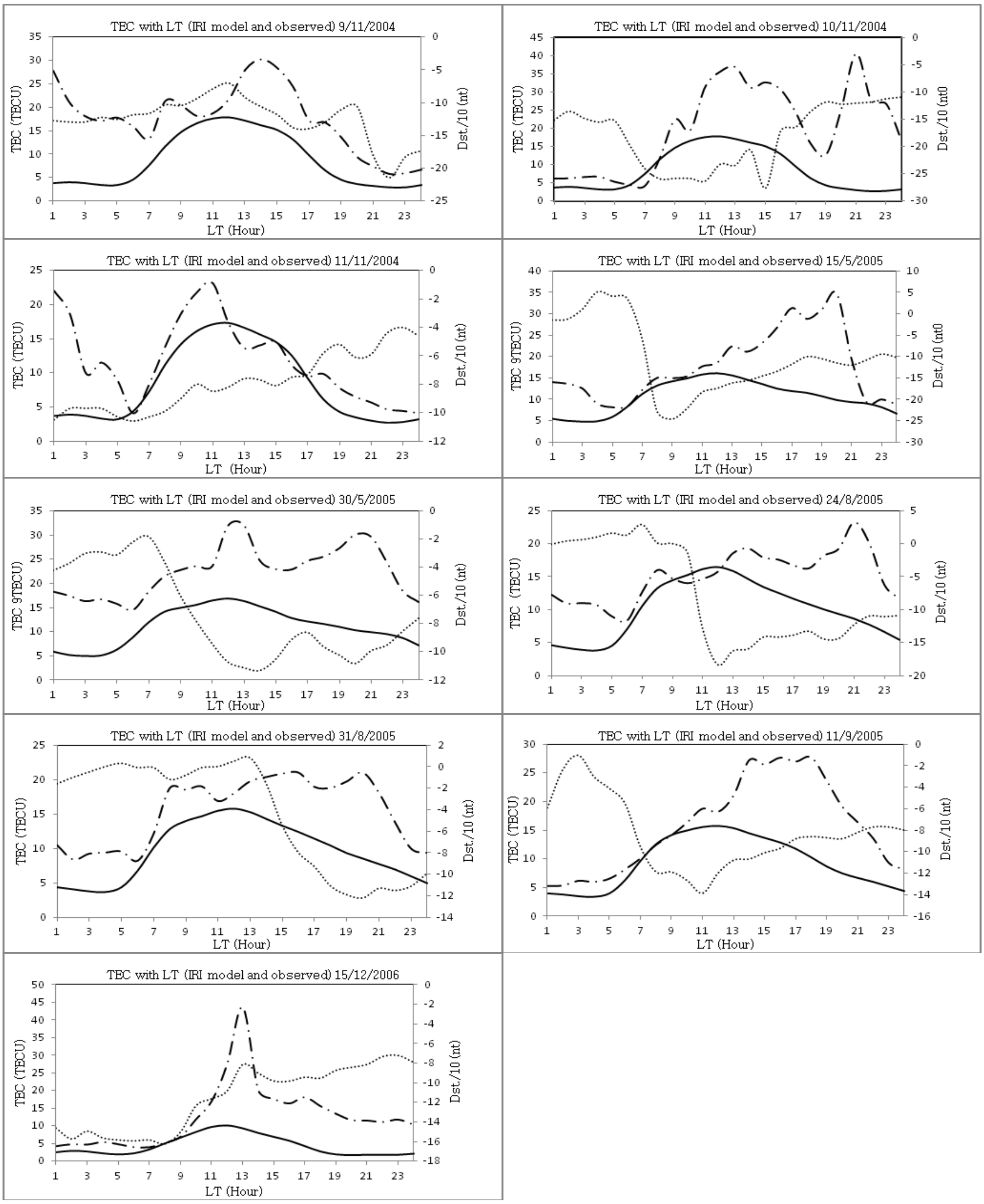

Figure 6- Daily variation of TEC comparing wih IRI and Dst for year 2004, 2005 and 2006 (____ IRI Model − · − · − observed, ····· Dst).

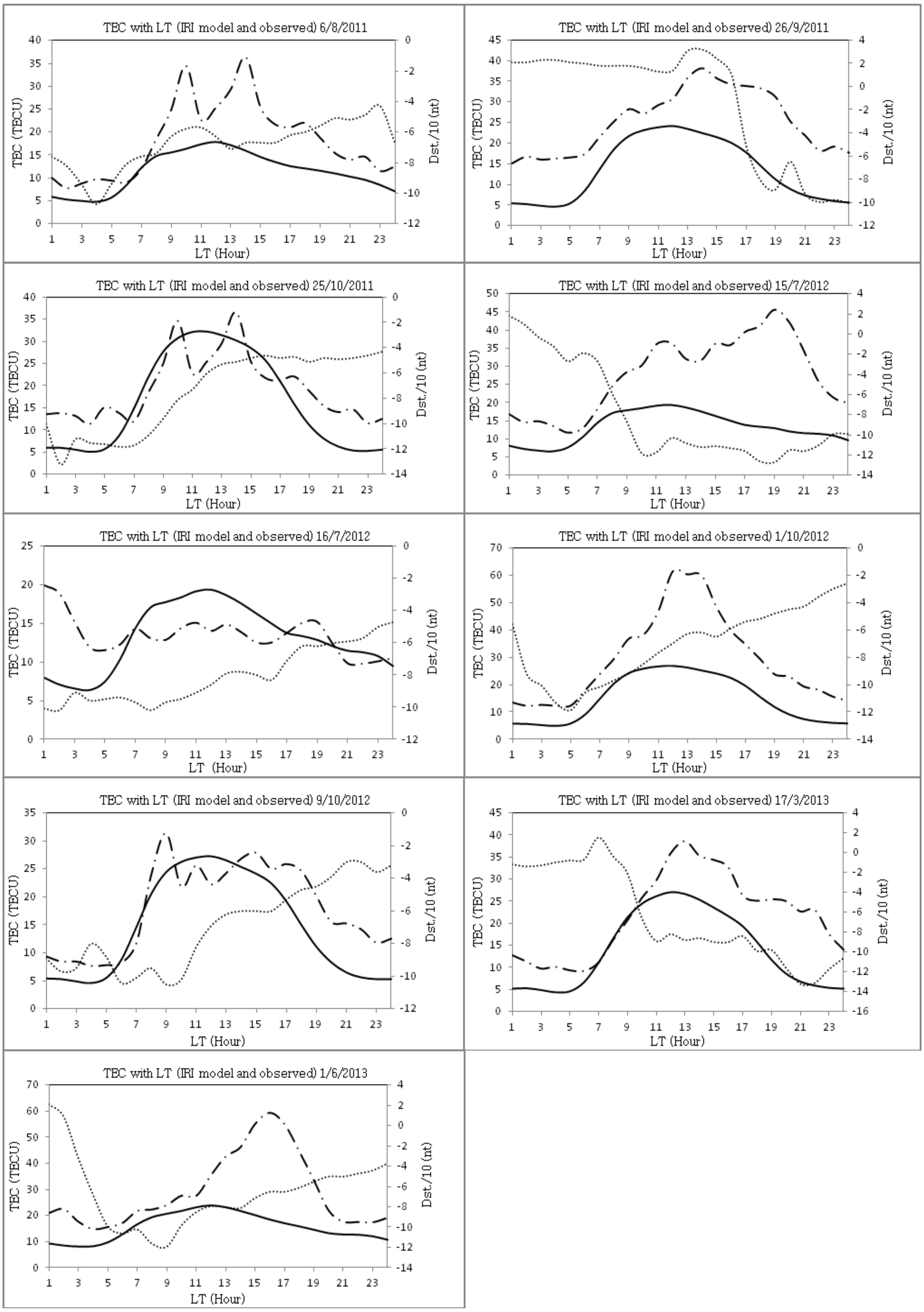

Figure 7- Daily variation of TEC comparing with IRI and Dst for year 2011, 2012 and 2013 (____ IRI Model − · − · − observed, ····· Dst).

Results and Discussion

From figure-1, we can see that a largest number of solar storms appeared in years from 2000 to 2005 at solar maximum from solar cycle 23 and the most powerful storm at (29-30 October 2003) with average daily Dst value (-350 nT). Also to see if there is any relation between the solar activity and the number of storms happened which is represented in table-2 and figure-8 plotted, which reveals the number of storms with years chosen in this research, from this graph we can see that there is a strong relation between the solar activity through the sunspot number it reveals that the number of storms increases with increasing the SSN. The classification of the present results is represented due to:

a) Diurnal Variation of TEC

Figures from 4-7 represent the daily variations of TEC and their behavior compared with predicted TEC calculated from IRI models for events from years selected respectively, which reveals that, in general

- It seen that there are a good preoperational between disturbance storm time index (Dst) and the total electron contents.
- The behavior of TEC is disturbed during the three types (strong, severe, and great) of geomagnetic storms with still values of TEC in daytime greater than nighttime, the profile of the curve reveals that the peak occurs at noon and the minimum value of TEC in sunrise and sunset.
- There is anomaly in case when the storm continued for several hours from the day the values of TEC remains great in day and night time, there is a highly a broad increasing in TEC started from sunrise to sunset, its appeared clearly in storms date (15-16/7/200, 30/5/2003 and 16/7/2012).
- It can be seen that two peaks or more appeared when two types of storms occurred remaining for one event or the storm remains for more than one day. The fluctuation in values of TEC due to the storm was continued for long time as in events date (12/2/2000, 16/7/2000, 6/10/2000, 29/10/2000, 19-20/4/2002, 1-2/10/2002, 4/10/2002, 20-21/11/2003, 9-11/11/2004, 30/5/2005, 24 & 31/8/2005, 6/8/2011, 25/10/2011, 15/7/2012, and 9/10/2012).
- There is approximately sharp peak at noon, when the storm started in early morning as in events date (7/11/2000, 15/12/2006, 1/10/2012 and 1/6/2013).
- From comparing between the observed and predicted (IRI model) values of TEC it is found that there is a weak correlation between observed and predicted values of TEC during great, serve, strong geomagnetic storm.

Table 2- Number of storms happen and SSN values for the years from 2000-2013.

Years	*No. of storms*	*SSN*
2000	14	119.57
2001	6	111.04
2002	7	104.06
2003	7	63.75
2004	3	40.48
2005	5	29.84
2006	1	15.23
2007	0	7.55
2008	0	2.82
2009	0	3.11
2010	0	16.47
2011	3	55.74
2012	4	57.68
2013	2	50.5

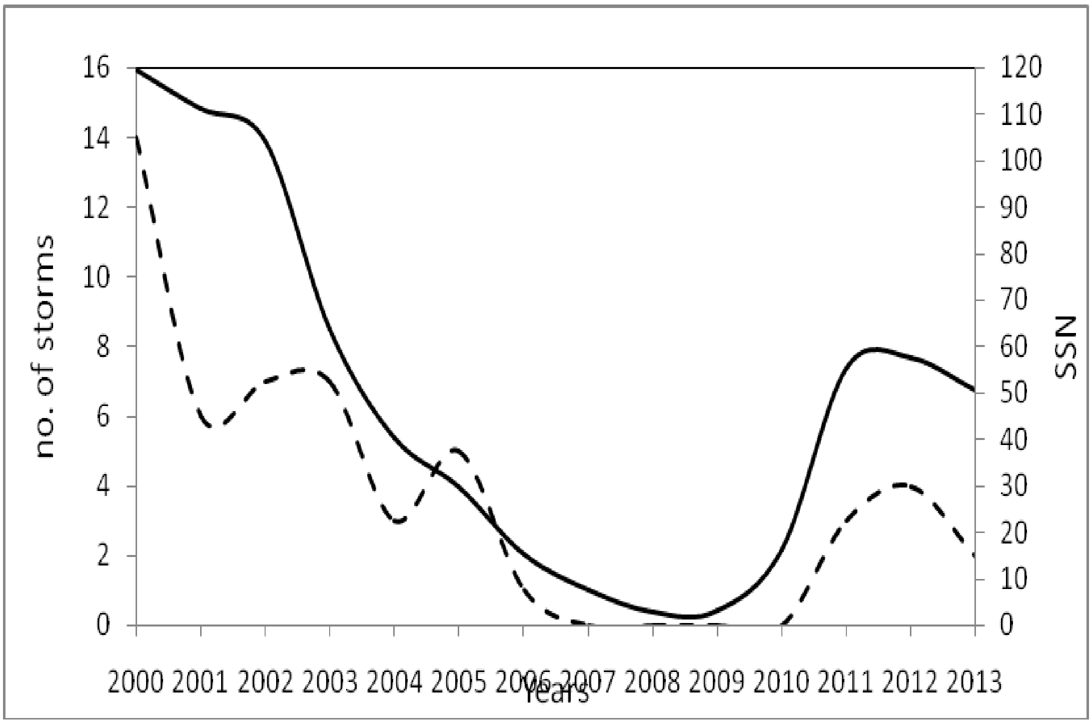

Figure 8- The relation between the no. of storms and SSN from year 2000-2013 (----- storms no.,____SSN).

b) Validity of IRI model

From figures 4-7 the ratio between the predicted and observed values was nonlinear with local time, so we sugested an empirical formulae (with polynomial form) to give the correction factor as a function of time. The general form of such formulae can be expressed as,

$$\mathrm{Corr} = a_o + a_1 T + a_2 T^2 + a_3 T^3$$

Where, T is the local time, (a_o, a_1, a_2, and a_3) correlation coefficients which are varied from event to other as in table-3; also they depend on the geomagnetic index (Dst). In this research efforts were made to assessing the correction formulae for each considered event. From these coefficient values the hourly survey daily correction charts were plotted and presented in figures 9- 12 reveal the observed, predicted and corrected values of the same years selected from 2000-2013 respectively, from these figures we can see that there is a good correlation between the corrected and observed values all over the years selected during the storm time as in table-4, which shows the root mean square error before and after correction for all events plotted.

Table 3- Correction coefficients for events.

Date	a_0	a_1	a_2	a_3
12/2/2000	0.7835	-0.0134	-0.02	0.0004
7/4/2000	0.4478	0.0049	0.0046	-0.0002
24/5/2000	0.533	0.028	0.0058	-0.0002
15/7/2000	0.9756	-0.0129	-0.0105	0.0002
16/7/2000	0.9963	-0.0053	-0.0281	0.0006
12/8/2000	0.8407	0.0046	-0.0075	0.0001
18/9/2000	0.7736	-0.009	-0.0138	0.0002
4/10/2000	0.6834	-0.0102	-0.0154	0.0003
5/10/2000	0.2152	0.0733	0.0297	-0.0008
6/10/2000	1.1722	-0.0196	-0.0009	-0.0002
29/10/2000	0.9789	-0.0265	-0.021	0.0005
6/11/2000	0.6981	-0.0088	-0.0099	0.0002
7/11/2000	0.6288	-0.0031	-0.005	-0.0006
29/11/2000	0.6961	-0.0179	-0.0107	0.0002
18/4/2002	0.499	0.0034	-0.0114	0.0002
19/4/2002	0.6105	0.0054	0.0004	-0.0001
20/4/2002	0.8088	-0.0074	-0.0204	0.0005
1/10/2002	0.6459	-0.008	-0.0099	0.0002
2/10/2002	2.4553	-0.091	0.0304	-0.0007
4/10/2002	1.0118	-0.0143	-0.0052	-0.0005
29/5/2003	0.5745	-0.0087	-0.0183	0.0004
29/10/2003	0.6269	-0.0144	-0.0155	0.0004
30/10/2003	0.8305	-0.0184	-0.0345	0.0009
31/10/2003	1.022	-0.0347	-0.023	0.0006
21/11/2003	1.0392	-0.0179	0.0045	-0.0002
9/11/2004	0.3671	0.0092	-0.00136	0.0003
10/11/2004	0.9453	-0.033	-0.0191	0.0004
11/11/2004	0.5452	0.0134	-0.0132	0.0002
15/5/2005	0.6666	-0.0012	-0.0287	0.0007
30/5/2005	0.4877	0.00009	-0.0101	0.0002
24/8/2005	0.6987	-0.0031	-0.015	0.0003
25/8/2005	1.2149	-0.01	-0.0199	0.0004
31/8/2005	0.6279	-0.0017	-0.0123	0.0003
11/9/2005	0.8601	-0.0176	-0.0162	0.0004
15/12/2006	0.7594	-0.0262	-0.0137	0.0003
6/8/2011	0.6707	-0.0015	-0.0066	0.0002
26/9/2011	0.5474	-0.0035	-0.0096	0.0002
15/7/2012	0.641	-0.0107	-0.0143	0.0004
1/10/2012	0.5458	-0.0039	-0.0046	-0.0009
9/10/2012	0.9529	-0.0143	-0.0131	0.0002
17/3/2013	0.7635	-0.0119	-0.014	0.0003
1/6/2013	0.6111	-0.0018	-0.0191	0.0005

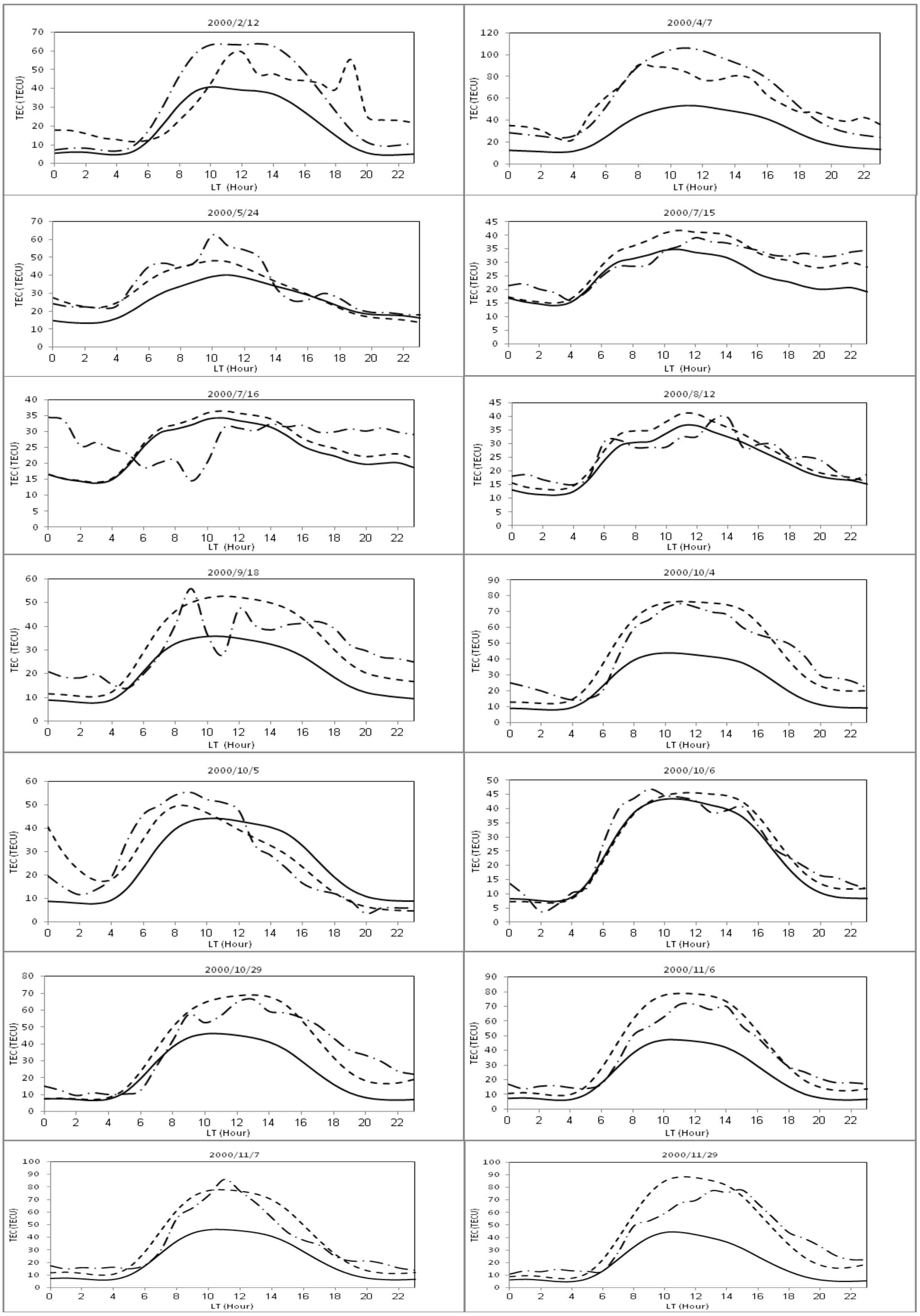

Figure 9- TEC for year 2000 (____ predicted IRI model, − · − · − observed, ------ corrected IRI).

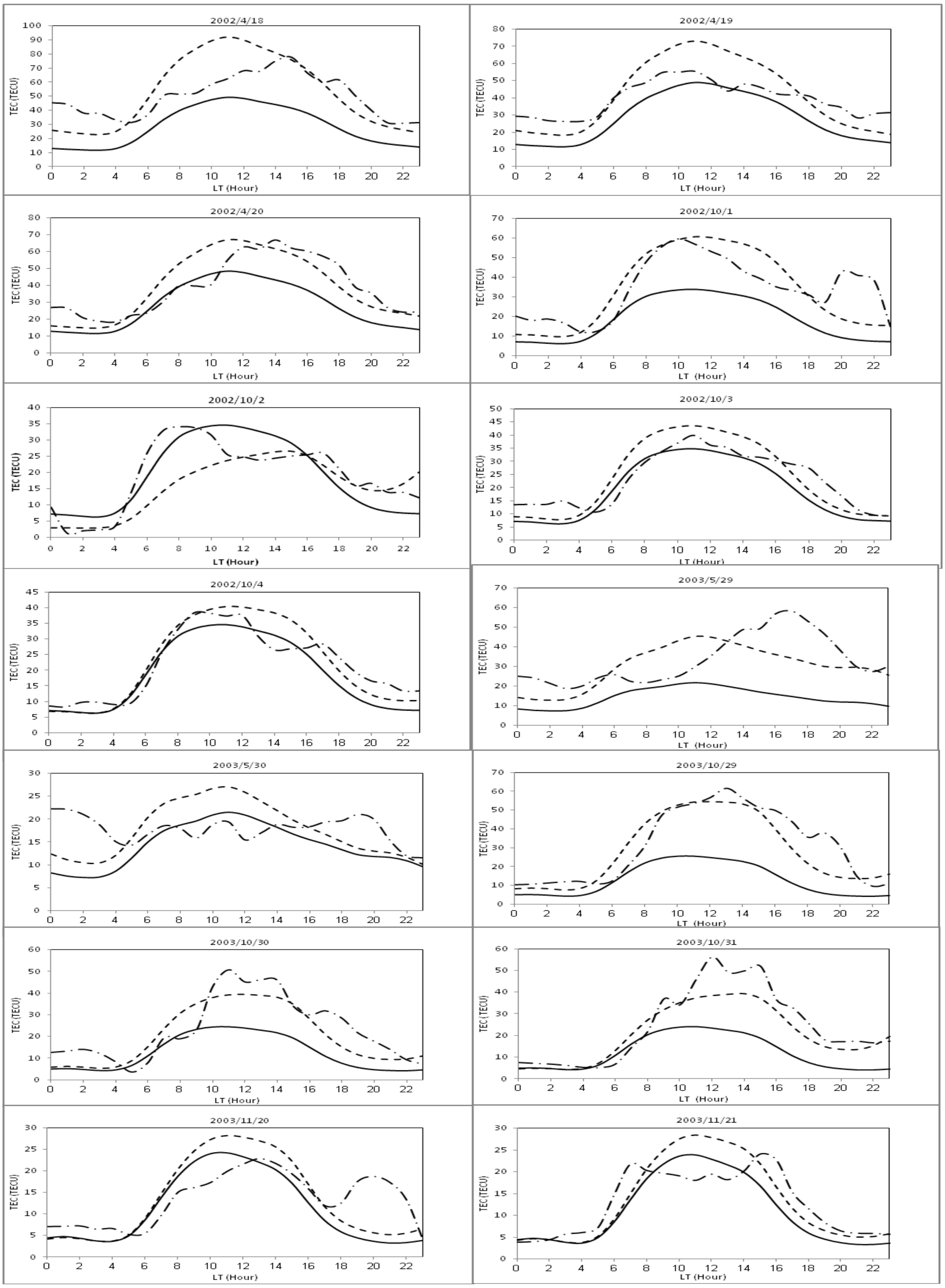

Figure 10- TEC for year2002 & 2003 (____ predicted IRI model, – · – · – observed, ------ corrected IRI).

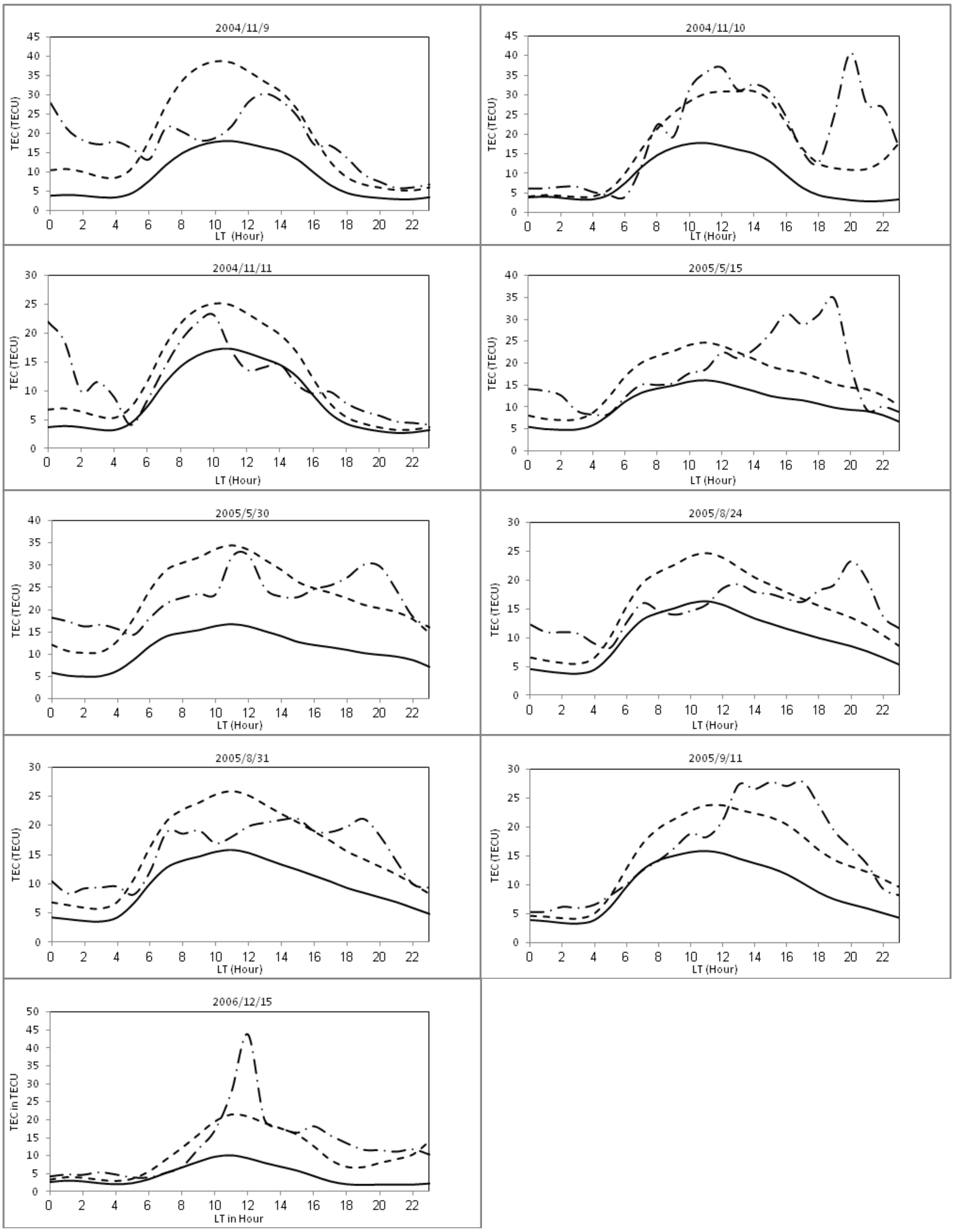

Figure 11- TEC for year 2004, 2005 and 2006(____ predicted IRI model, ─ · ─ · ─ observed,**------** corrected IRI).

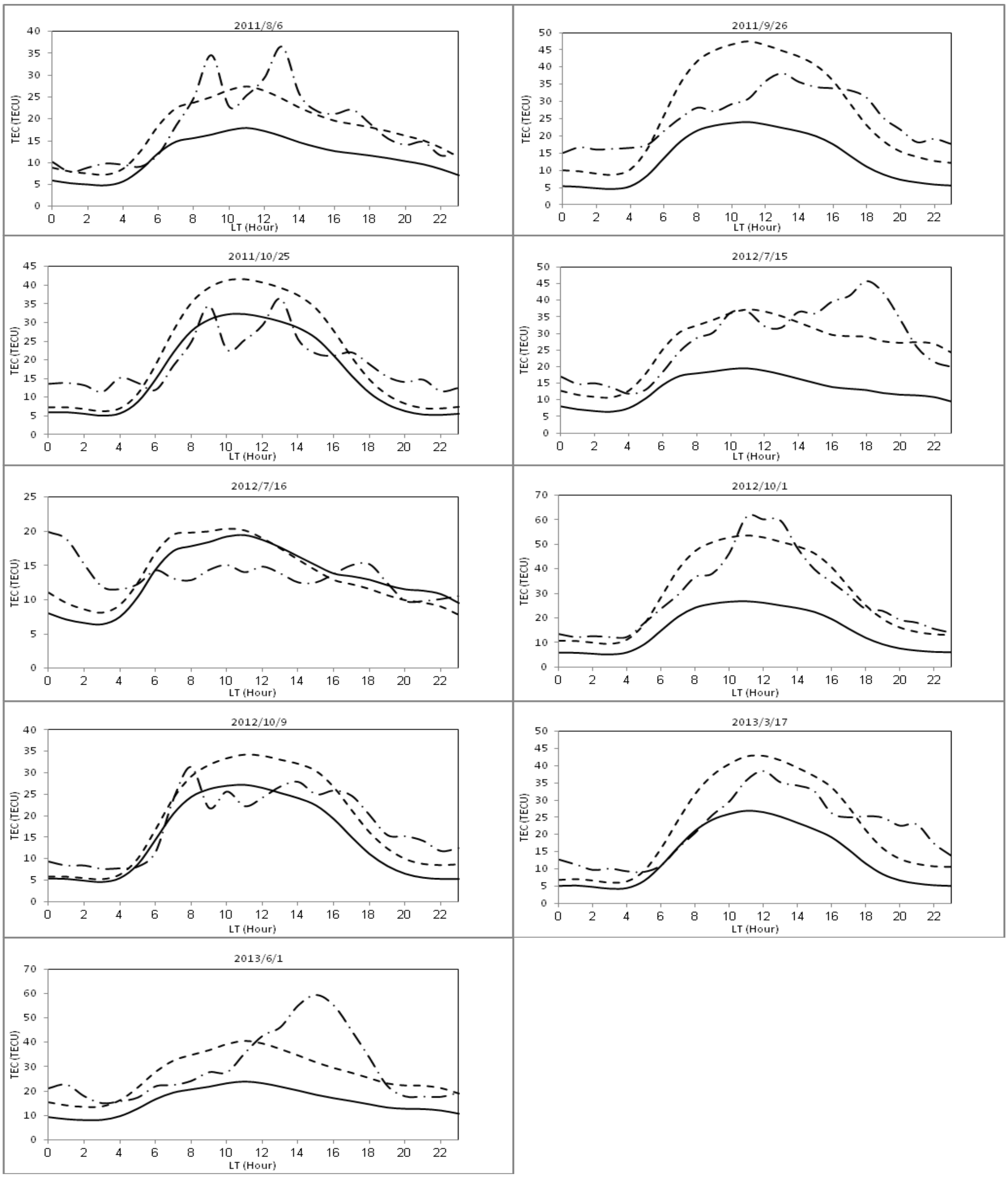

Figure 12- TEC for year 2011, 2012 and 2013(___ predicted IRI model, − · − · − observed, **------** corrected IRI).

Table 4- Root Mean Square Error between Obs. and Predicted TEC before and after correction.

Events	**Root Mean Square Error.**	
Date	**Before corr.**	**After corr.**
12/2/2000	13.5873	12.45696
7/4/2000	26.792917	10.26747
24/5/2000	8.63162	3.93591
15/7/2000	6.16004	3.97682
16/7/2000	8.88433	8.50091
12/8/2000	3.80425	3.57430
18/9/2000	10.91425	8.70571
4/10/2000	18.81504	7.13984
5/10/2000	9.79187	5.794573
6/10/2000	3.28175	3.188514
29/10/2000	14.04658	6.98662
6/11/2000	13.32325	6.632383
7/11/2000	13.19621	6.693451
29/11/2000	20.61863	9.690732
18/4/2002	21.97833	13.41073
19/4/2002	11.192625	10.1855
20/4/2002	12.18121	7.93381
1/10/2002	15.55842	8.6707
2/10/2002	5.053625	4.9271
4/10/2002	4.16404	3.83677
29/5/2003	19.04063	10.3727
29/10/2003	18.02138	6.45721
30/10/2003	11.65575	6.79532
31/10/2003	13.0425	5.46239
21/11/2003	3.64983	3.57841
9/11/2004	9.07158	7.10892
10/11/2004	11.8945	5.2220
11/11/2004	4.47256	4.02308
15/5/2005	7.27116	6.02686
30/5/2005	11.41395	5.10228
24/8/2005	5.36033	4.61907
25/8/2005	1.99791	1.53032
31/8/2005	5.86812	3.35148
11/9/2005	6.27366	3.6512
15/12/2006	8.18891	3.7006
6/8/2011	6.80079	2.85368
26/9/2011	11.72116	7.79529
15/7/2012	14.481	5.36942
1/10/2012	14.3290	4.616678
9/10/2012	4.71837	4.50847
17/3/2013	7.98295	6.1982
1/6/2013	13.4205	8.4170

Conclusion

There are disturbances in intensity of Total Electron Content (TEC) values which is directly proportional to the strength of the storm, it appears a high disturbance values at day time and least at night. From this study it concluded that the behavior of TEC disturbed during strong, severe, and great geomagnetic storms for all the years selected (2000-2013) appeared a fluctuation in values of TEC due to the storm changing from type to another. When two types of storms occurred remaining for one event two or more peaks in TEC instead one peak appeared.There is a great proportional between disturbance storm time index (Dst) and the total electron contents, the values of TEC in daytime greater than nighttime except in case when the storm continued for all over the day the values of TEC remains great in day and nighttime. The number of storms increases with increasing the SSN, in year 2000 when the solar activity maximum there is approximately storms in each month for that year, but when the solar minimum for years 2007-2010 there is no storms at all. Concerning the validity of the IRI model during strong, great, and severe geomagnetic storm it seen that there is a bad correlation between the observed and predicted TEC values, so that the model corrected during the major geomagnetic storms.

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