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Disturbances of Ionospheric Total Electron Content during Great and Severe Geomagnetic Storms above Iraq and Surrounding Areas

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Abstract

Several studies have been made to understand the behavior of Total Electron Content (TEC) in the topside of the ionosphere during two types of geomagnetic storms. The aim of this research is to examine the ionospheric disturbances using the TEC parameter during the great and severe geomagnetic storms that occurred during the period (28-30 October 2003). Theexamination was conducted for the region,includingIraq and surrounding areas that cover the area (latitude 27-39^{o}N; longitude 27-54^{o}E). TEC data were obtained fromthe Defense Meteorological Satellite Program (DMSP), to determine the type of geomagnetic storm, the Disturbance storm time (Dst) index was gathered for the selected days from the website Koyota, Japan WDC.Fromthe results,it wasfound that there was a good relationship between Dst-indexand TEC parameter values. There is a discrepancy in observations recorded about TEC values during the period of geomagnetic storms.There were significant enhancements in the values of TEC during storms; however, there was an anomaly when the storm continued for several hours during the day, there was a highly broad increase in TEC from sunrise to sunset. Moreover, when two types of storms occurred, two peaks or more appeared, and they remained for one event, or even for more than one day. Comparisons between the observed TEC and the predicted values were applied in order to check the validity of the IRI-20 ionospheric model during the storm time above the mid-latitude studiedareas;it found that there is a non-linear correlation between them within24 hours and three days, so the model wouldneed some modification in the future to be suitable for the Iraq region during storm time.

Keywords:DST-index; Geomagnetic storm; IRI model; Top-side ionosphere; Total electron content (TEC).

أضطرابات المحتوى الالكتروني الكلي للايونوسفير خلال العواصف الجيومغناطيسية الكبرى والشديدة فوق العراق والمناطق المحيطة به

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جامعة بغداد، كلية العلوم، قسم الفلك والفضاء، بغداد، العراق

الخلاصه

تم إجراء العديد من الدراسات لفهم سلوك إجمالي للمحتوى الإلكتروني للغلاف الايوني العلوي أثناء العديد من أنواع العواصف الجيومغناطيسية. يهدف هذا البحث إلى دراسة اضطرابات الغلاف الأيوني باستخدام

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معامل المحتوى الالكتروني الكلي خلال العواصف الجيومغناطيسية الكبيرة والشديدة التي استمرت لمدة ثلاثة أيام خلال الفترة 28–30 تشرين الأول 2003) فوق العراق والمناطق المحيطة بها (خط عرض 27–39 درجة شمالاً، وخط طول 27 –54 درجة شرقا). بيانات المحتوى الالكتروني اخذت من من برنامج الأقمار الاصطناعية للأرصاد الجوية الدفاعية، ولتحديد نوع العاصفة المغناطيسية تم أخذ بيانات لمؤشر العاصفة الجيومغناطيسية من الموقع الياباني العالمي (WDC). طبقا لتحليل البيانات والنتائج التي حصلنا عليها خلال هذا البحث تبين ان هنالك تناسب جيد بين مؤشر العاصفة وقيم المحتوى الالكتروني للايام المأخوذة. تبين هناك تناقض في الملاحظات المسجلة حول قيمTECخلال فترة العواصف المغناطيسية الأرضية، وكانت هناك زيادة في قيم المحتوى الالكتروني اثناء العاصفة، وان هناك بعض الحالات الشاذة عندما استمرت العاصفة لعدة ساعات خلال النهار، وكانت هناك زيادة كبيرة جدًا في المحتوى الالكتروني من شروق الشمس حتى غروبها. علاوة على ذلك، عند حدوث نوعين من العواصف، تظهر قمتان أو أكثر وتبقى اثناء الحدث الواحد أي اثناء استمرار العاصفة لاكثر من يوم. وأجريت مقارنات بين القيم المرصودة من الموقع والقيم المحسوبة من الموديل النظري العالمي (IRI-20) وذلك لغرض التحقق من كفاءة الموديل النظري للايونوسفير خلال العواصف الكبيرة والشديدة للمناطق المأخوذة في هذا البحث للعراق والمناطق المحيطة بها عند خطوط العرض الوسطى، ووجدنا أن هناك علاقة غير خطية بينهما للاربعة وعشرين ساعة وللثلاثة أيام العاصفة، لذا فإن الانموذج النظري يحتاج إلى بعض التعديلات مستقبلاً ليكون مناسباً لمنطقة العراق أثناء وقت العاصفة.

الكلمات المفتاحية: الغلاف الأيوني العلوي؛ المحتوى الإلكتروني الكلي؛ مؤشر العاصفة الجيومغناطيسية؛ الموديل النظري العالمي للايونوسفير.

1. Introduction

Energy transferred from the Sun's radiation (UV and X-ray) to the Earth's atmosphere particles produces ionization, in which ions and electrons are controlled by the plasma processes (dissociation and recombination) [1], which areaffected by many factors like season, position in the solar cycle, and geomagnetic activity [2]. The top part of the ionosphere, which has a limit from the F layer peak to about 2000 km, naturally varies from day to day, season to season, and location to location on the globe [3]. Ionospheric parameters such as electron density (N_e) and total electron content (TEC) can be changed depending on solar or magnetic field disturbances, so that ionospheric disturbances are associated directly or indirectly with the events on the Sun [4]. Geomagnetic disturbances are also created by events that beginwith the Sun; nevertheless, these events primarily influence the outermost geomagnetic field line (also known as the magnetopause) and compress the geomagnetic field, resulting in geomagnetic disturbances[5,6]. Some of the researchers who studied the TEC, such as Baranet al. (2001), analyzed the spatial and temporal TEC changes through time series in chosen northern hemisphere regions in contrast to the variance of quiet TEC for a storm in November 1997 [7]. In 2004, Ezuqer*et al*. investigated the behavior of the TEC from ten American stations during the maximum of solar activity in 1999. In the study area from latitude 18.4°N to 64.7°N and longitude from 281.3°W to 297.7°W, the results showed that the daylight hours TEC variability was around 30% of the median or less, and during night hours it was more than the stated percentage, particularly in thelast hours of the night near the northern peak of the Equatorial Anomaly (EA) [8]. Mendill (2006) used 180 storms to conduct a comprehensive study to determine the effect of the solar cycle and season on electronic content during storms [9]. Bhuyan and Borah (2007),reported for the period2003-2004, 18 stations throughout the Indian subcontinent were utilized to measure TEC using GPS and TEC projected by the IRI model; the findings indicated that the anticipated TEC values were greater than the actual ones at nearly all local times [10]. Later, several attempts were made to study the electronic content during geomagnetic storms. In (2009) Stankov, studied the TEC variation during the geomagnetic storms' intensity. He discovered that the greatest and yet shortest negative phase is recorded during the equinox, whereas the most positive phase is observed during winter at 50.1°N, 04.6°E, using European IGS (International Global Navigation Satellite System (GNSS) Service) stations[11]. From 2010 to 2013, several studies were made to compare the observations withthe theoretical models during storms, earthquakes, and other environmental factors, which led to the improvement of the theoretical IRI model. Efforts weredone by researchers for many regions in the world (for different latitudes) to enhance theIRI model during geomagnetic storms, such as Sethi *et al*. (2010), who employed ATS-6 analyzed results to compare with the IRI-2007 model during the solar minimum throughout the Indian sector, covering equatorial to low-mid-latitude stations, and the study indicated a considerably higher agreement with the TEC measurements than IRI-2001[12]. Also, Habarulema*et al*. **(**2010)measured TEC and modeled it using a developed neural network (NN) over Southern Africa during magnetic storms [13], while Natali and Meza (2011) studied seasonal variations of the TEC during high solar activity in 2000 at low, mid, and high latitude regions by choosing two hours at noon and at night. They revealed that the variations of TEC at night were smaller than those obtained at noon, and the seasonal variation in high and low latitudes washigher than in mid-latitude regions [14].

Olwendo*et al*. studied in 2012 the TEC over the Kenyan region during the descending phase of solar cycle 23 using the International Reference Ionosphere (IRI) 2007 model [15]. Essam *et al*. in 2016 made a comprehensive analysis of the geomagnetic storms that occurred between February 18 and March 2, 2014, in Egypt [16]. The effect of geomagnetic storms on low latitude ionosphere has been investigated by Singh*et al*. and Chakraborty*et al* in (2014 and 2015) with the help of Global Positioning System Total Electron Content (GPS-TEC) data. The investigation has been done with the aid of TEC data from the Indian equatorial region, Port Blair (PBR) and equatorial ionization anomaly region, Agartala (AGR). During the geomagnetic storms on 24th April and 15th July 2012, significant enhancement up to 150% and depression up to 72% in VTECwas observed in comparison to the normal day variation [17, 18]. Najatand Surain (2016), they studied the effects of different kinds of geomagnetic storms on the topside ionosphere of the total electron content during the period 2000-2010, they found that for all types of geomagnetic storms the behavior and profile of diurnal TEC variation appeared with maximum values when there wasa moderate storm, but for seasonal variations the maximum appearedwhen there wasa strong storm, so for that reason it is important to take the diurnal than the seasonal variations. When two types of storms occurred remaining for one event two peaks in TEC instead onepeak was appeared [19]. After that, Vieira et al. in (2017 and 2022), investigated the ionospheric response through TEC due to sudden stratospheric warming (SSW) over three regions: Brazilian, American, and African sectors.They found that the TECdecreased on most days in different latitude regions [20, 21]. The same study by Fagundes *et al*. in 2015 and 2016 discovered that the TEC at all 17 GPS and two ionosonde stations showed large variations extending for many days after the SSW temperature peak in the Southern Hemisphere equatorial, low, and middle latitudes[22, 23]. AlessioPignalberi*et al*. conducted several studies in 2023on the different International Reference Ionosphere topside options. After a comparison with derived TEC data, their study concluded that the representation of the hours around the solar terminator at dawn has to be improved, particularly at low and mid latitudes [24- 26].The main objective of this study is to examine the TEC variations during different kinds of geomagnetic storms over Iraq and surrounding mid-latitude regions, and then to find out the validity of the last versionof theIRI-20 model to predict the TEC values during the storm time by comparing with the observed TEC values for the mid latitude region.

2. Data Selection

The criteria bywhich the Total Electron Content (TEC) data for Iraq and surrounding regions (see Figure 1) was selected from solar cycle 23 as isavailable from the US Air Force, which has been responsible for a program called the Defense Meteorological Satellites Program (DMSP) since the mid-1960s. A series of spacecrafts were launched to investigate the Earth's environment from an altitude~800 km. They were all put into sun-synchronous near-polar orbits (inclination ~ 99 degrees) on the website (https://ngdc.noaa.gov/eog/dmsp.html). In this research the year 2003 was chosen, because 21 geomagnetic storms occurred in this year, 11 of which were strong, 6 weresevere and 4 weregreat. Only the storm that occurred in the period from October 28-30, 2003,is taken into accountin which great and severe geomagnetic storms appeared and continued for three days, Figure 2 reveals that. The Disturbance storm time index (Dst) on the basis of the presence or absence of a geomagnetic stormwas taken (see Table 1) from the Koyota Japan WDC sited in (http://wdc.kugi.kyoto-u.ac.jp/dst) for the same year of study.The ionospheric reference international model (IRI-20) was used to calculate the predicted hourly TEC valuesfor the same period selected to be compared with the observed one for validation of this model topredict the TEC values for Iraqi and surrounding regions during geomagnetic storms.

Figure 1: Iraq and surrounding regions [Google Map].

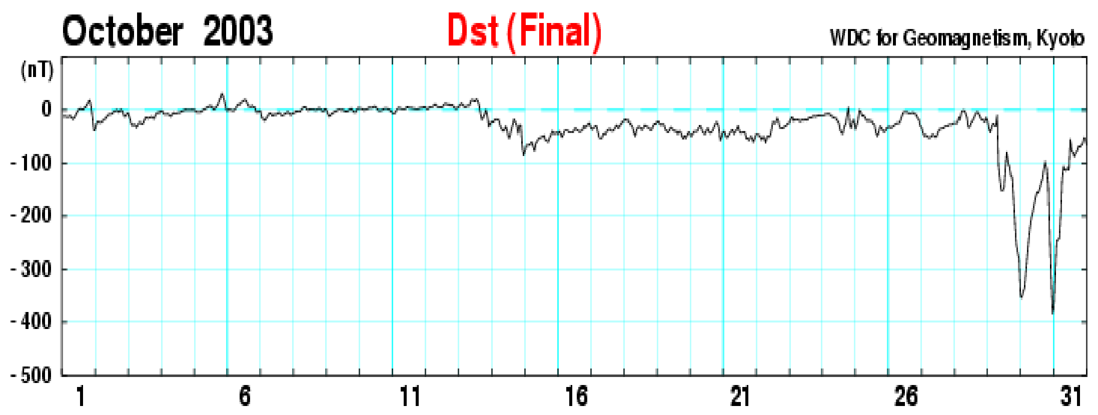


Figure 2: DailyDst index (nT) for October (2003), from the Koyota Japan WDC sited in (http://wdc.kugi.kyoto-u.ac.jp/dst).

Table 1: Date, time beginning, time end and types of 28-30 October 2003 geomagnetic storms, as taken from the Koyota Japan WDC sited in (http://wdc.kugi.kyoto-u.ac.jp/dst).

Event no.	Day	month	year	Time Beginning (hour)	Time End (hour)	Storm type
1	29	5	2003	23	24	Strong
2	30	5	2003	1	4	Strong
3	18	6	2003	8	12	Strong
4	18	8	2003	8	24	Strong
5	19	8	2003	1	3	Strong
6	29	10	2003	8	13	Strong
7	29	10	2003	16	19	Strong
8	29	10	2003	20	23	Severe
9	29	10	2003	24	-----	Great
10	30	10	2003	1	3	Great
11	30	10	2003	4	8	Severe
12	30	10	2003	9	20	Strong
13	30	10	2003	21	22	Sever
14	30	10	2003	23	24	Great
15	31	10	2003	1	4	Severe
16	31	10	2003	5	11	Strong
17	20	11	2003	14	16	Strong
18	20	11	2003	17	-----	Severe
19	20	11	2003	18	24	Great
20	21	11	2003	1	3	Severe
21	21	11	2003	4	18	Strong

3. Data Analysis

Figure 2 shows the daily Dst index in (nT) for month October (2003) in which the great and sever geomagnetic storms occurred during days 28-30, while Table 2 represents the hourly Dst values during days (28-30) in which the storms occurred. By using MATLAB program, the values of hourly TEC with latitude and longitude for the studied areas were drawn in three dimensions (3D), Figures 3, 4, and 5 illustrate for days 28, 29, and 30 respectively. It should be noted that the values of electron content are measured in electrons per meter square multiplied by 10^{16}. To check the validity of the IRI-20 ionospheric model during the storm time above the selected areas, a comparison between the observed hourly TEC and the hourly predicted values from the model was made through the period selected in this study case. Figures (6-9) represent the hourly observed and predict TEC by taking the five latitudes for Iraq and surrounding area (27, 30, 33, 36 and 39^o N) with changing the four longitude lines (27, 36, 45 and 54^o E) respectively to cover the whole twenty different locations that distributed within the studied area selected in this study case, for three stormy days from 28-30 October 2003.

Table 2: The hourly Dst index values for days 28-30 October 2003, from the Koyota Japan WDC sited in (http://wdc.kugi.kyoto-u.ac.jp/dst).

Hour (UT)	Dst (nT)		
	Day28	Day29	Day30
1	-24	-34	-353
2	-24	-42	-341
3	-14	-32	-335
4	-18	-25	-303
5	-4	-28	-273
6	-1	-30	-244
7	-1	-10	-220
8	-5	-105	-203
9	-14	-130	-192
10	-32	-151	-178
11	-32	-151	-164
12	-24	-147	-155
13	-20	-111	-156
14	-16	-79	-148
15	-8	-99	-138
16	-4	-107	-129
17	-4	-124	-111
18	-9	-126	-97
19	-16	-169	-111
20	-18	-213	-142
21	-19	-253	-240
22	-22	-268	-316
23	-14	-281	-383
24	-20	-350	-371

4. Results and Discussion

In this research, the Dst-index represents one of the important indices that can indicate the strength of the geomagnetic storms. The Dst index has been used to classify the tested geomagnetic storms according to its values into different types, as mentioned in Tables 1 and 2. While Figure 2 shows the values of the DST index during the month of October 2003, in which the geomagnetic storm begun on October 28, and thenreached its peak on October 29, continued until the next day, and then ends on October 31.The 3D drawing between variation of TEC anddifferent selected geographical latitudes and longitudes during these three days (tested period) revealed that there werepositive phase enhancement in TEC value in 29 October above Iraq and surrounding areas, but this enhancement varied among latitudes and longitudes it as appears clearly in Figures (6-9). From these figures it can be seen thatin general, the TEC in day time greater than night due to solar radiation.As the latitude increases, the values of the electron content decrease for all selected longitudes, and for all three days except for storm day 29 October, there is an equatorial anomaly at latitude 27 (in low latitude), so the values are slightly lower than the latitude line 30 beyond it.While the Figures (6-9) reveal that in two days 28 and 30 in the beginning and end of storm in which the peaks value began to expand or more peaks appeared, because there were two geomagnetic storms that toke placed (strong) during these days.In the same Figures (6-9), the predicted values of electronic content calculated using the theoretical IRI-20 model are shown (dash line), in order to compare them with the observed values and for all geographical locations (latitudes and longitudes) chosen in this research. It was found that there is a non-linear behavior between the observed and predicted values for the 24 hours and three days.To clearly reveal this non-linearity in relations between the observed and predicted TEC values for 24 hours and three days by taking the ratio of the predicted TEC value calculated from the model to the observed value for each hour of the three days. Figure 10 represents the ratio (predicted TEC/observed TEC) in the blue line with hour, while the fifth-order polynomial curve fitting in the black line gives the corrected predicted value in the modified IRI model to match the observation.Table 3 shows the trend line equations;it was found that this ratio increases with increasing latitudes approximately with all longitudes chosen for Iraq and surrounding areas. Therefore, the validity of IRI-20 model in storm time for mid-latitudes need some modification in thefuture by using the equations in table 3 in which (y) represent the correction function, also by studying more events in which great and severe storms occurred to increase the accuracy of enhancing predicted results, which are needed in many predicted space research and weather forecasts.Finally, from theFigures above,it can be seenthat there is anenhancement in observed TEC values during storm time, which appeared in day 29 October 2003.To study this behavior, the peak TEC observed values (blue line) in Figure 11 are taken and drawn with latitudes and longitudes for Iraq and the surrounding area during the geomagnetic storm 28-30 October 2003, while the polynomial curve fitting (black line) appeared to showthis behavior through trend line equations shown in Table 4.This gives the percentage of this change or enhancement in TEC during the geomagnetic storms.

5. Conclusions

In this research it can be concluded that:

1- In general, the values of TEC duringday time are greater than during the night time due to solar radiation.

2- The 3D drawing between the variation of TEC and different geographical locations (latitudes and longitudes) selected during the period of three days reveals that there is a positive phase enhancement in the TEC value on October 29 above Iraq and surrounding areas.

3- There is a mismatch between the observed and predicted TEC values using IRI-20 model in non-linear behavior through 24 hours and within three days (28-30) October 2003.

4- The peak TEC value appears that to reacha maximum valueat 29 October due to storm peak time for all mid-latitudes and longitudes selected, due to increasing in solar activity during a geomagnetic storm.

5- The IRI-20 model needs some modification for mid-latitude regions during great and severe geomagnetic storms.

6- In two days 28 and 30 in the beginning and end of thestorm in which the peaks value began to expand or more peaks appeared, because there were two geomagnetic storms that took place (strong) during these days.

7- As the latitude increases, the values of the electron content decrease for all selected longitudes and for all three days except in storm day 29 October there is an equatorial anomaly at latitude 27 (in low latitude), so the values are slightly lower than the latitude line 30 beyond it.

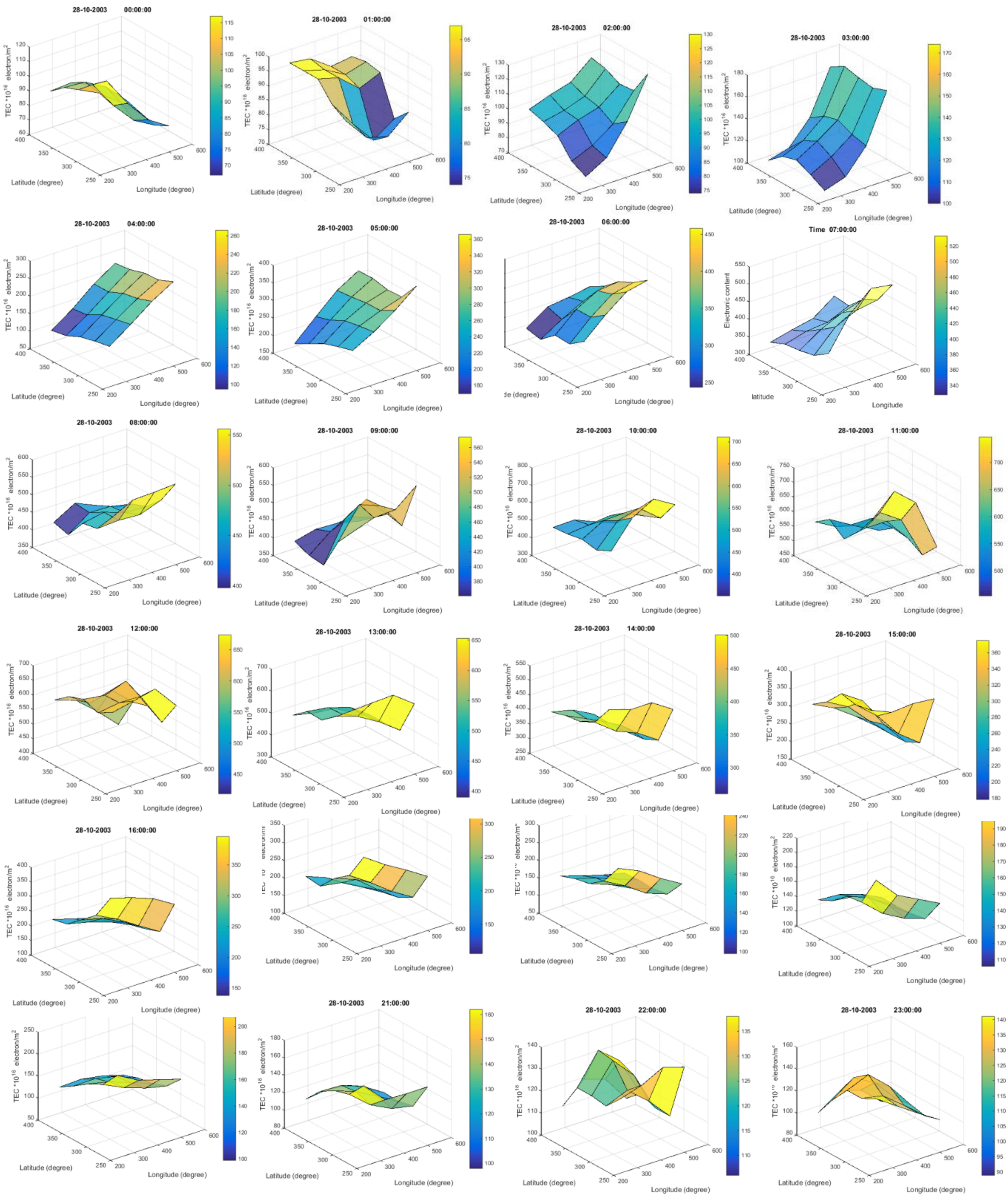


Figure 3: 3TEC with latitude and longitude above Iraq and surrounding area in 28/10/2003.

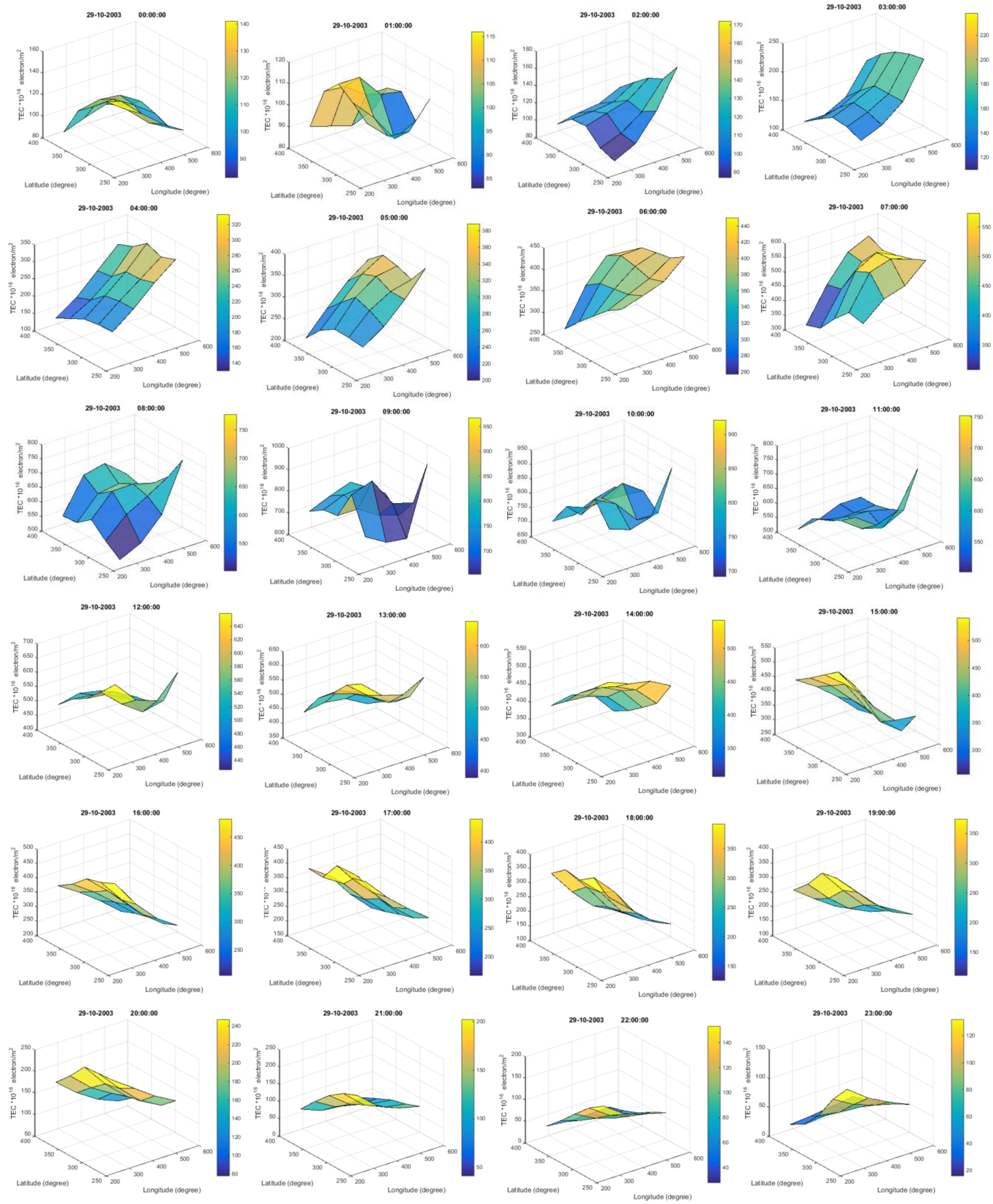


Figure 4: 3D TEC with latitude and longitude above Iraq and surrounding area in 29/10/2003.

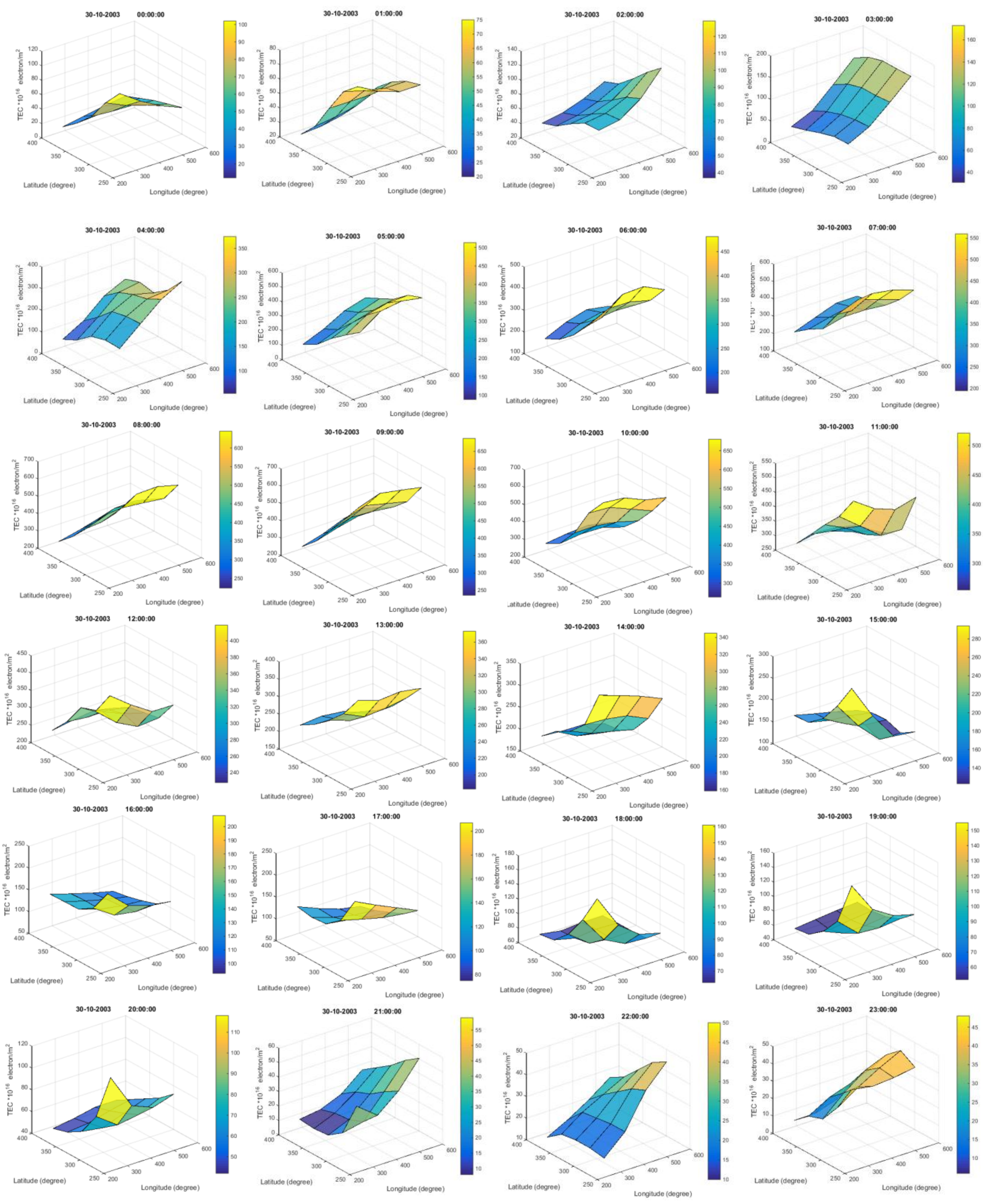


Figure 5: 3D TEC with latitude and longitude above Iraq and surrounding area in 30/10/2003.

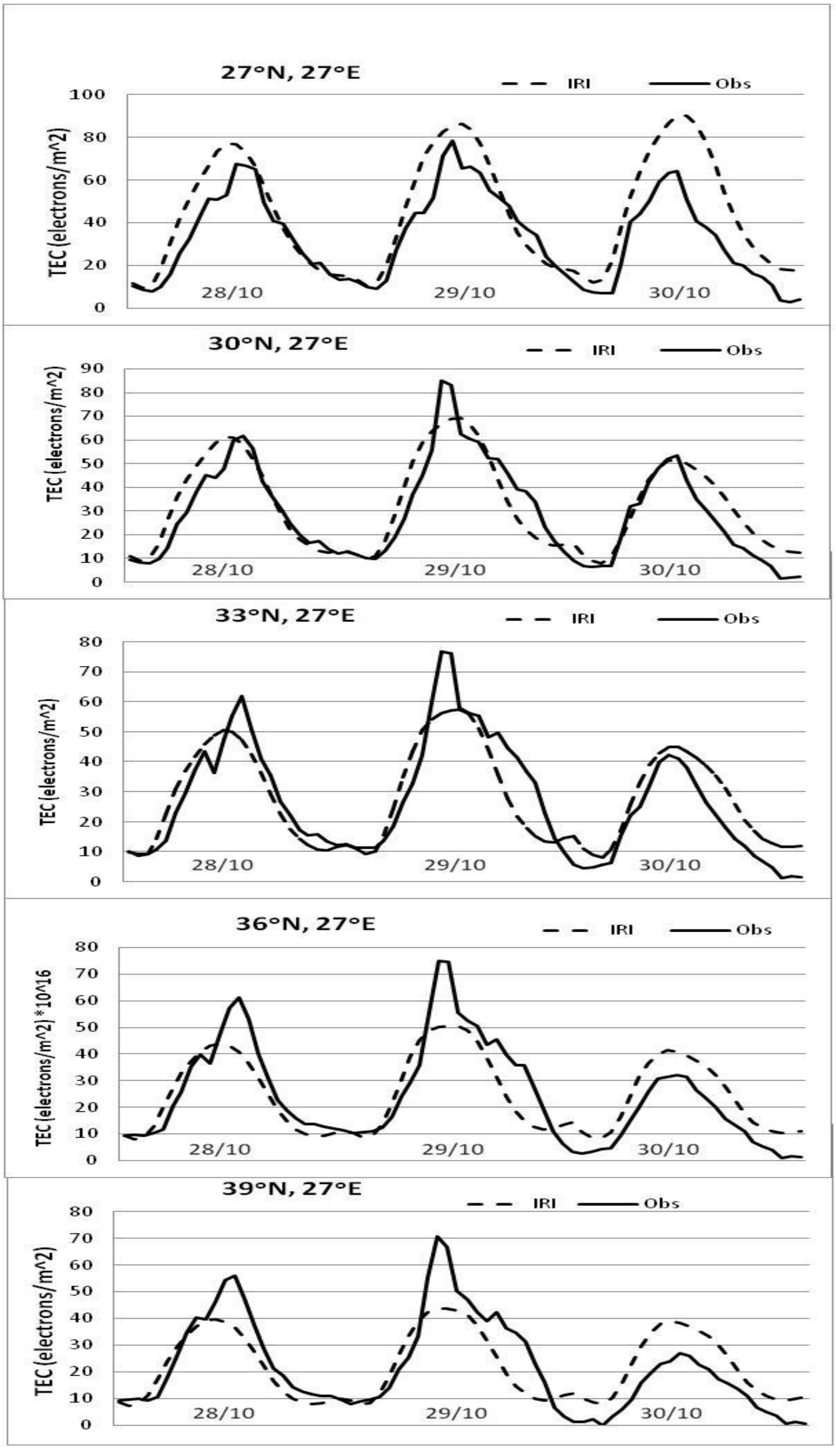


Figure 6: Hourly observed and predicted TEC for latitudes27, 30, 36 and 39^{o}N; longitude 27^{o}E.

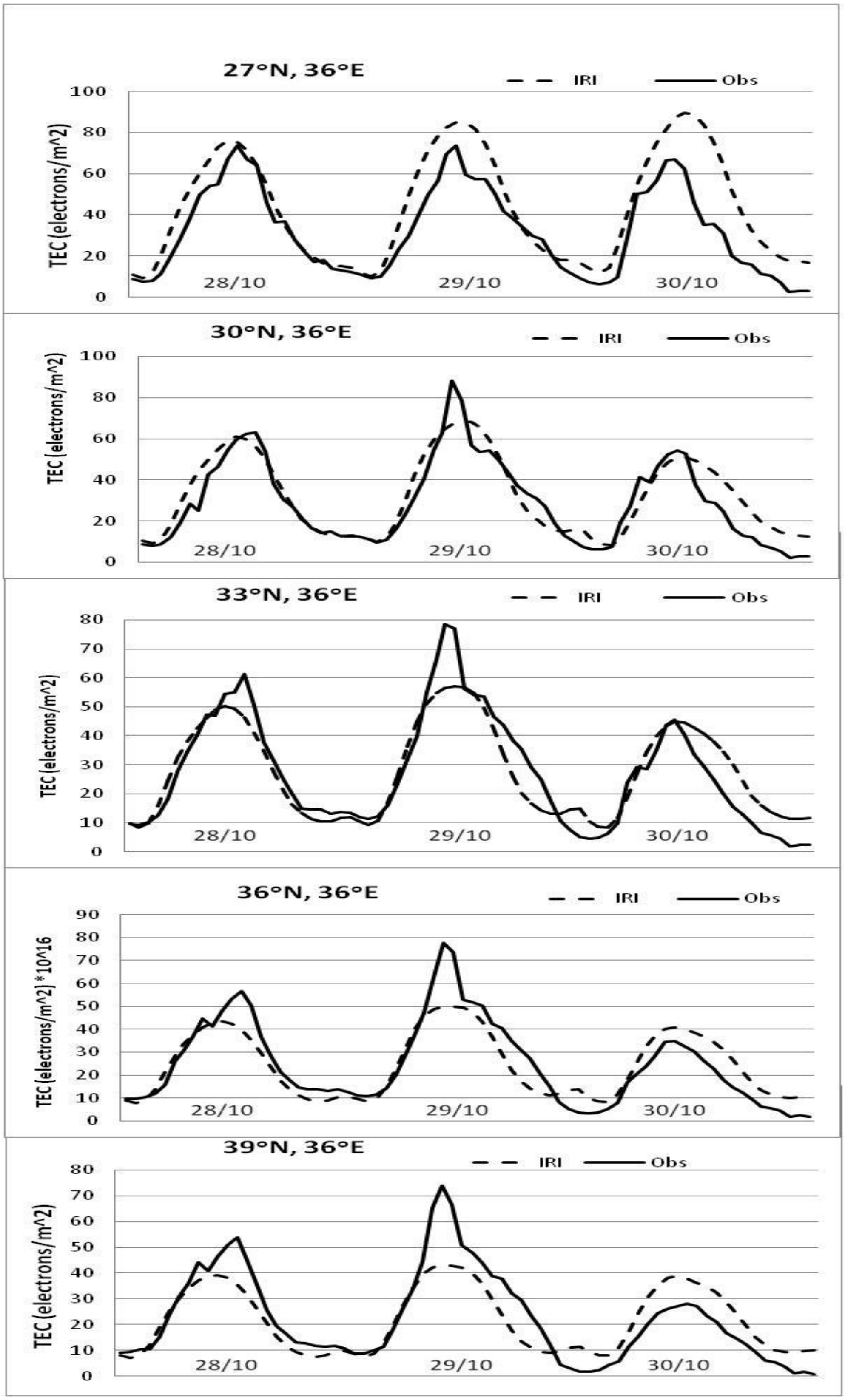


Figure 7: Hourly observed and predicted TEC for latitudes 27, 30, 36 and 39^{o}N; longitude 36^{o}E.

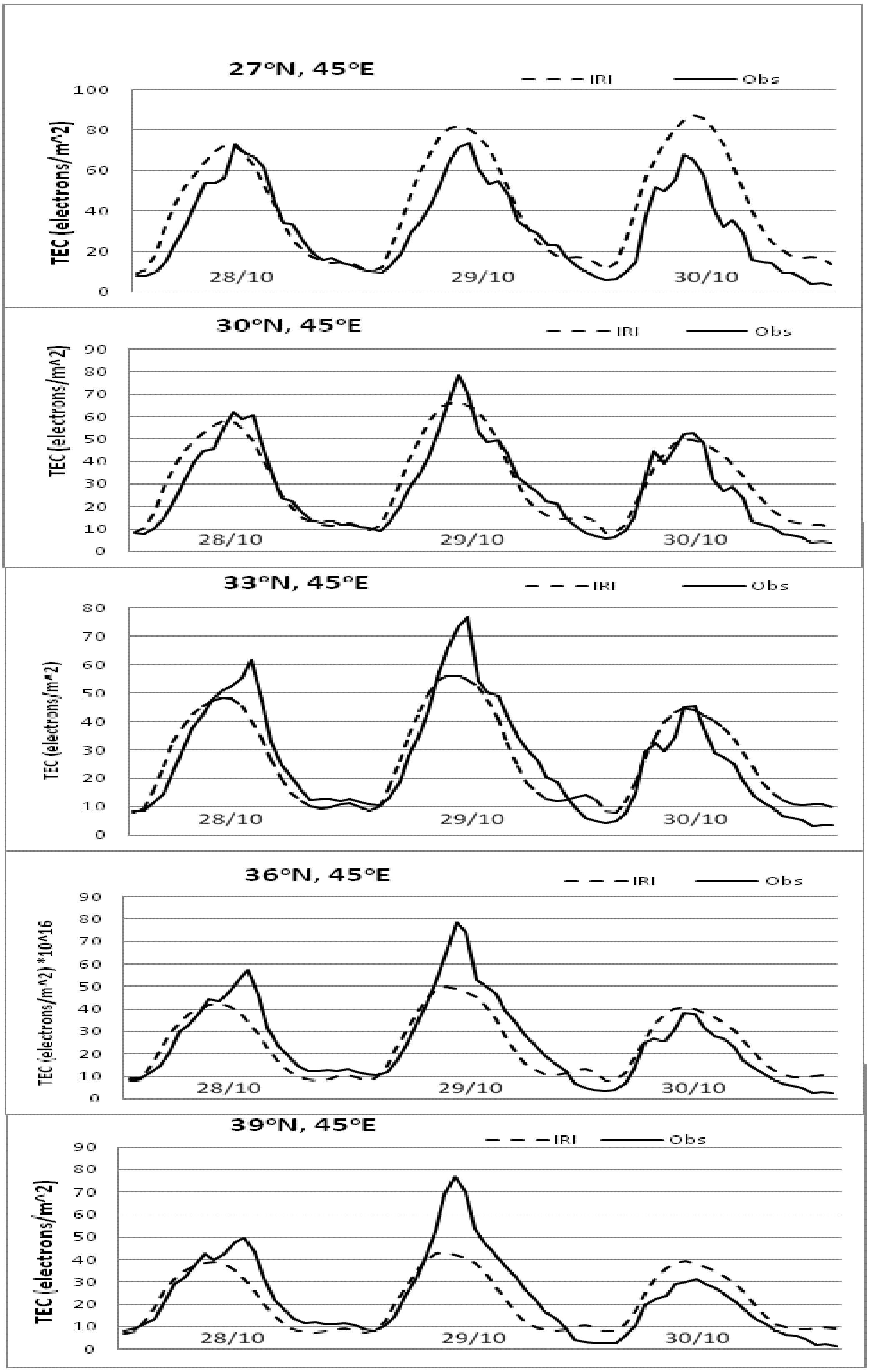


Figure 8: Hourly observed and predicted TEC for latitudes27, 30, 36 and 39^{o}N; longitude 45^{o}E.

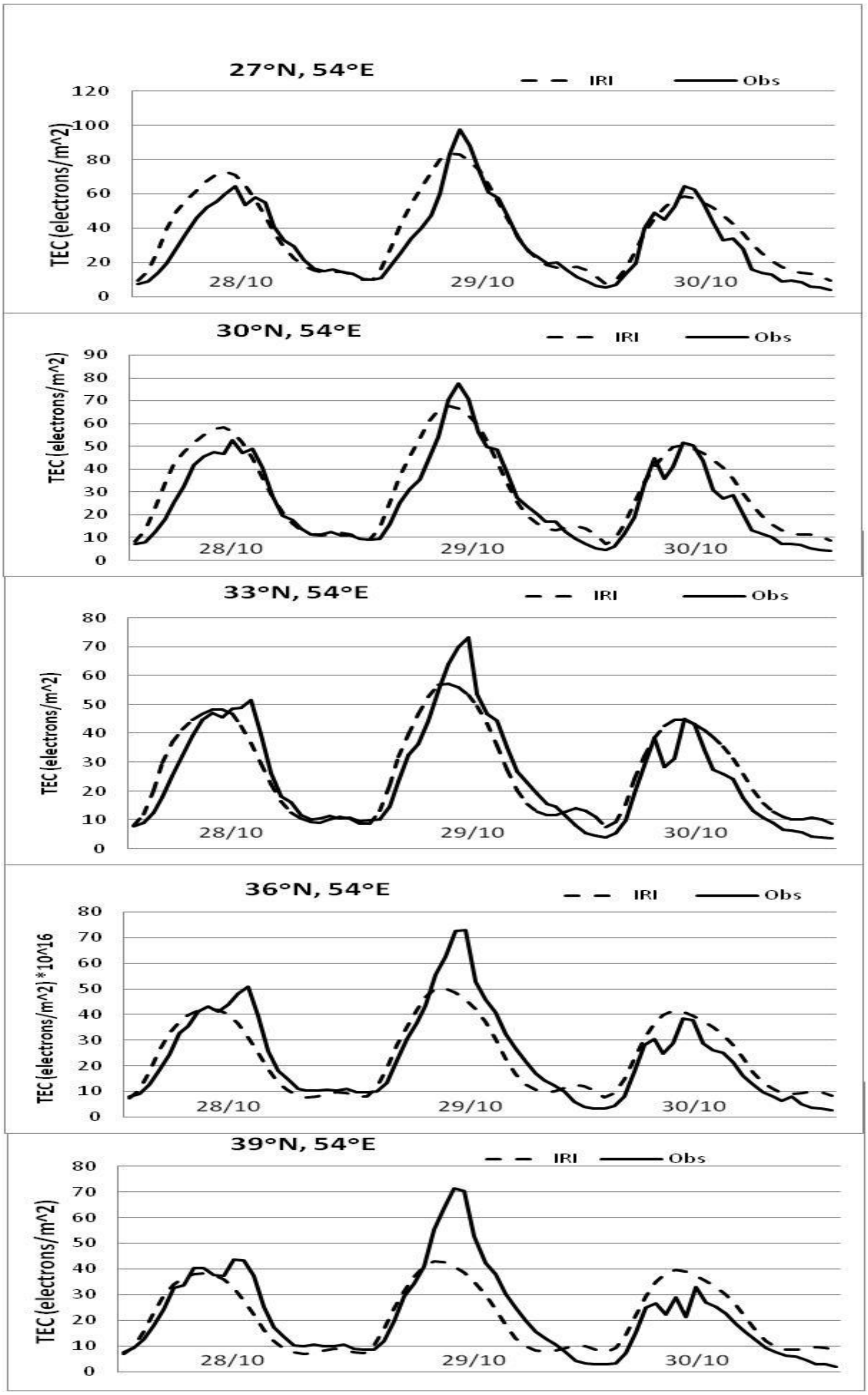


Figure 9: Hourly observed and predicted TEC for latitudes 27, 30, 36 and 39^{o}N; longitude 54^{o}E.

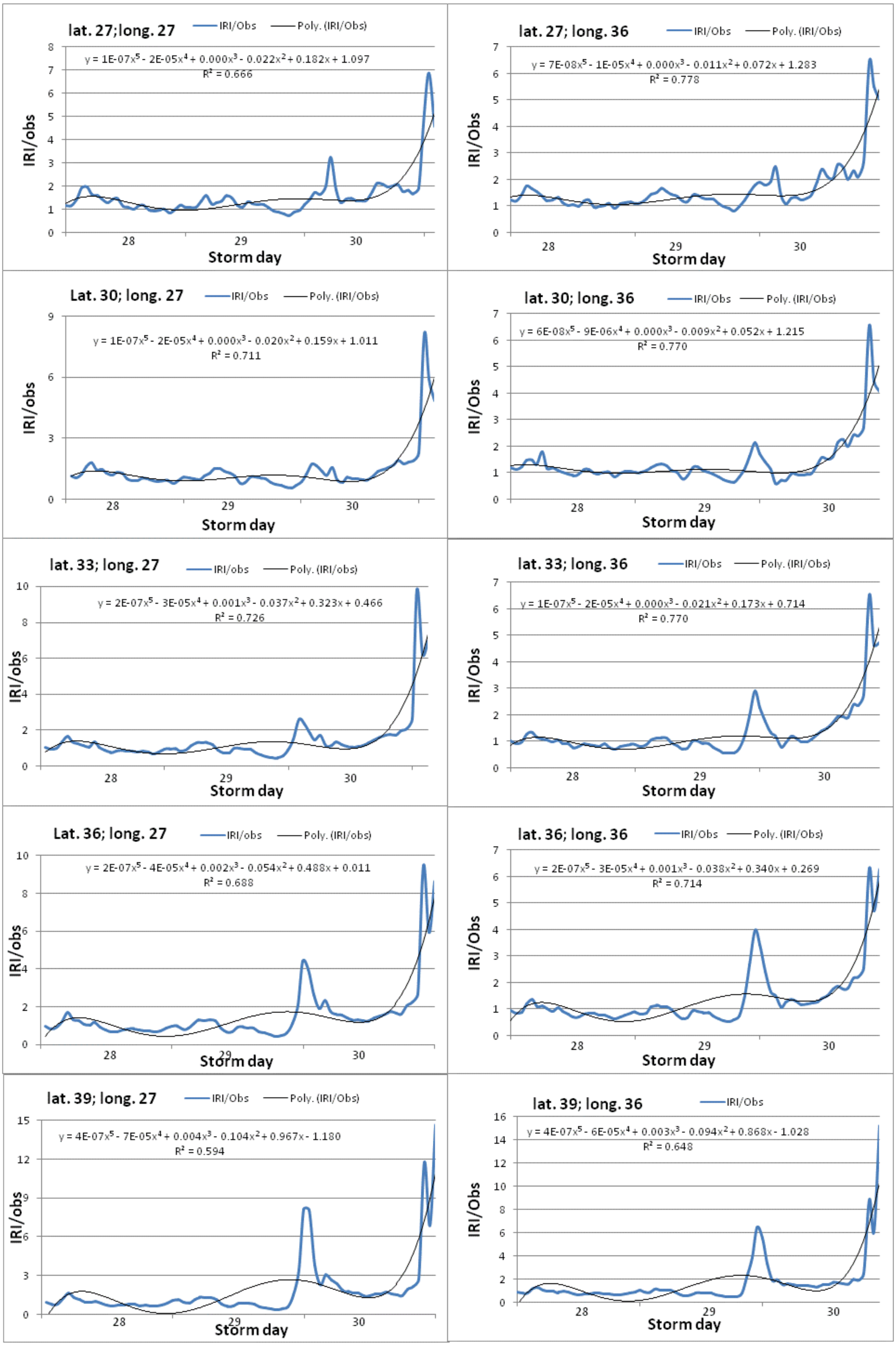
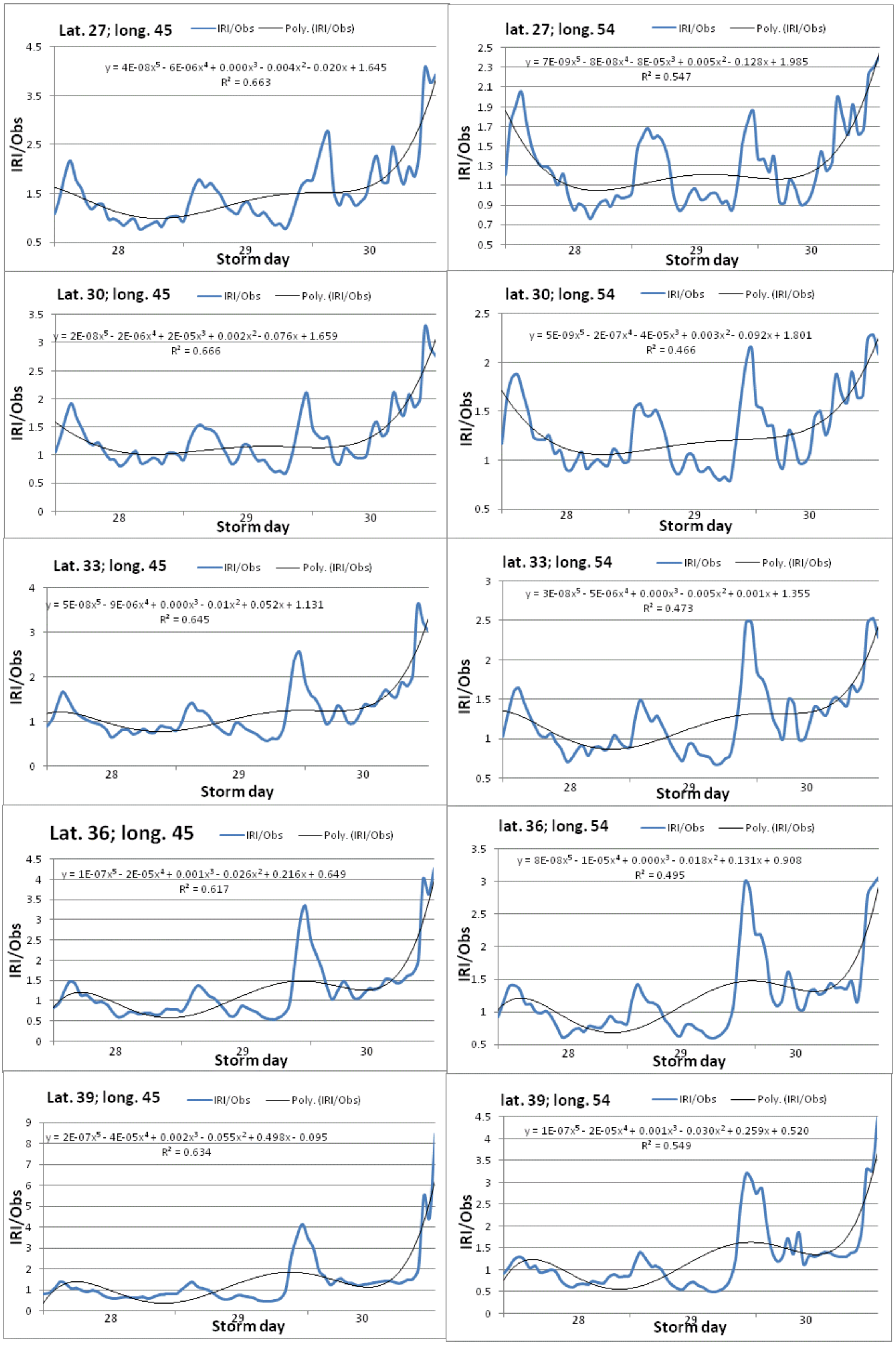


Figure 10: Polynomial curve fitting for ratio of TEC calculated from observed values.



Continued figure 11

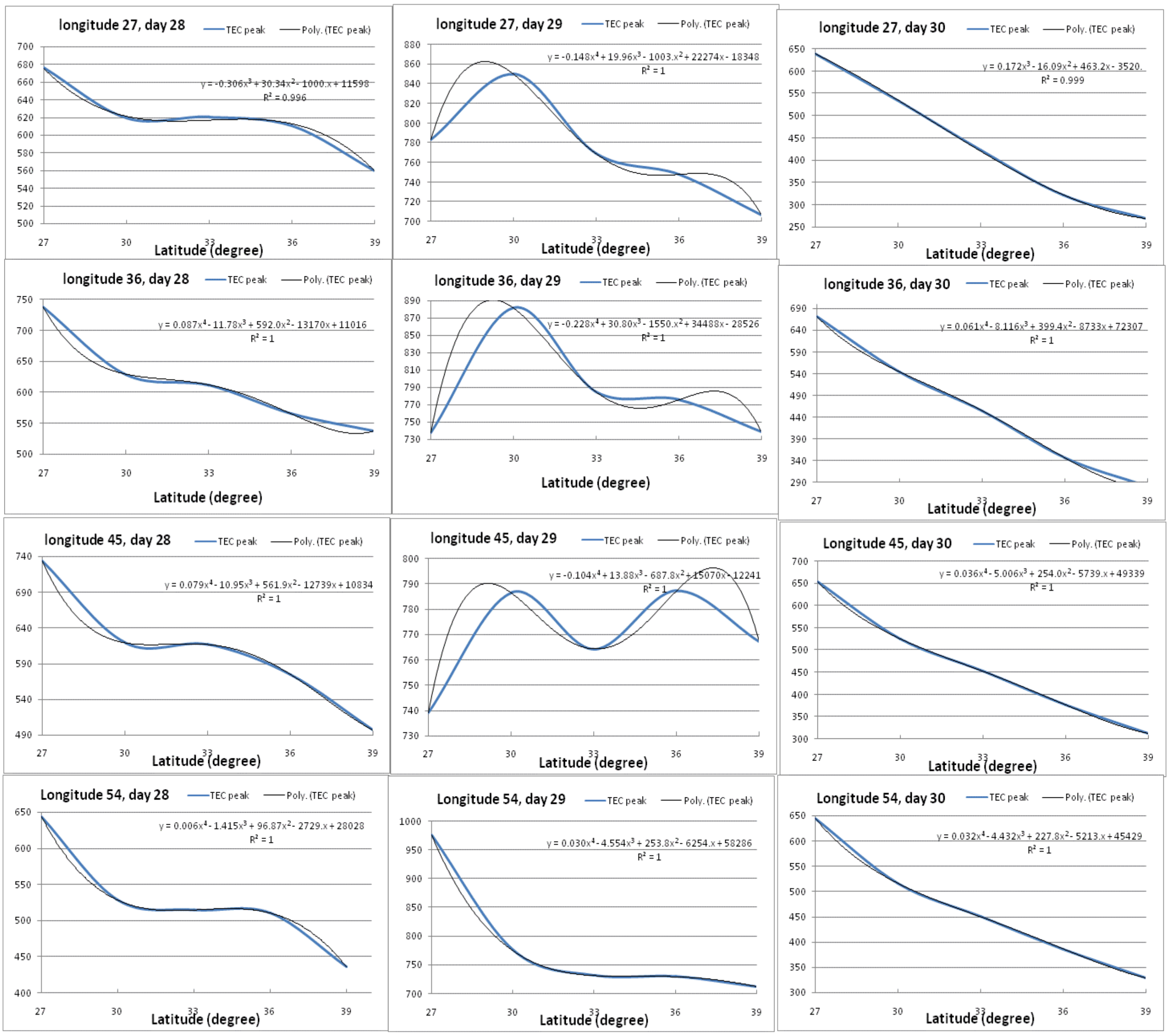


Figure 11: TEC peak (blue) and polynomial curve fitting (black) with latitudes and longitudes for Iraq and surrounding area during geomagnetic storm 28-30 October 2003.

Table 3: Polynomial curve fitting equations and cross correlation (R^2) for ratio of TEC calculated by IRI-20 model to observed values for Iraqi region and surrounding area.

Lat.; long. (degree)	Polynomial curve fitting equation	R^2
27; 27	$y = 1E-07x^5 - 2E-05x^4 + 0.000x^3 - 0.022x^2 + 0.182x + 1.097$	0.666
30; 27	$y = 1E-07x^5 - 2E-05x^4 + 0.000x^3 - 0.020x^2 + 0.159x + 1.011$	0.711
33; 27	$y = 2E-07x^5 - 3E-05x^4 + 0.001x^3 - 0.037x^2 + 0.323x + 0.466$	0.726
36; 27	$y = 2E-07x^5 - 4E-05x^4 + 0.002x^3 - 0.054x^2 + 0.488x + 0.011$	0.688
39; 27	$y = 4E-07x^5 - 7E-05x^4 + 0.004x^3 - 0.104x^2 + 0.967x - 1.180$	0.594
27; 36	$y = 7E-08x^5 - 1E-05x^4 + 0.000x^3 - 0.011x^2 + 0.072x + 1.283$	0.778
30; 36	$y = 6E-08x^5 - 9E-06x^4 + 0.000x^3 - 0.009x^2 + 0.052x + 1.215$	0.770
33; 36	$y = 1E-07x^5 - 2E-05x^4 + 0.000x^3 - 0.021x^2 + 0.173x + 0.714$	0.770
36; 36	$y = 2E-07x^5 - 3E-05x^4 + 0.001x^3 - 0.038x^2 + 0.340x + 0.269$	0.714
39; 36	$y = 4E-07x^5 - 6E-05x^4 + 0.003x^3 - 0.094x^2 + 0.868x - 1.028$	0.648
27; 45	$y = 4E-08x^5 - 6E-06x^4 + 0.000x^3 - 0.004x^2 - 0.020x + 1.645$	0.663
30; 45	$y = 2E-08x^5 - 2E-06x^4 + 2E-05x^3 + 0.002x^2 - 0.076x +1.659$	0.666
33; 45	$y = 5E-08x^5 - 9E-06x^4 + 0.000x^3 - 0.01x^2 + 0.052x + 1.131$	0.645
36; 45	$y = 1E-07x^5 - 2E-05x^4 + 0.001x^3 - 0.026x^2 + 0.216x + 0.649$	0.617
39; 45	$y = 2E-07x^5 - 4E-05x^4 + 0.002x^3 - 0.055x^2 + 0.498x - 0.095$	0.634
27; 54	$y = 7E-09x^5 - 8E-08x^4 - 8E-05x^3 + 0.005x^2 - 0.128x + 1.985$	0.547
30; 54	$y = 5E-09x^5 - 2E-07x^4 - 4E-05x^3 + 0.003x^2 - 0.092x + 1.801$	0.466
33; 54	$y = 3E-08x^5 - 5E-06x^4 + 0.000x^3 - 0.005x^2 + 0.001x + 1.355$	0.473
36; 54	$y = 8E-08x^5 - 1E-05x^4 + 0.000x^3 - 0.018x^2 + 0.131x + 0.908$	0.495
39; 54	$y = 1E-07x^5 - 2E-05x^4 + 0.001x^3 - 0.030x^2 + 0.259x + 0.520$	0.549

Table 4: Trendline equations for polynomial curve fitting for peak TEC with latitude and longitude during geomagnetic storm 28-30 October 2003 above Iraq and surrounding area.

year	month	day	Longitude (degree)	Trendline equation	R^2
2003	**10**	**28**	**27**	$y = -0.306x^3+0.34x^2-1000+11598$	**0.996**
2003	**10**	**28**	**36**	$y = 0.087x^4-11.78x^3+592x^2-1317x+11016$	**1**
2003	**10**	**28**	**45**	$y = 0.079x^4-10.95x^3+561.9x^2-12739x+10834$	**1**
2003	**10**	**28**	**54**	$y = 0.006x^4-1.415x^3+96.87x^2-2729x+28028$	**1**
2003	**10**	**29**	**27**	$y = -0.148x^4+19.96x^3-1003x^2+22274x-18348$	**1**
2003	**10**	**29**	**36**	$y = -0.228x^4+30.8x^3-1550x^2+34488x-28526$	**1**
2003	**10**	**29**	**45**	$y = -0.104^4+13.88x^3-687.8x^2+15070x-12241$	**1**
2003	**10**	**29**	**54**	$y = 0.03x^4-4.554x^3+253.8x^2-6254x+58286$	**1**
2003	**10**	**30**	**27**	$y = 0.172x^3-16.09x^2+463.2x-3520$	**0.999**
2003	**10**	**30**	**36**	$y = 0.061x^4-8.116x^3+399.4x^2-8733x+2307$	**1**
2003	**10**	**30**	**45**	$y = 0.036x^4-5.006x^3+254x^2-5739x+49339$	**1**
2003	**10**	**30**	**54**	$y = 0.032x^4-4.432x^3+227.8x^2-5213x+45429$	**1**

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