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Day to Day variation of Ionosphere Electron and Ion Temperature during Great and Severe Geomagnetic Storms

Najat M. R. Al-Ubaidi*, Karam H. Gmayhs
Department of Astronomy & Space, College of Science, Baghdad University, Baghdad, Iraq

Abstract

The ionospheric characteristics exhibit significant variations with the solar cycle, geomagnetic conditions, seasons, latitudes and even local time. Representation of this research focused on global distribution of electron (Te) and ion temperatures (Ti) during great and severe geomagnetic storms (GMS), their daily and seasonally variation for years (2001-2013), variations of electron and ion temperature during GMS with plasma velocity and geographic latitudes. Finally comparison between observed and predicted Te and Ti get from IRI model during the two kinds of storm selected. Data from satellite Defense Meteorological Satellite Program (DMSP) 850 km altitude are taken for Te, Ti and plasma velocity for different latitudes during great and severe geomagnetic storms from years 2001 to 2013 according to what is available appeared that there is 22 events for severe and great geomagnetic storms happened during years 2001-2005 only from years selected, from maximum solar cycle 23. From data analysis, in general the temperature of the electron is greater than the temperature of the ion, but there are some disturbances happened during the storm time, in the day there is fluctuation in values of Te and Ti with the value of Ti greater than Te. Through the Dst index, Te and Ti do not depend on the strength of the geomagnetic storm. Plasma velocity variation shows the same profile of Te and Ti variation during the storm time and there is a linear relation between (Te) & (Ti) and plasma velocity. The variation of electron and ion temperature with geographic latitude during severe and great storms appears that as the latitude increases the temperature of ions increases reaches its maximum value approximately 80000K at poles.

From comparing the predicted Te and Ti values calculating from IRI model during the great and severe storms with observed values, it's found that the predicted values from IRI model much less than the observed values and the variation was nonlinear along 24 hours, from this we can conclude that the model must be corrected for Te and Ti for these two kinds of storms.

Keywords: Electron and Ion Temperature, Geomagnetic Storm, IRI model.

التغيرات من يوم لاخر في درجات حرارة الالكترونات والايونات للايونوسفير أثناء العواصف الجيومغناطيسية الشديدة والقوية

نجاة محمد رشيد رؤوف العبيدي*، كرم حنون غميس
قسم الفلك والفضاء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

خصائص الغلاف الأيوني يبدي اختلافات كبيرة مع الدورة الشمسية، وطبيعة المجال المغناطيسي للارض والمواسم وخطوط العرض وكذلك التوقيت المحلي. يهدف البحث الى دراسة توزيع درجات حرارة الالكترونات والايونات وتغيراتها اليومية والفصلية خلال العواصف الجيومغناطيسية الشديدة والكبيرة وللاعوام 2001–

*Email: najatmr10@yahoo.com

2013 وكذلك دراسة درجات حرارة الالكترونات والايونات مع سرعة البلازما وخطوط العرض الجغرافية اثناء نوعي العواصف المختارة في هذه الدراسة. واخيرا جرت مقارنة بين قيم درجات حرارة الالكترونات والايونات المرصودة مع القيم المتنبأ بها والمحسوبة من الموديل العالمي IRI أثناء العاصفتين المختارة. البيانات أخذت من القمر الصناعي DMSP وعلى ارتفاع 850 كم لدرجات حرارة الالكترونات والايونات وكذلك سرعة البلازمة ولخطوط عرض مختلفة ولنوعي العواصف الجيومغناطيسية التي تم اختيارها لهذه الدراسة من الاعوام 2001 ولغاية 2013 ولما هو متوفر ، تبين ان هنالك 22 عاصفة جيومغناطيسية شديدة وقوية حدثت خلال الاعوام 2001-2005 فقط من السنوات التي اختيرت للدراسة وهي من ضمن الدورة الشمسية العالية. من خلال تحليل البيانات وجد وبصورة عامة أن درجات حرارة الالكترونات أعلى من درجات حرارة الايونات ولكن اثناء فترة العواصفحدثت اضطرابات وتذبذبات في قيم درجات الحرارة بحيث اصبحت خلال النهار درجات حرارة الايونات اعلى من درجات حرارة الالكترونات. من خلال عامل الاضطراب المغناطيسي Dst تبين ان قيم درجات حرارة الالكترونات والايونات لاتعتمد على شدة او نوع العاصفة الجيومغناطيسية. سرعة البلازما تظهر تغيرات تكاد تكون مشابهة لتغيرات درجات حرارة الالكترونات والايونات اثناء نوعي العاصفتين المختارة وان هنالك تقريبا علاقة خطية بينهم. التغيرات في درجات الحرارة مع خطوط العرض أثناء العواصف بينت بأن قيم درجات الحرارة تزداد مع زيادة خطوط العرض وصولا لمنطقة الاقطاب بحيث تصل في بعض الاحيان اعلى قيم لها 80000 كلفن. أجريت مقارنة بين قيم درجات الحرارة المرصودة للالكترونات والايونات مع القيم المتنبأ بها والمحسوبة من الموديل النظري IRI وجد بأن القيم المحسوبة اقل من المرصودة وهنالك تغيرات بين القيمتين للاربع وعشرين ساعة من يوم العاصفة المختارة ان هذه التغيرات غير خطية وعليه يجب اجراء تصحيح للموديل النظري لنوعي العواصف الشديدة والقوية.

Introduction:

The ionosphere is the ionized portion of the upper atmosphere of the Earth. The photoionization of neutral molecules is the main source of plasma in the ionosphere. Then several processes may occur, chemical reactions between the ions produced and the neutrals take place, ions recombine with the electrons, ions diffuse to either higher or lower altitudes, or they are transported via neutral wind effects. Notice that the Earth's intrinsic magnetic field, which is dipolar at ionospheric altitudes, strongly influences the diffusion and transport effects. At different latitudes, different physical processes dominate, but the electron density variation with altitude which leads to variation in temperature still displays the same basic structure except that at high latitudes the O^+ density differs from that at mid-latitudes [1].

Within the lowest regions of the ionosphere, electrons and ions typically possess equal temperatures and move at a characteristic thermal speed which is dictated by both this temperature and the mass of the charged particle. With an increasing altitude however, the difference between the temperatures increases and at the F region peak, typical electron and ion temperatures are 2000K and 1400K respectively. Any external driving force, such as that supplied by an electric field, will also serve to accelerate the charged particles and consequently act as a source of energy that heats the plasma. As a result of the large difference in mass between the ions and electrons, it is principally the electron temperature that is enhanced significantly when the plasma is heated [2]. The high-latitude ionosphere is strongly coupled to the magnetosphere–thermosphere system via electric fields, particle precipitation, field-aligned currents, heat flows, frictional interac- tions, chemical interactions, and feedback mechanisms, and these have a significant impact on the high-latitude ionospheric density and thermal structure [3]. In an effort to understand the effects that these processes have on the iono- sphere, many numerical physics-based models have been developed over the years and these models have been very useful in understanding ionospheric behavior [4].

Previous Studies:

Several studies are made conducted in this regard mention some of them related to our study, Buonsato M. J. (1989) studied the Millstone Hill incoherent scatter (IS) observations of electron density (N_e), electron temperature (T_e) and ion temperature (T_i) which are compared with the International Reference Ionosphere (IRI-86) model for both noon and midnight, for summer, equinox and winter, at both solar maximum and minimum. Generally it shown that in winter N_e larger than in summer, this is apparently due to photoelectron heating during winter [5]. Forme F. et al. (1993) Performed one-dimensional time-dependent model calculations of the effects of low frequency turbulence, due to three different current driven instabilities, on the ion and electron temperatures in the topside ionosphere [6]. Pavlov A. V. et al. (2001) studied a comparison of the electron density and temperature behavior measured in the ionosphere during the period 25–29 June 1990. The evaluation values of the nighttime additional heating rate that should be added to the normal photoelectron heating in the electron energy equation in the plasmasphere region above 5000 km along the magnetic field line to explain the high electron temperature [7]. Sethi N. K. et al. (2004). Studied Incoherent scatter radar data from Arecibo, for solar maximum and minimum periods, are used to study the seasonal and solar activity variations in (Te) for noontime conditions. In spite of large day-to-day variations, clear seasonal variations in average Te can be identified for both solar activity periods, with winter temperatures significantly higher in the topside (400–700 km) ionosphere [8]. Gulyaeva T. L. and J.E. Titheridge (2006). Analyzed a plasmasphere extension has been incorporated in the IRI using the Russian standard model of the ionosphere SMI, at altitudes from 1000 km to the plasmapause (636,000 km). [9]. Jiuhou Lei et al., (2007) studied ionospheric (Te) data for more than two solar cycles are compared with the theoretical Te calculated from the Model (NCAR-TIEGCM) to investigate the temporal variations of Te. The simulations show that the daytime bulge of Te tends to occur at low latitudes and high solar activity, as seen in the observations, and the significant morning peak at low solar activity over Arecibo is associated with the equatorial anomaly [10].

M.V. Klimenko, et al .,(2008). Worked on The results from the numerical calculations of the global distribution of topside ionospheric parameters such as H+ ions and ion and electron temperatures up to 1500km height are presented for equinoctial conditions at solar minimum [11]. Schunk A. and Nagy (2010) found the theory and an observation relating to electron temperatures in the F region, the review covers electron temperature variations with altitude, latitude, local time, season, geomagnetic activity, and solar cycle [12]. David M. et al., (2011) studied the electron energy balance in the ionosphere is affected by numerous local heating include thermal conduction and thermoelectric heat flow [4]. In (1913) Slominska and Hanna studied is oriented on the dataset gathered in 2005and 2008. Within conducted analysis, global maps of electron temperature for months of equinoxes and solstices have been developed. Furthermore, simultaneous studies on two-dimensional time series based on DEMETER measurements and predictions obtained with the IRI-2012 model supply examination of the topside ionosphere during recent deep solar minimum [13]. De Meneses F.C. et al., (2013) studied the simultaneous in-situ measurements of Ne and Te in the nighttime equatorial region were performed by a rock experiment launched under solar minimum and geomagnetic quiet conditions [14]. The purpose of this paper is to study the diurnal variation of ionospheric electron and ion temperature during severe and great geomagnetic storms, then to reveal the validity of IRI model during these kinds of storms.

Temperature of Ionosphere:

Temperature can be defined in different ways due to different degrees of freedom – Otherwise the definition of temperature is the same for all matter (i.e. fluids, solid matter, gas and plasma): temperature is the energy related to random motion. There are several kinds of random motion: translational, rotational and vibrational each one contributes with different degrees of freedom to the determination of the temperature in thermal equilibrium. Each degree (G) of freedom contributes with (G kT)/2 to the total energy, where T is the temperature, (k) is Boltzmann's constant and G is typically 3 in plasma physics applications (F-region and topside the region above F2 layer [8]). In the ionosphere, the temperature (thermal energy) of a particle is directly proportional to average random kinetic (translational) energy and the neutral temperature will in general increase dramatically above the mesopause (~80 km) into the thermosphere, until it reaches an overall maximum of about 1000 K. However, the maximum and minimum of the neutral temperature depend on time, latitude, solar activity. Typically, between midnight and noon during solar minimum (maximum), the temperature varies between approximately (1000 – 1700 K)[15]. The neutral temperature maximum will typically occur at about 400 km, in the region called exobase, and then the temperature becomes constant with altitude in the exosphere. In the exosphere (> 600 km), individual atoms have the possibility to escape from the Earth's gravitational attraction if the temperature is high enough (escape velocity $v_e = (2GM/r)^{0.5}$ where G is a gravitational constant, M the mass of the planet, (r) the distance between planet center and position).The background exospheric temperature is normally between 1000 and

1500 K, too low to escape, but if the temperature increases, so will the velocity, and the minimum escape velocity is about 9.7 km/s at 2000 km. This is somewhat less than the escape velocity ($½mv^2$=3/2KT) at the Earth's surface, which is ~11.2 km/s. In general, it requires a huge temperature for O and He to escape. A factor 16 and 4 more than for H is related to O and He, respectively, and the escape temperature is equal to or greater than 4900 K (> 0.63 eV) at about 500 km. Thus the escape velocity (~11 km/s) is more than twice the mean thermal velocity (4.98 km/s) of atomic hydrogen at a temperature of 1000 K [16] as shown in Figure-1.

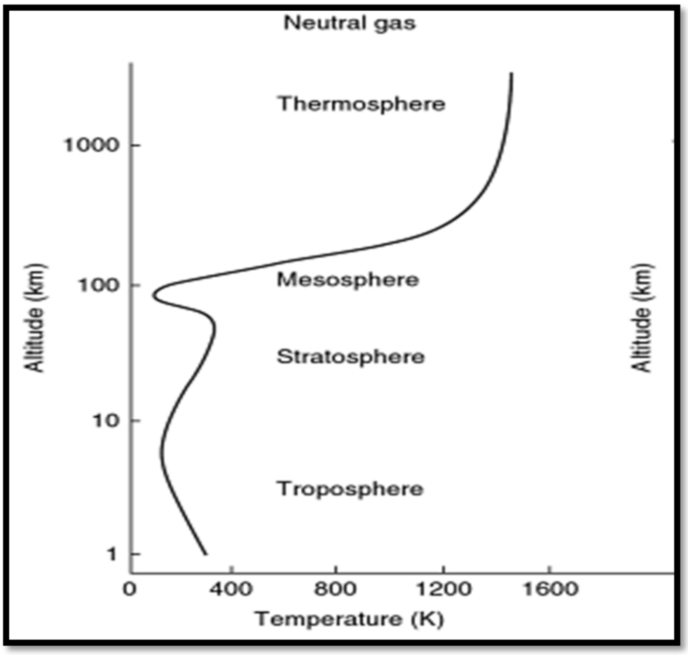

Figure 1- Typical profiles of neutral temperature [17].

Geomagnetic Storm index Disturbance storm time (Dst):

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 [18].

The minimum Dst value reached is often used to classify the strength of a geomagnetic storms as in table-1.

Table 1- Geomagnetic storm classification [18].

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

International Reference Ionosphere Model (IRI):

The International Reference Ionosphere (IRI) project was initiated by the Committee on Space Research(COSPAR) and by the International Union of Radio Science (URSI) in the late sixties with the goal of establish in international standard for the specification of ionospheric parameters based on all worldwide available data from ground-based as well as satellite observations. COSPAR and URSI specifically asked for an empirical model to avoid the uncertainties of the evolving theoretical understanding of ionospheric processes and coupling to the regimes below and above [48]. From early on the model was made available in electronic form as a FORTRAN program and more recently also as an interactive web interface accessible from the IRI homepage. IRI describes monthly average of the electron density, electron and ion temperature, ion composition (O+, H+, N+,He+, O2, NO+, Cluster+), and ion drift in the current ionospheric altitude range of 50–2000 km [19] [20].

Data Selection:

In this research the data of electron temperature, ion temperature and plasma velocity are taken from satellite Defense Meteorological Satellite Program (DMSP) 850 km altitude from site (http://ngdc.noaa.gov/eog/) during great and severe storm from years 2001 to 2013 according to what is available. For the same years the Dst values are taken from (http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html). Solar activity through sunspot number (SSN), ionosphere index (IG12) are needed to predict the Te and Ti calculated from IRI model, which are taken from site Solar indices data center (SIDC).

Data Analysis:

The factor which presents type of geomagnetic storm (GMS) is Dst, the great (Dst> -320 nT) and severe (Dst> -200 nT). From figure-2 it is found that there is only (22) great and severe geomagnetic storms occurred during years 2001-2005 (at solar maximum) from the years selected (2001-2013) which shown in table 2, it reveals the date of storm, beginning and end of the storm time, Dst, and SSN. To see the behavior of Te and Ti before, during and after the storm figures from 3-7 were plotted which represent the hourly variation of observed electron (Te red line) and ion (Ti blue line) temperature for 13 events selected which continued for several hours from years 2001, 2003, 2004 and 2005 chosen respectively. To study the plasma velocity with electron and ion temperature graphs are plotted as in Figures from 8-12. Figure-13 shows the variation of ion and electron temperature with latitudes. To reveal validity of IRI model graph between observed and predicted Te and Ti values, figure-14 reveals the Te and Ti observed (sold line) and predicted (dash line).

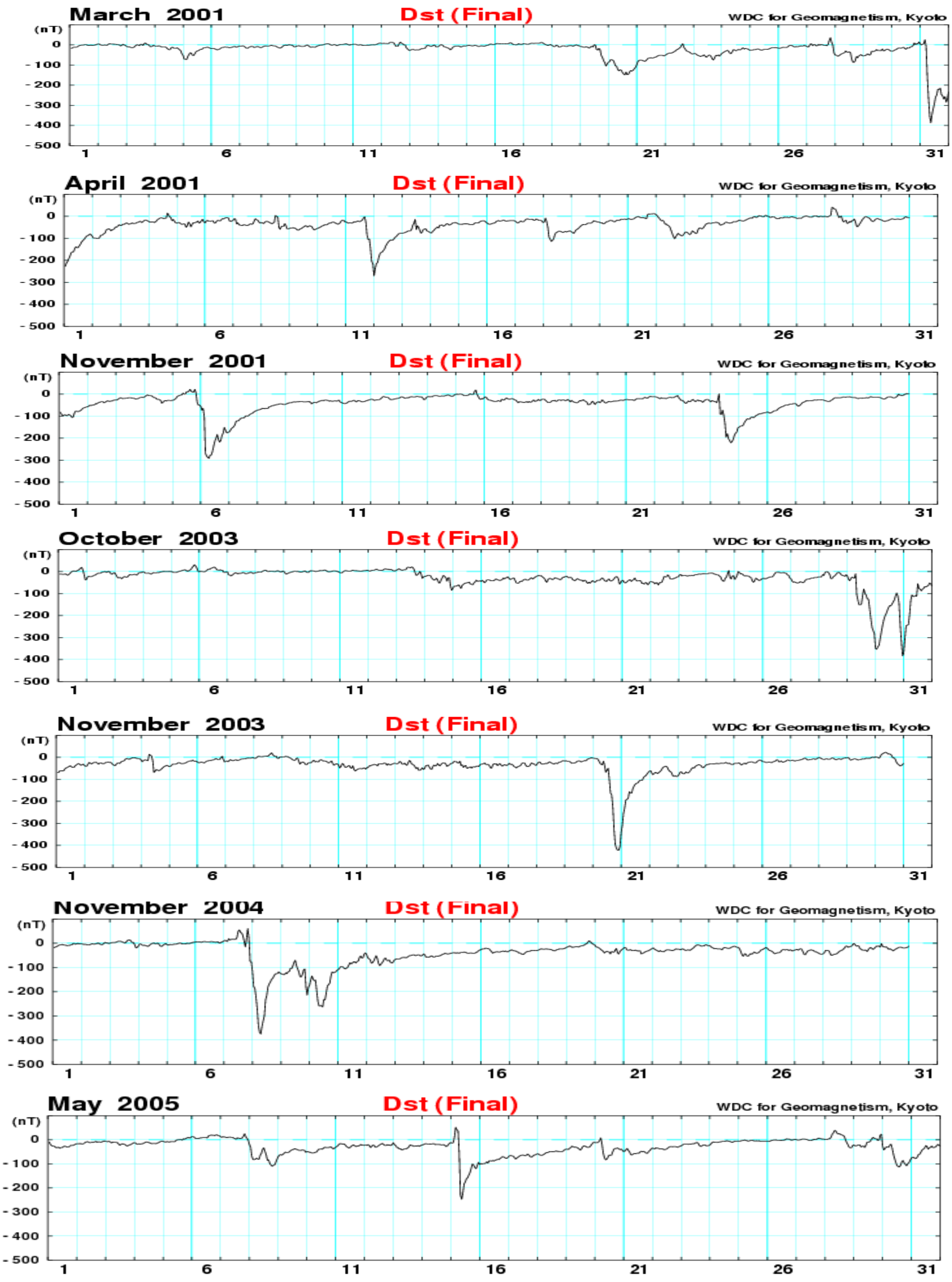

Figure 2- Disturbance solar time (Dst) for years 2001-2005

Table 2- severe & great beginning and end storm time with Dst &SSN

Event no.	Date of strom	Hour of Beginning & End event	Dst (nT)	SSN	Type storm
1	31/3/2001	7	-262	111	Severe
2	31/3/2001	8 – 10	-351 -387 -346	111	Great
3	31/3/2001	11 – 24	-317-292-259-249-220-222 -214-247-254-269-256-284-269-233	111	Severe
4	1/4/2001	1 – 3	-228 -213 -205	111	Severe
5	11/4/2011	22 -24	-205 -215 -271	111	Severe
6	12/4/2001	1 – 3	-236 -215 -210	111	Severe
7	24/11/2001	15 -19	-202 -211 -221 -216 -205	111	Severe
8	29/10/2003	20 – 23	-213-253-268-281	63.7	Severe
9	29/10/2003	24	-350	63.7	Great
10	30/10/2003	1-3	-353 -341 -335	63.7	Great
11	30/10/2003	4 -8	-303 -203	63.7	Severe
12	30/10/2003	21-22	-240 -316	63.7	Severe
13	30/10/2003	23 – 24	-383 -371	63.7	Great
14	31/10/2003	1 – 4	-307 -246 -244 -241	63.7	Severe
15	20/11/2003	17	-229	63.7	Severe
16	20/11/2003	18 – 24	-329-396-413-422-422-405-343	63.7	Great
17	21/11/2003	1 – 3	309-256-230	63.7	Severe
18	8/11/2004	3 – 4	224-272	40.4	Severe
19	8/11/2004	5 – 9	-342-368-374-343 -320	40.4	Great
20	8/11/2004	10 – 12	-299-234-215	40.4	Severe
21	10/11/2004	7 -14	-240-259 -258-258-263-232-234-206-	40.4	Severe
22	15/5/2005	8 – 10	-229 -247-222	29.8	Severe

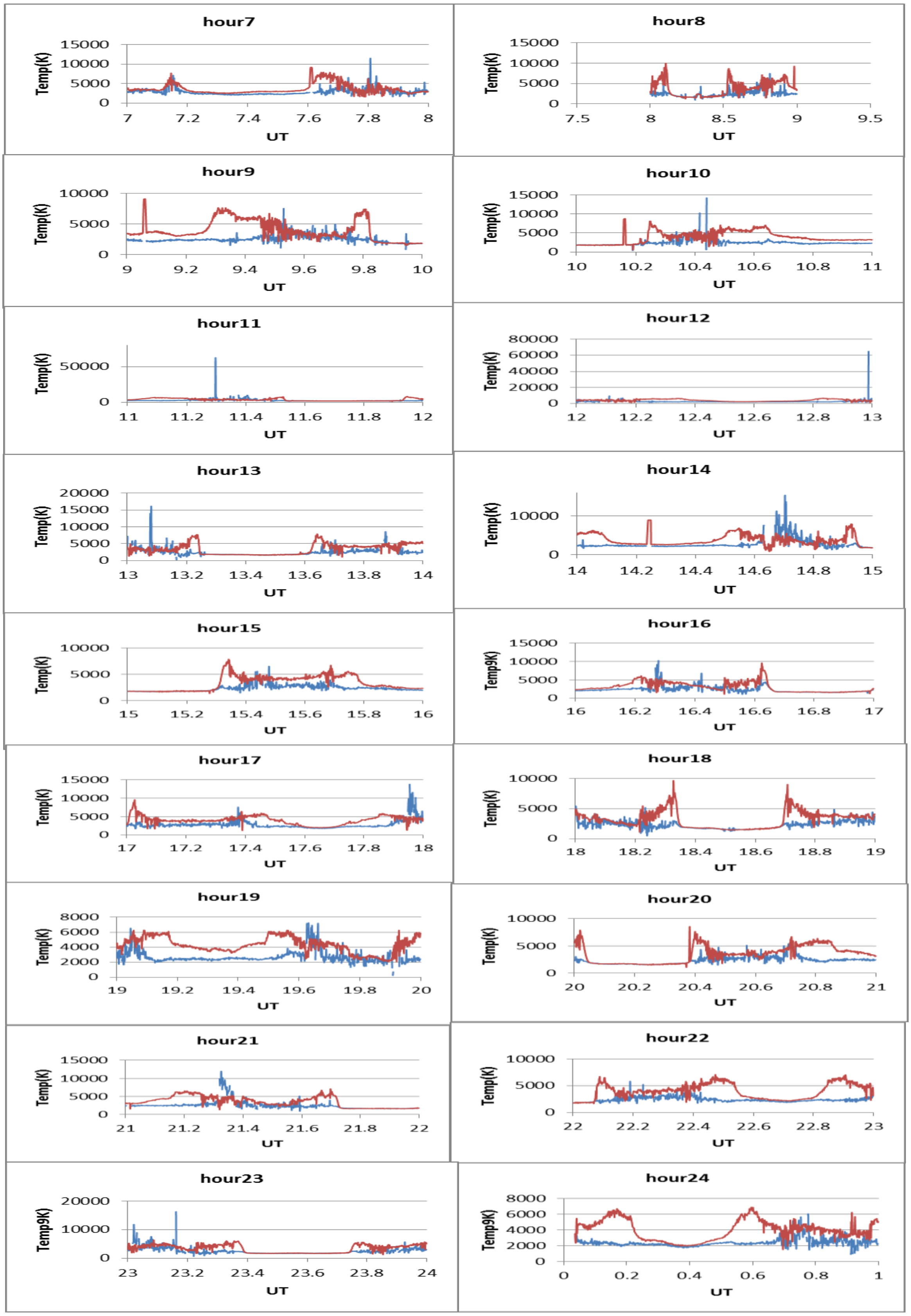

Figure 3- Hourly variation electron temperature (red) and ion temperature (blue) during the geomagnetic Storm of 31 Mar 2001.

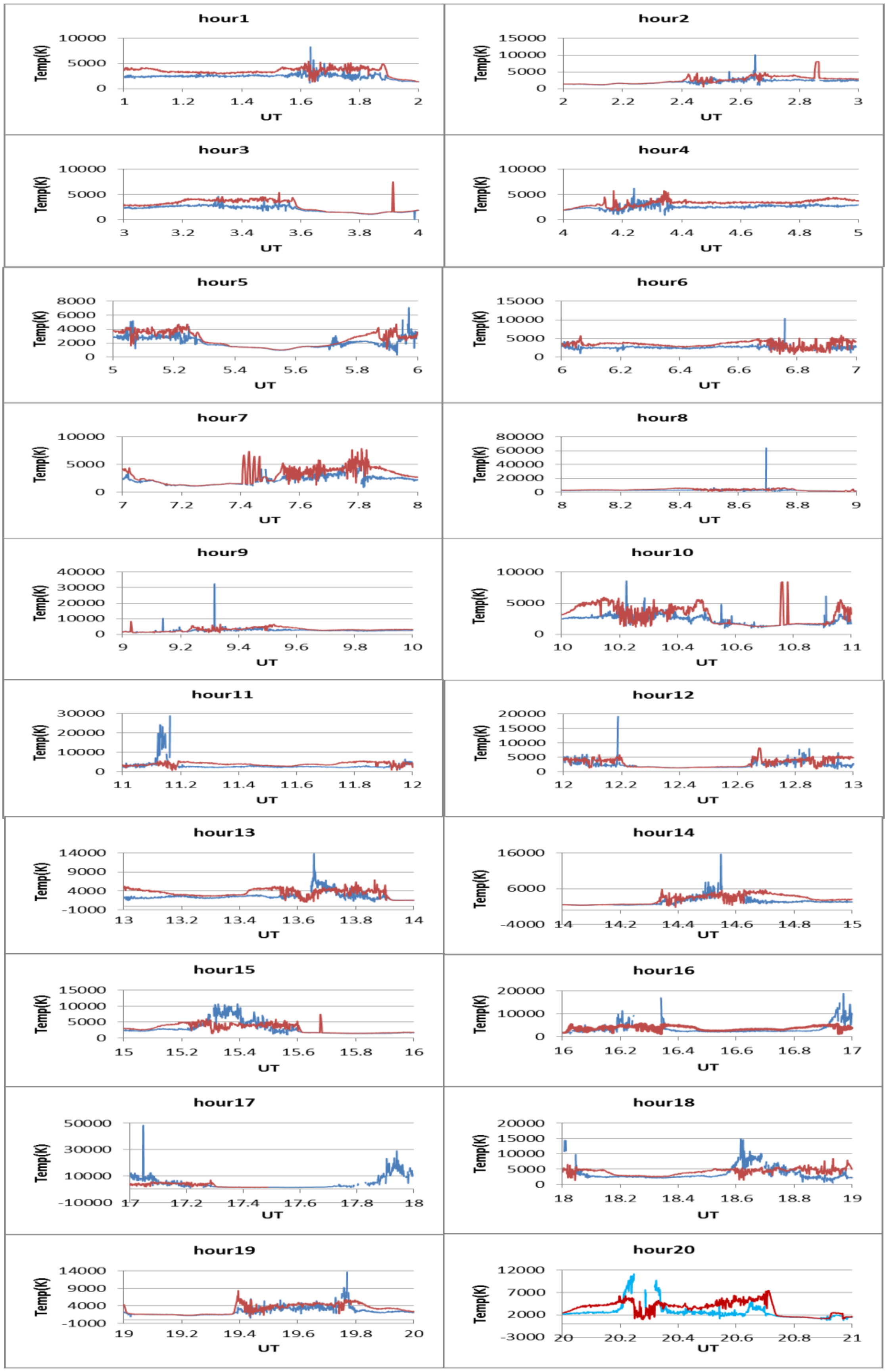

Figure 4- Hourly variation electron temperature (red) and ion temperature (blue) during the Geomagnetic Storm of 29 Oct. 2003.

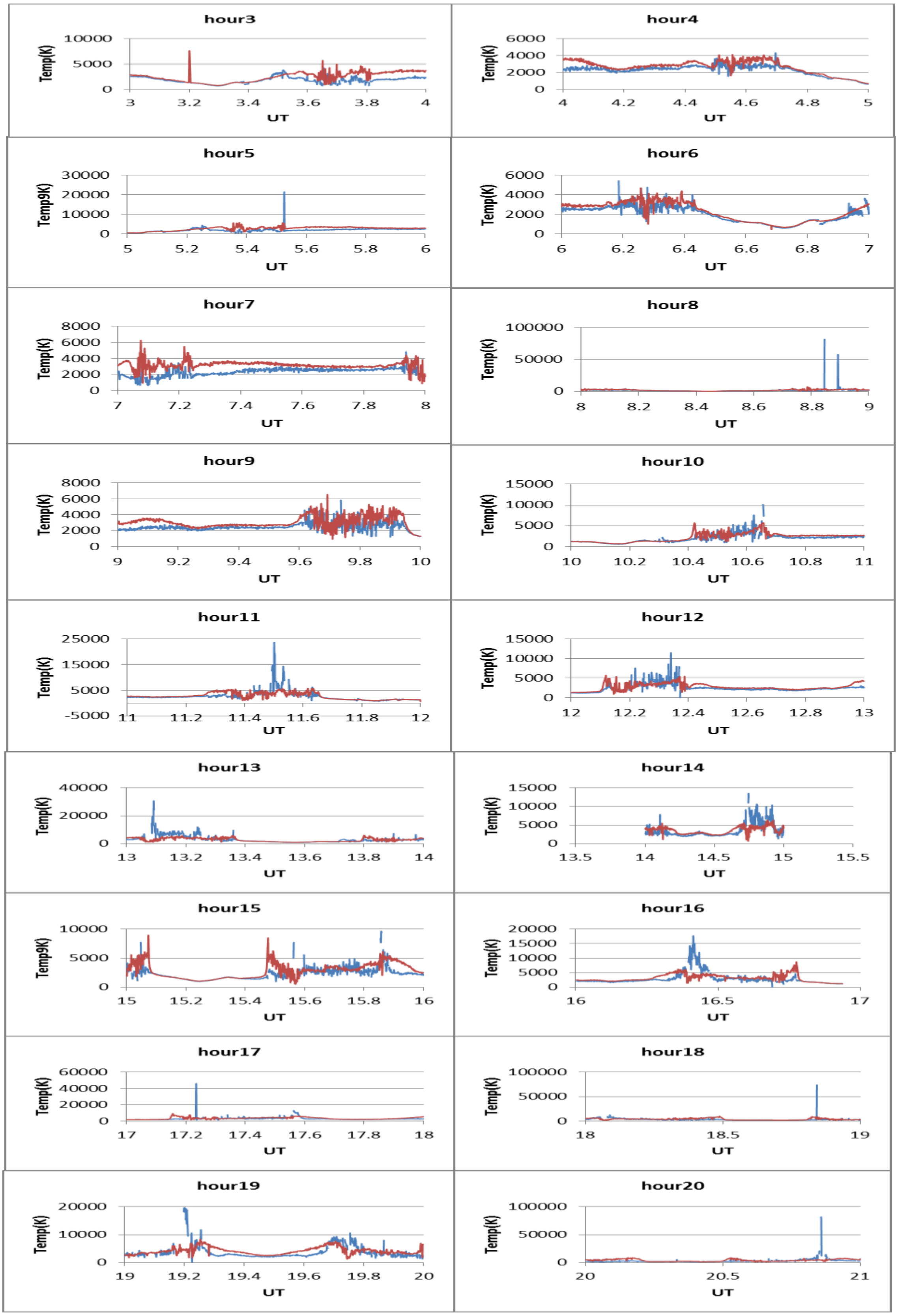

Figure 5- Hourly variation electron temperature (red) and ion temperature (blue) during the Geomagnetic storm of 20 Nov. 2003.

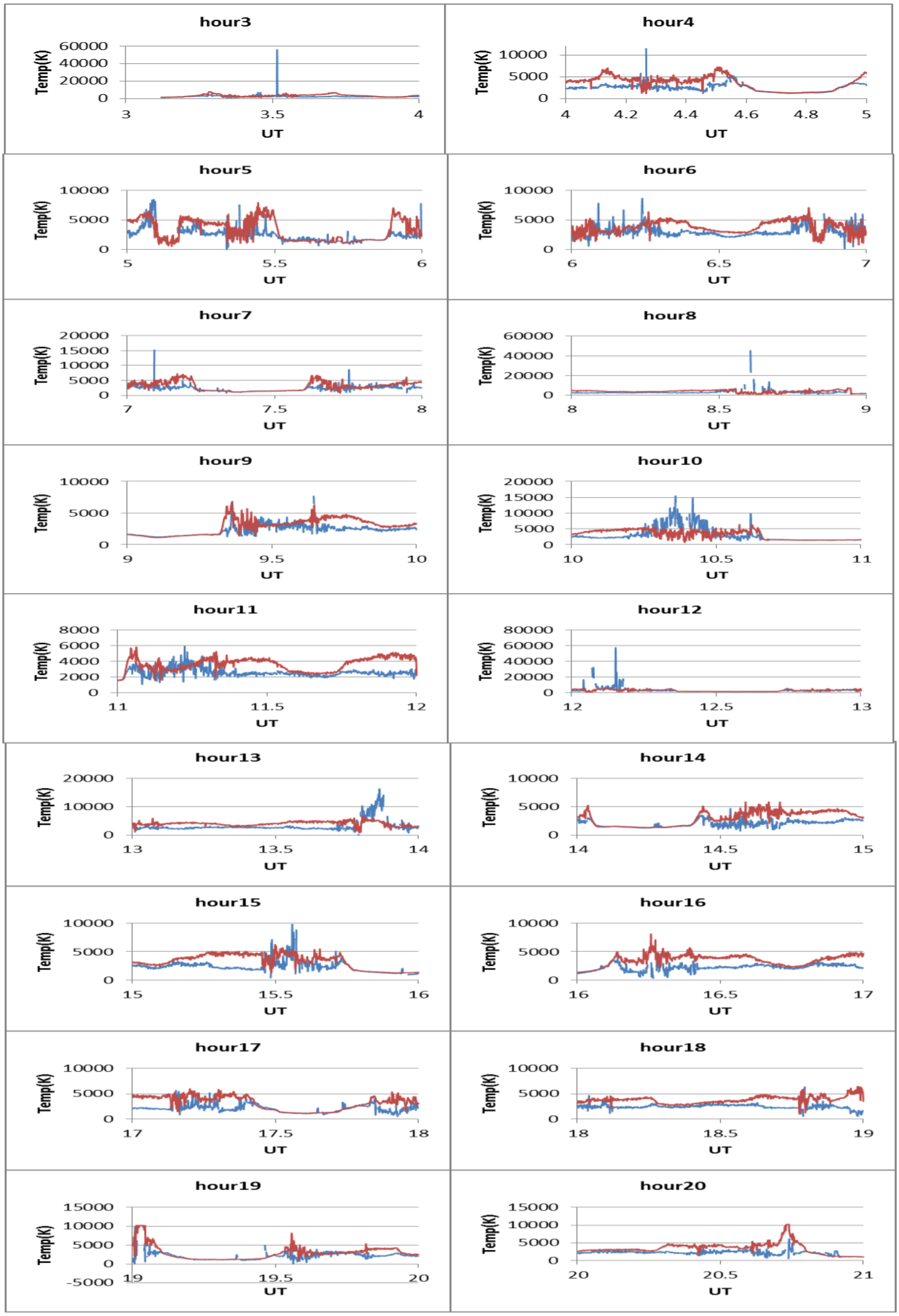

Figure 6- Hourly variation electron temperature (red) and ion temperature (blue) during the Geomagnetic storm of 8 Nov. 2004.

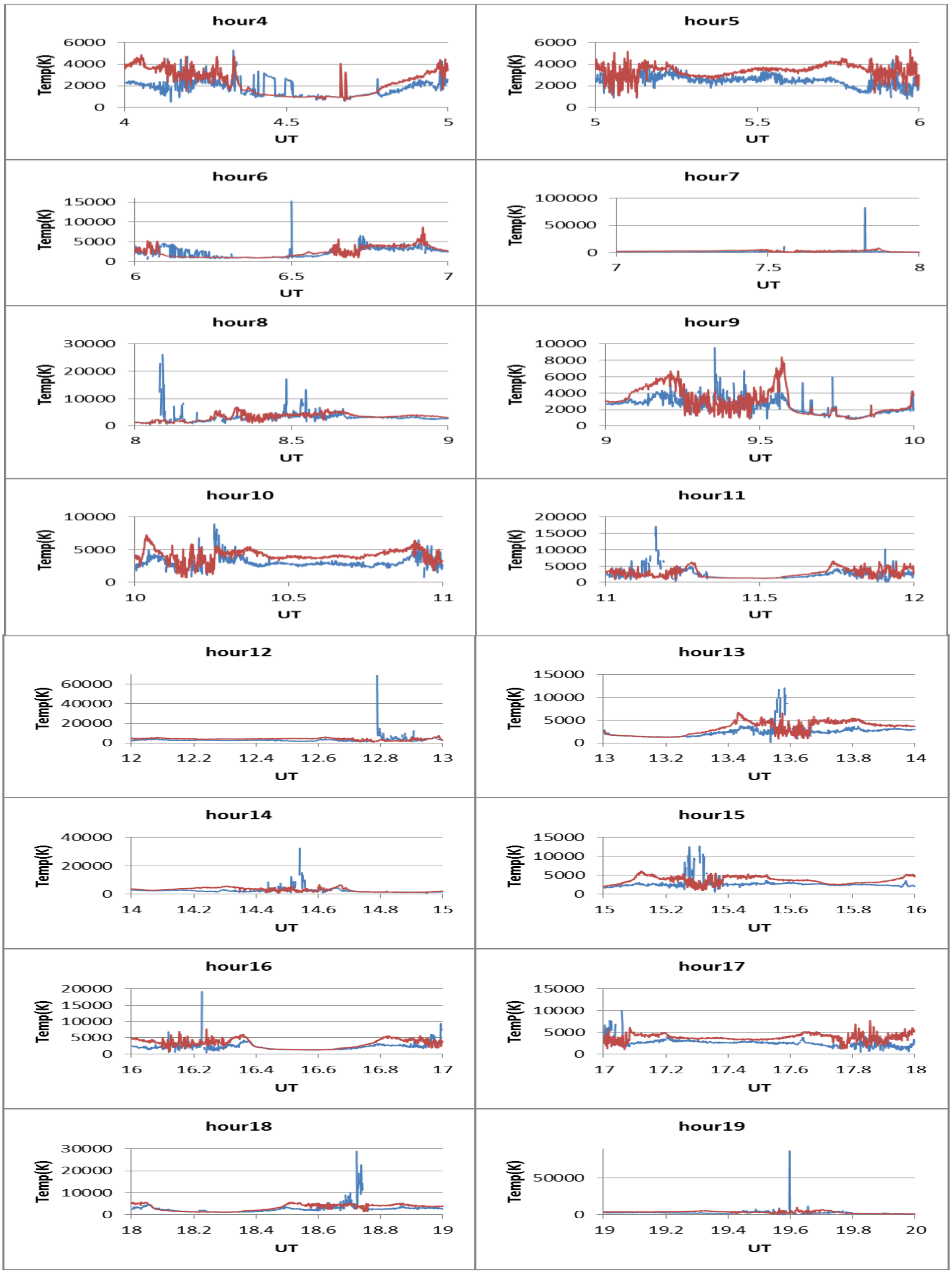

Figure 7- Hourly variation electron temperature (red) and ion temperature (blue) during the Geomagnetic storm of 15 May 2005.

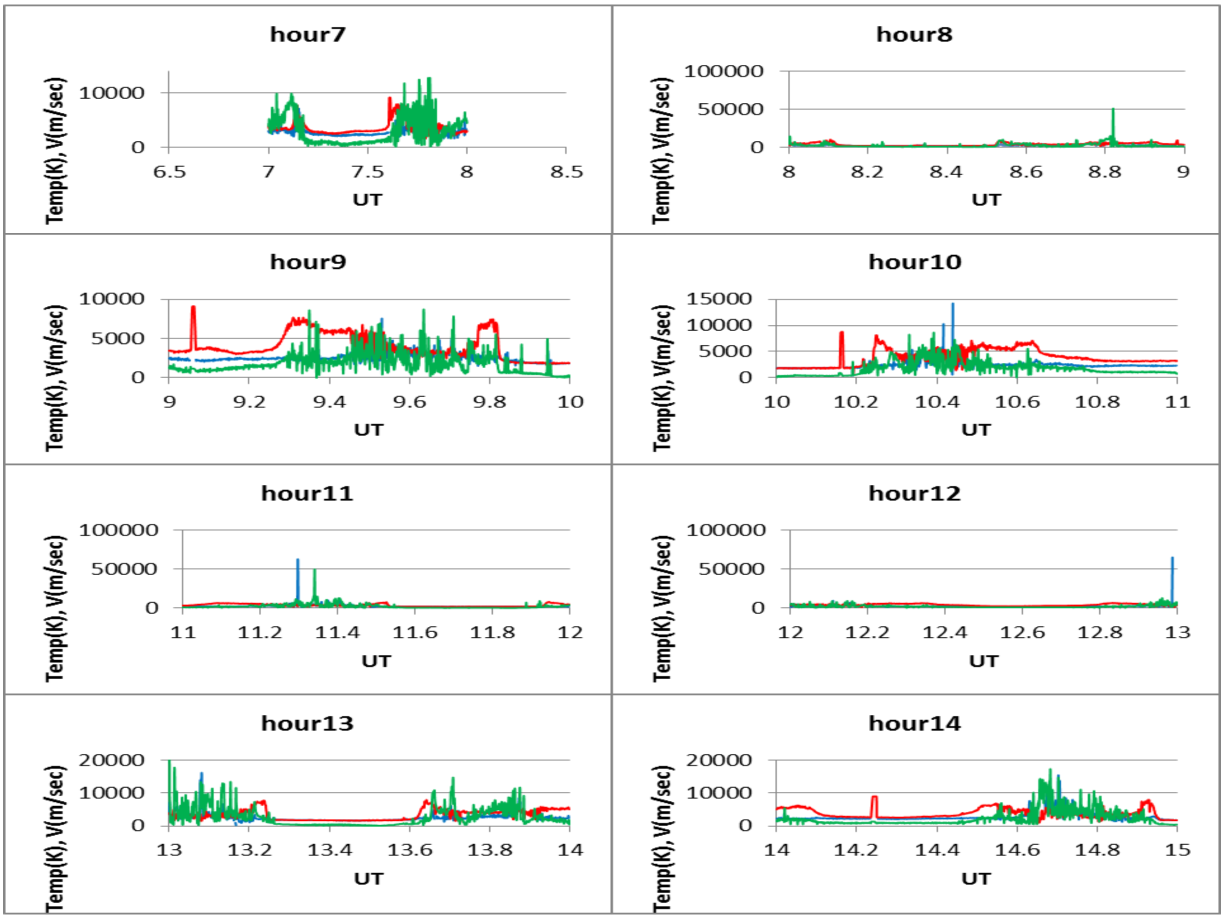

Figure 8- Hourly variation electron temperature (red), ion temperature (blue) and plasma velocity (green) during the geomagnetic storm peak hours of 31 Mar 2001.

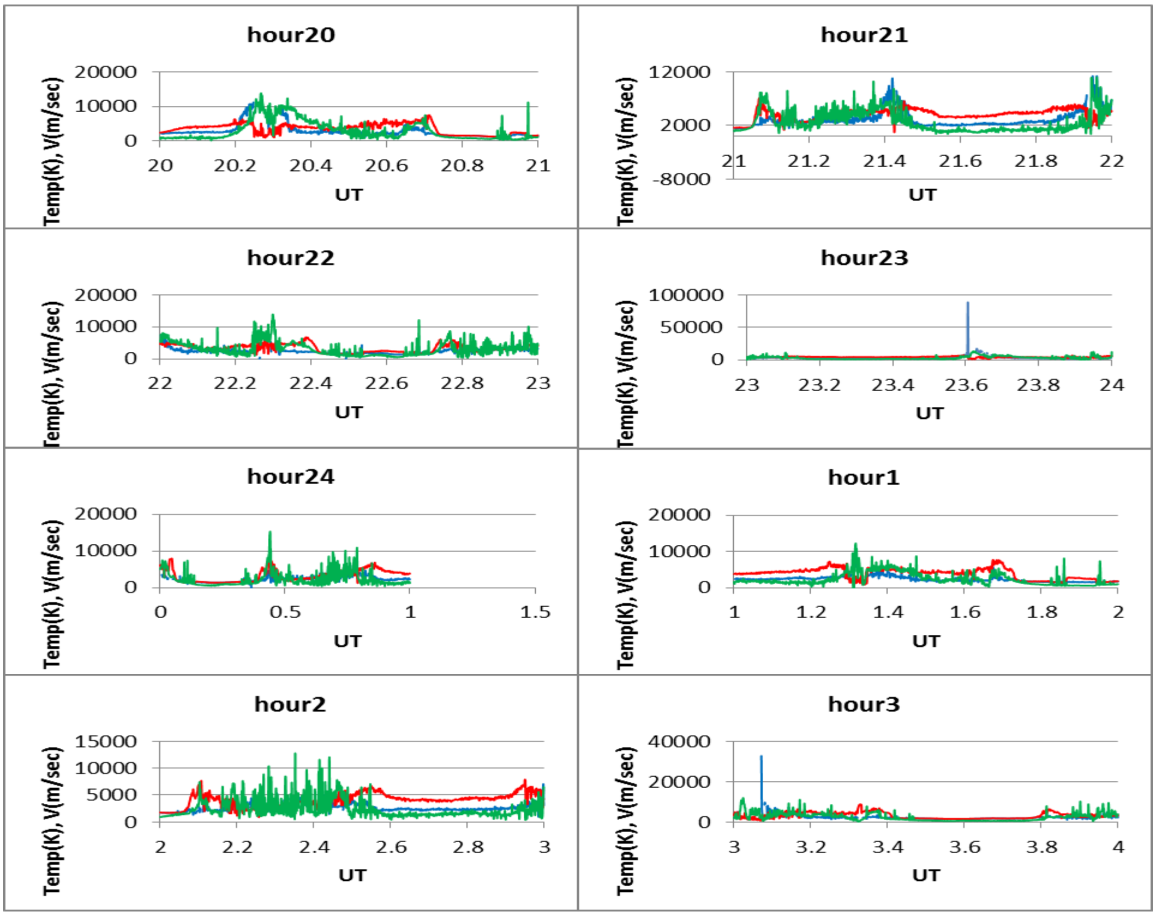

Figure 9- Hourly variation electron temperature (red), ion temperature (blue) and plasma velocity (green) during the geomagnetic storm peak hours from 29-30 Oct. 2003.

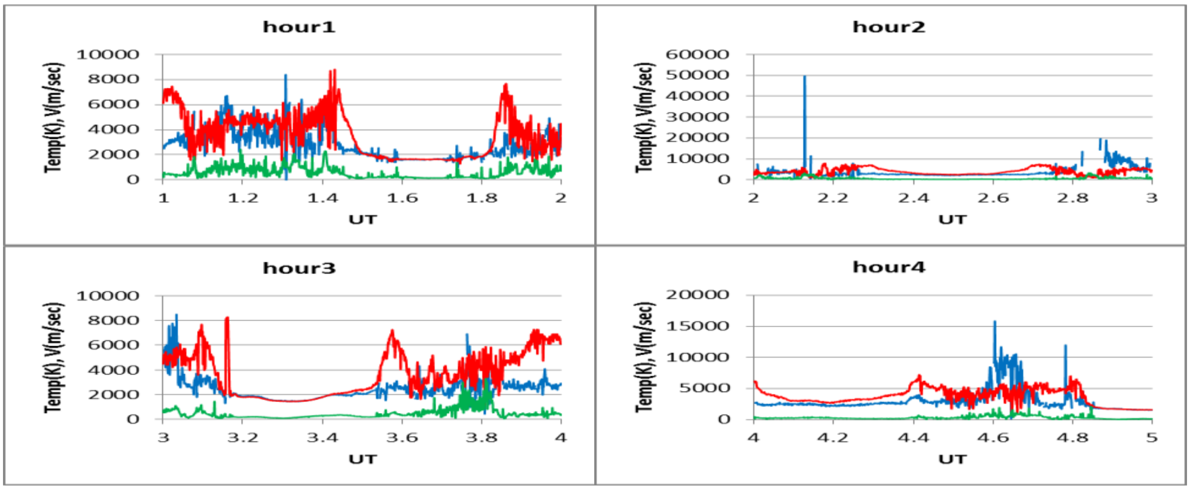

Figure 10- hourly variation electron temperature (red), ion temperature (blue) and plasma velocity (green) during the geomagnetic storm peak hours from 31 Oct. 2003.

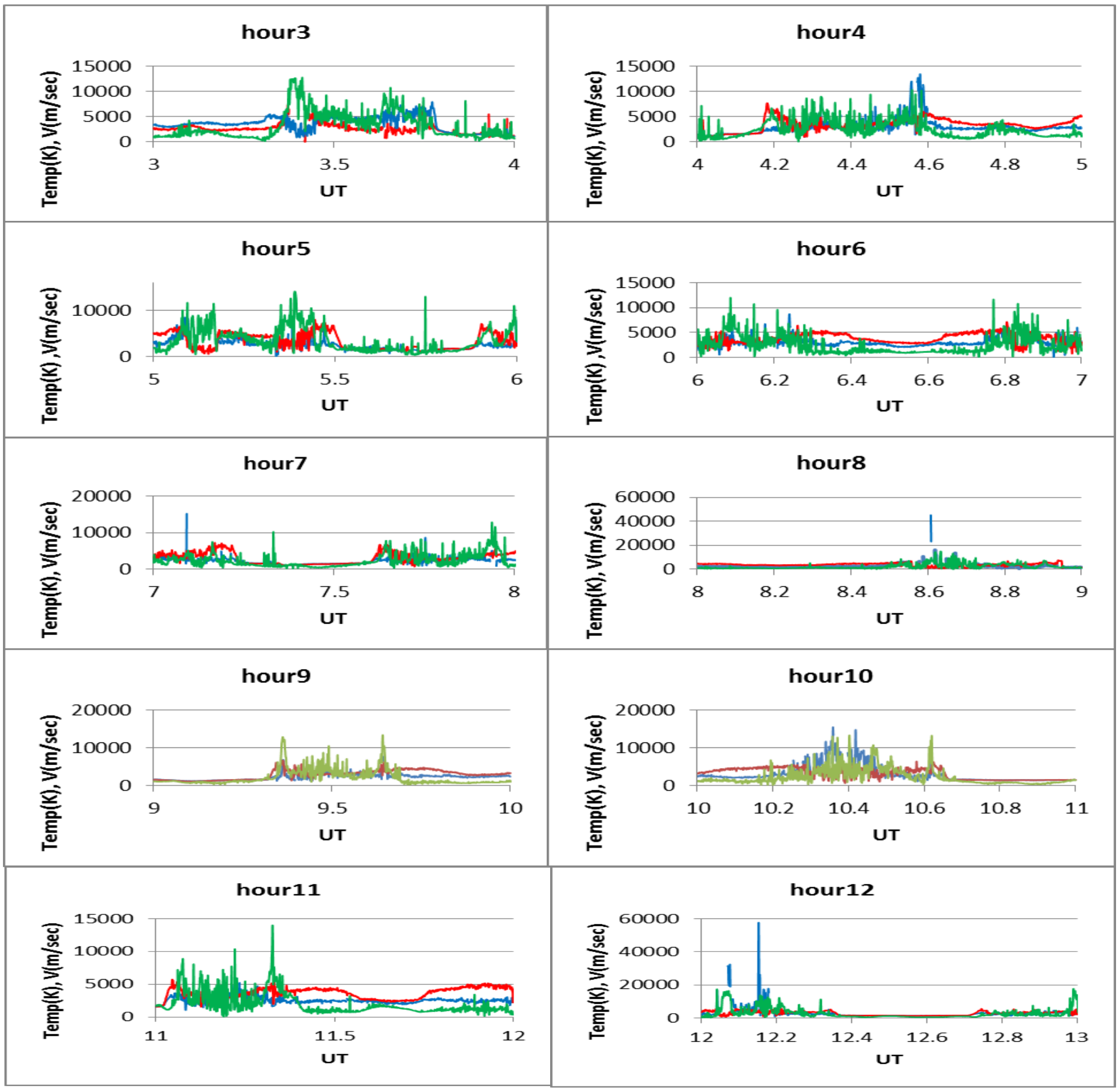

Figure 11- Hourly variation electron temperature (red), ion temperature (blue) and plasma velocity (green) during the geomagnetic storm peak hours from 8 Nov. 2004.

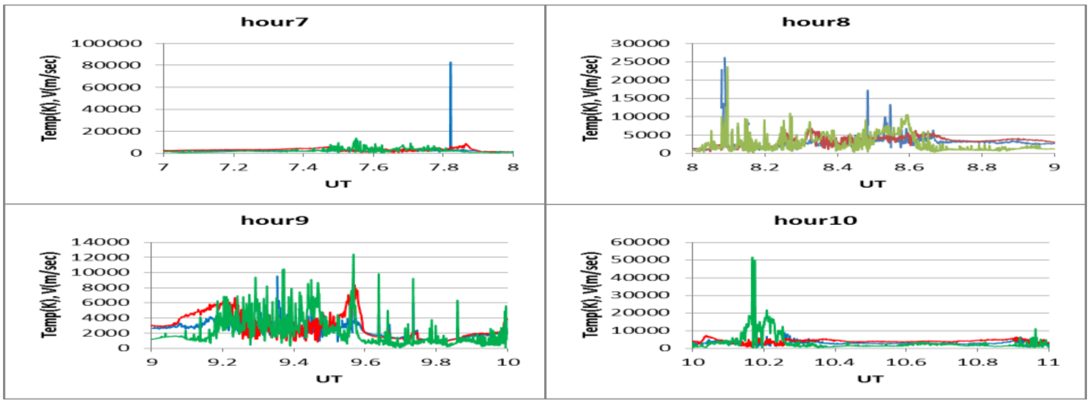

Figure 12- Hourly variation electron temperature (red), ion temperature (blue) and plasma velocity (green) during the geomagnetic storm peak hours from 15 May 2005.

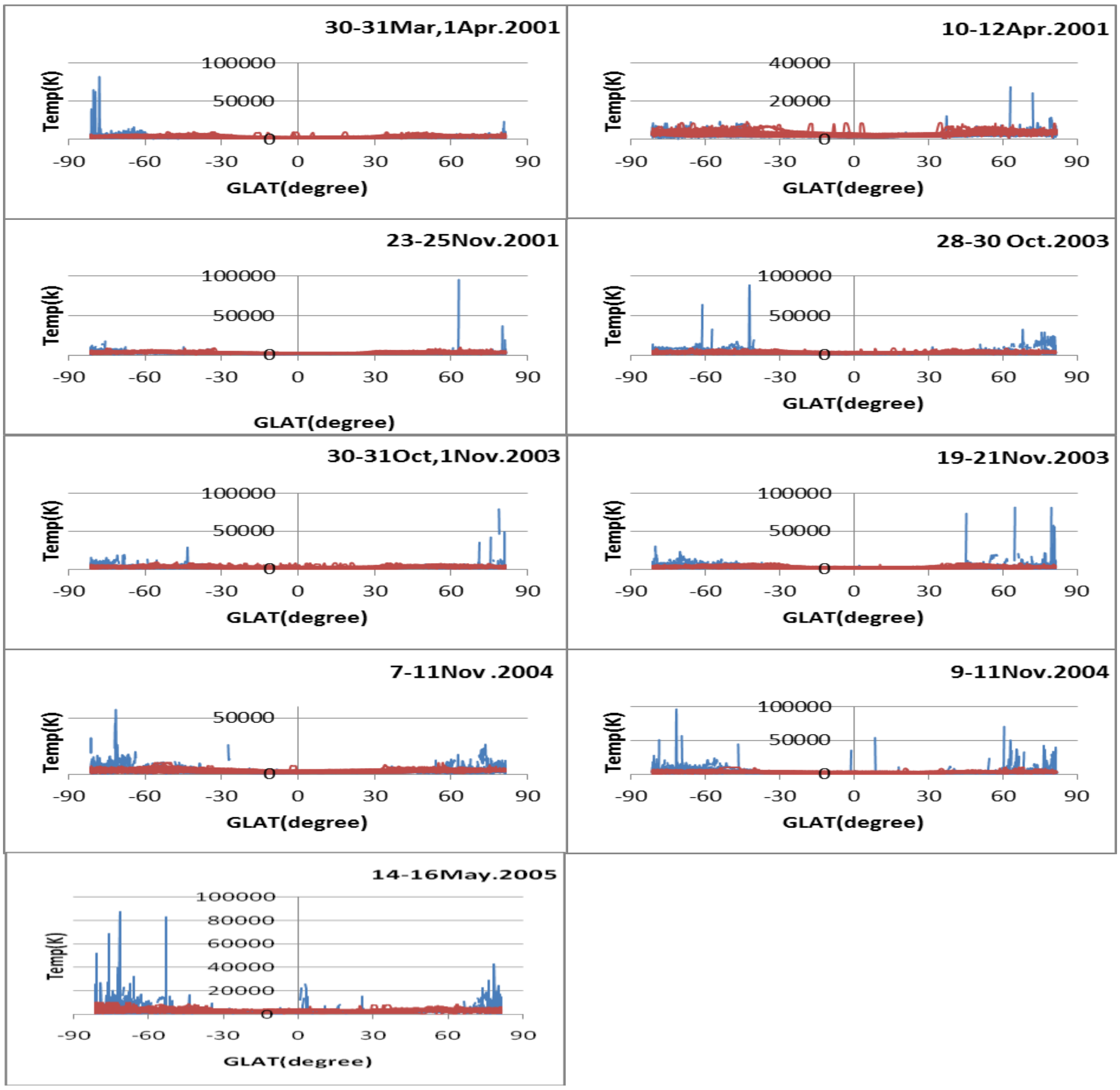

Figure 13- Electron and ion temperature with latitude

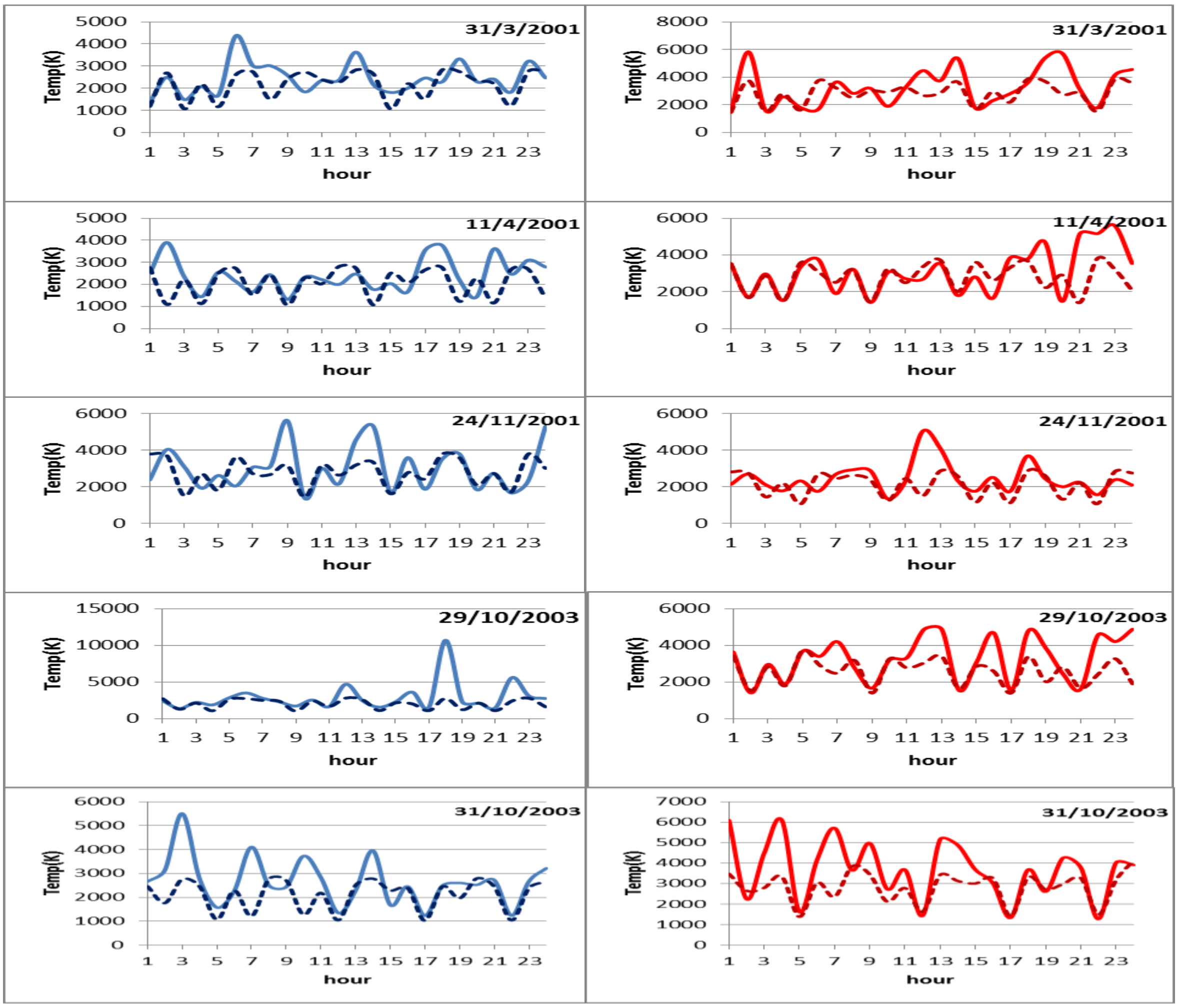

Figure 14- Observed (solid) and predicted (dash) of Te (red) and Ti (blue) values.

Results and Discussion:

From data analysis it's found that there are four branches that we can discuss, these are:-

a. Electron and ion temperature variation

From figures 3-7, in general the temperature of the electron is greater than the temperature of the ion, but there are some disturbances happened during the storm time, its seen that in year 2001 there was (7) severe and great storms happened in which the electron temperature has greater values than the ion temperature before the storm. In storm day, it is changed in the day and night there is fluctuation in values of Te and Ti or there is a disturbances in temperature during the storm time, Ti greater than Te in (31/3/2001) there is three severe and great events, the Ti peaks hours seen from figure 3 are (4.34, 7.8, 9.5, 10.45, 11.3, 13.1, 13.1, 13.9, 14.7, 15.45, 16.25, 17.98, 19.1, 19.6, 21.3, 23-23.2). For other storms continues to the same behavior, related to the storm happened in 2003 in day (29/10/2003) figure 4, it seen a peak Ti in hours (1.55, 2.55, 4.25, 6, 6.77, 8.7, 9.3, 10.2, 11.1-11.2, 12.2, 13.65, 14.56, 15.3-15.4, 16.2, 16.35, 16.9-17.1, 18.6-18.7, 19.57, 20.2-20.3, 21.4, 21.9-22, 23.6), in day (20/11/2003) as in figure 5, Ti peak hour are (5.5, 6.2, 8.86-8.9, 10.6, 11.5, 11.5, 12.2-12.4, 13.1, 14.7-15, 15.6-15.8, 16.4, 17.22, 18.8, 19.2, 20.85).

In 2004 it reveals that there are many peaks of Ti value which is greater than Te as in figure 6, day (8/11/2004) Ti peak hours (2.5, 3.5, 4.26, 5.1-6.3, 7.1, 8.6, 9.61, 10.3-10.5, 11.3, 12.2, 13.9, 15.5-15.6,). In year 2005 there is one event in one day (15/5/2005) shown in figure (7) Ti peaks appeared at (1.1, 2.6, 3.4, 12.8, 13.57, 14.56, 15.3, 16.2, 17, 18.72, 19.6, 20.4, 21.1, 23, 23.8).

This means that the severe and great geomagnetic storms suffer changes in Te and Ti.

Te and Ti do not depend on the strength of the geomagnetic storm (through the Dst index), for example at hour 9 in 31/3/2001 the value of (Dst -387nT) the value of Ti approach 8000K, while at hour 7 in 1/4/2001the value of (Dst -161nT) Ti approach 85000K. To discuss this point there may be other factors which appeared during the storm which effect on the Te and Ti values like the coronal mass ejection (CME), related to table 1, it’s found that the appearance of severe and great storms increases with increasing SSN value.

b. Plasma velocity variation

From Figures 8-12 it reveals that plasma velocity variation seems to have the same profile of Te and Ti variation during the storm time. To reveal the relation between plasma velocity and electron temperature figure-15 is drawn to represent that there is linear relation between them.

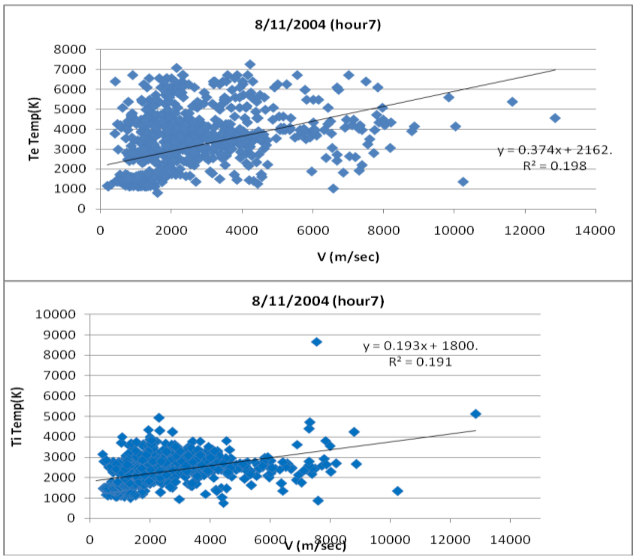

Figure 15- Plasma velocity with electron and ion temperature.

c. Latitude variation of Te and Ti

From figure 13 the variation of electron and ion temperature with latitude during severe and great storms shows that as the latitude increases and reach the poles the temperature of ions increases starting from 50 degree northern and southern hemisphere reaches maximum values approximately 80000K. The reason for this may be due to the absence of magnetic field near poles.

d. Validity of IRI model

To check the validity of IRI model for calculating the electron and ion temperature during the great and severe storms, six days (for 24 hours) are selected in which the storms happened from two years 2001 and 2003. Comparing the predicted Te and Ti values with observed one it’s found from figure 14 that the predicted values from IRI model are much less than the observed values and the variation was nonlinear along 24 hours, from this we can say that the model must corrected to these two kinds of storms.

Summary:

From data analysis and results we can conclude that, in general:

- The temperature of the electron is greater than the temperature of the ion, then it begin to disturbs during the storm time it show the same values, but in the day and night there is fluctuation in values of Te and Ti, Ti greater than Te the value of Ti approach 60000K.
- It is clear that, through the Dst index, Te and Ti do not depend on the strength of the geomagnetic storm. Plasma velocity variation seems to be of the same profile of Te and Ti variation during the storm and there is a linear relation between plasma temperature and velocity.
- The variation of electron and ion temperature with latitude during severe and great storms shows that as the latitude increases and reaches the poles the temperature of ions increases starting from 50 degree northern and southern hemisphere reaches maximum values approximately 80000K.
- To check the validity of IRI model for calculating the electron and ion temperature during the great and severe storms, it’s found that the predicted values from IRI model much less than the observed values and the variation was nonlinear along 24 hours.

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