Seismic Effects in F2 Region Related to Electron Temperature

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Исследовано влияние землетрясений в ионосферном диапазоне F2 с использованием данных индийского спутника SROSS-C2 о космической электронной температуре вокруг Индийского сектора в диапазонах 0—34° N и 40—100° E за период 1995—1997 гг. Проанализировано пять эпизодов землетрясений и наблюдавшиеся аномалии при средней электронной температуре от 29 до 10 % большей, чем в предшествовавшие дни, и от 16 до 4 % большей, чем в дни после землетрясения, а также широтная вариация указанной температуры. Показано, что рост этой температуры был максимальным в день, предшествовавший землетрясению, и в течение нескольких часов до и после него. Аномалии, наблюдавшиеся вокруг (в ±2-градусном широтном диапазоне), были эпицентром землетрясения. Они наблюдались, вероятно, в силу электромагнитного излучения во время активности землетрясения. Период с 1995 по 1997 г. для данного исследования принимали как период спокойных геомагнитных условий.

Досліджено вплив землетрусів в іоносферному діапазоні з використанням даних індійського супутника SROSS-C2 стосовно космічної електронної температури навколо Індійського сектору в діапазонах 0—34° N і 40—100° E за період 1995—1997 рр. Проаналізовано п'ять епізодів землетрусів і спостережувані аномалії за середньої електронної температури від 29 до 10 % більшої, ніж у попередні дні, та від 16 до 4 % більшої, ніж у дні після землетрусу, а також широтну варіацію зазначеної температури. Показано, що зростання цієї температури було максимальним у день, що передував землетрусу, і протягом кількох годин до і після нього. Аномалії, що спостерігались навколо (у ±2-градусному широтному діапазоні), були епіцентром землетрусу. Їх спостерігали, ймовірно, завдяки електромагнітному випромінюванню під час активності землетрусу. Період з 1995 по 1997 р. для цього дослідження вважали періодом спокійних геомагнітних умов.

1. Introduction. Electromagnetic emissions associated with earthquakes and their effects on ionosphere have already been discussed since last three decades. Number of publications brought out show that ionospheric variations do exist which are associated with the seismo-electromagnetic activity and these appear several hours before or around the earthquake day [Silina et al., 2001; Molchanov et al., 2002; Pulinets et al., 2003]. Hayakawa et al. [1994, 1996] reported seismo-electromagnetic waves in the frequency range from DC to HF have been considered as an ionospheric disturbance frequency. Seismo-electromagnetic emissions propagate towards the ionosphere and perturb it.

There are two methods for observation of earthquake signatures. The first one is the direct observation of electromagnetic emissions from the lithosphere and the second one is to detect seismo-electromagnetic emissions using satellite observations [Hayakawa et al., 2007]. In recent decades, some authors using the satellite data showed that the lithosphere-atmosphere-ionosphere interaction exit in the region of seismic activity. Satellite observations have the major advantage of covering almost all the areas of seismic activities throughout the world very quickly.

Satellite observations, related to electromagnetic and ionospheric perturbations associated with seismic activity, have been published by many scientists [Parrot et al., 1993; Gokhberg et al., 1995; Hayakawa, 1997; Liperovsky et al., 2000; Sarkar et al., 2007]. Gokhberg et al. [1983] reported the results of local plasma density and temperature variations measured using onboard AE-C and ISIS-2 satellites associated with seismic activity. Boskova et al. [1993, 1994] have observed using the data of Intercosmos-24 satellite changes in ion composition before earthquakes over the earthquake preparation zone. Also, several observational data suggest that an anomalous state of the ionosphere exists in seismically active regions both after [Blanc, 1985] and before [Shalimov, 1992; Liperovsky et al., 1992] earthquakes.

Ionospheric disturbances with scales of few hours in F, D and E regions of the ionosphere before the earthquakes have been reported in several papers [Popov et al., 1996; Sharadze et al., 1991; Liperovsky et al., 1999; 2000; Popov et al., 2004]. Sorokin et al. [2001; 2006 *a*, *b*], Sorokin and Chmyrev [2002] have formulated the electrodynamic model of ionospheric precursors to earthquakes. This model gives an explanation to some electromagnetic and plasma phenomena preceding earthquakes by amplification of DC electric field in the ionosphere over a seismic region. Such electric fields have been reported from the satellite observations made over earthquake regions (M=4,8).

Study of anomalous behavior in ionospheric parameter due to seismic activity such as enhancement in electron and ion temperatures and ion density, gives good hints for the earthquake predication. In the present paper, ionospheric electron temperature data of SROSS C2 satellite have been analyzed for the study of seismoelectromagnetic effect on ionosphere perturbation. The observation of electron temperature measured by SROSS C2 is also compared with the values simulated from International Reference Ionosphere 2001.

2. Database and observational methodology. In this study, earthquake information was retrieved from USGS website for moderate earthquakes that occurred in latitude range of 0 to 34 °N and longitude range of 40 to 100 °E during 1995 to 1997. The SROSS-C2 satellite was launched by Indian Space Research Organization (ISRO) on 4 May 1994 with the help ASLV-D4 rocket. It had a perigee of 430 km, an apogee of 930 km and orbit inclination of 46°. In July 1994, the orbit of the satellite was trimmed to 630×430 km. It was successfully operated continuously for seven years and it returned to earth on July 12, 2001. It covered geographic latitude belt of 31 °S to 34 °N and the longitude range from 40 ° to 100 °E. The electron and ion temperatures were measured separately by two retarded potential analyzer (RPA) payloads aboard by the Indian SROSS-C2 satellite. Detail of retarded potential analyzer (RPA) payload has been given by Garg and Das [1995]. The RPA sensors for electron and ion consist of four grids and a collector electrode, which are mechanically identical but provided with different grid voltages suitable for collection of ions and electrons. The data from the RPAs were transmitted to the ground station through a serial digital format at 8 kbps. The data were sampled at every 22 ms, which when translated into distance is ~176 m taking the satellite velocity to be 8 km/s. The RPA experiment was switched on only during the satellite visibility over the ground station at Bangalore (12,6 °N, 77,3 °E geographic). On an average, two overhead passes lasting ~10 min w tracked daily. Data points of SROSS satellite were obtained at different longitude, latitude, altitude and time.

3. Data selection and analysis. Study of ionospheric perturbation due to seismo-electromagnetic emissions associated with seismic activity using satellite data is a very difficult task because the satellite passes very rarely over the earthquake epicenter. Data used in the study span over 3 years, i.e. from January 1995 to December 1997. In the present work, satellite data for electron temperature (Te) over a wide range from latitude 0 to 30°N and longitude range from 40 to 100 °E have been used for study. Five earthquake events have been analyzed that occurred during 1995—1997. In these three years, the electron temperature data were analyzed in the following way-

First we compared the earthquake occurrence date, time, longitude, latitude with satellite passing date over earthquake zone, longitude, latitude of the satellite and approaching time of the satellite in earthquake zone. In this way, we neglected perturbation due to latitudinal, longitudinal and time effects. The average electron temperature data were used for three days, which included one each for pre, post and earthquake day sequencially. Here, we could get only three day's electron temperature data in three year because of the fact that the satellite hardly passes over the same longitude, latitude, altitude and time. In these three years, we have observed only five similar events occurring in above positions and time. Maximum 3° zone around the epicenter has been selected to minimize the latitudinal, longitudinal and altitude effects. In this way, we have neglected temperature variation due to longitude, latitude and time. The average distance from the epicenter to satellite recording was around 500 km. However, the data recorded in each earthquake event laid approximately at 10 km altitude variation. The temperature variation due to altitude is negligible in the present study. Also we have studied latitudinal variation of the electron temperature per days. Here all the temperature data recorded by the SROSS-C2 satellite are within the error limit of ±50 K in the temperature range of 500—5000 K [Garg, Das, 1995] The contribution of geomagnetic effect on electron temperature has been examined by utilizing Kp index data obtained from the World Data Center, Kyoto, Japan through internet (http://swdcwww.kugi.kyoto-u.ac.jp/kp/index.html). All electron temperature data studied were free from geomagnetic effect.

4. Result and discussion. Two earthquakes of magnitude 4,9 and 4,5 occurred on March 19, 1995 at different times with an epicenter location (8,08 °N, 93,82 °E) and (8,23 °N, 94,01 °E) respectively. Fig. 1, *a* shows the day to day variation in average electron temperature obtained from satellite data and Kp Index. In Fig. 1, *a*, variation in electron temperature is shown 8 hours 16 minute after the earthquake occurrence and the satellite passed around 2° differences in longitude and

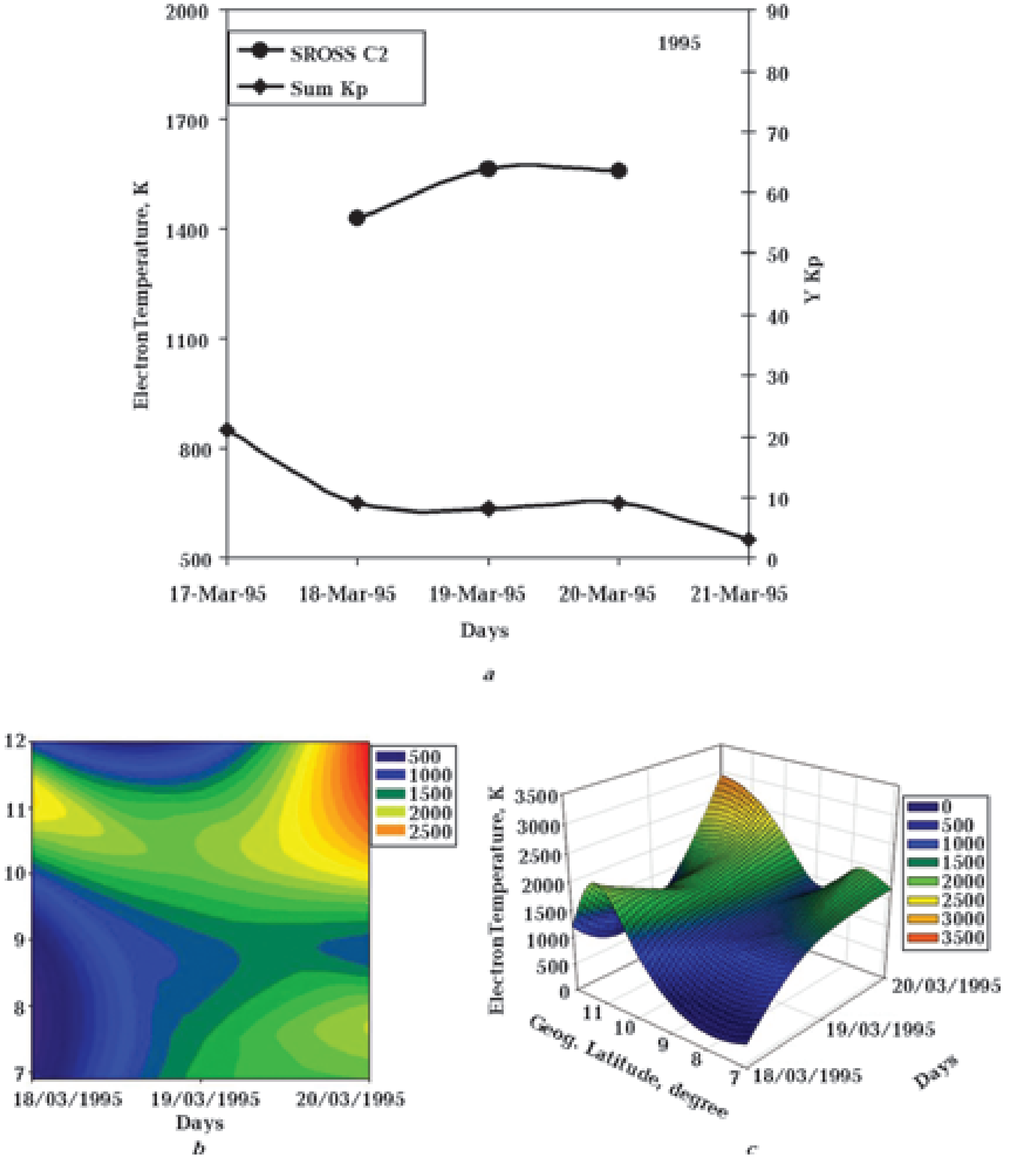

Fig. 1. Day to day variation in measured electron temperature and Kp index for 19 March 1995 earthquake (*a*), latitudinal variation of electron temperature with geog. latitude and days for 19 March 1995 earthquake (*b*), 3D plot of electron temperature as a function of geog. latitude and days for 19 March 1995 earthquake (*c*).

latitude with that of the earthquake. The corresponding data of this event are shown in Fig. 1, *a*. In Fig. 1, *a*, 2, *a*, 3, *a*, 4, *a* and 5, *a*, abscissa shows days and left side ordinate shows electron temperature and right side ordinate shows Kp index. In this event, the average electron temperature of satellite on earthquake day was 10 % greater than its pre earthquake day and 5 % times greater than its post earthquake day. Right side ordinate shows geomagnetic indices in terms of ΣKp index. ΣKp is the sum of three hourly values of Kp. The Kp is global geomagnetic index whose values lies between 0 to 9. ΣKp was less than 30 implies slight disturbance in the magnetic activity, ΣKP was greater than 40 implies strong disturbance in magnetic activity [Hattori et al., 2002]. During 17—21 March, 1995 ΣKp were less than 20 which indicate that 17—21 March was geomagnetically quiet. Table 1 shows detailed information of the earthquake events. Table 2 shows the time difference between passes of satellite and earthquake occurrence and enhancement in electron tempera-

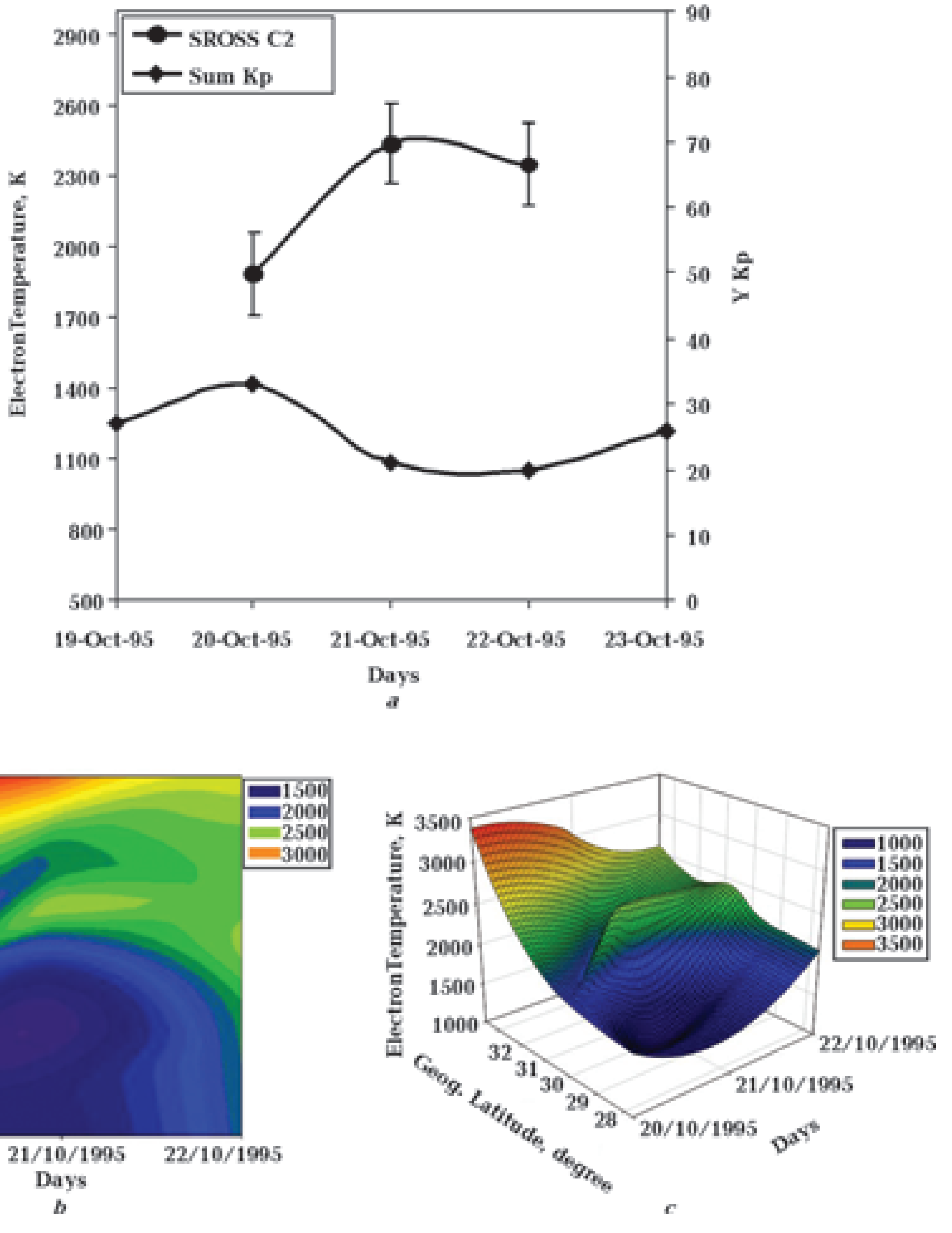

Fig. 2. Day to day variation in measured electron temperature and Kp index for 21 October, 1995 earthquake (*a*), latitudinal variation of electron temperature with geog. latitude and days for 21 October, 1995 earthquake (*b*), 3D plot of showing electron temperature as a function of geog. latitude and days for 21 October 1995 earthquake (*c*).

ture over pre and post earthquake day. Table 3 represents average electron temperature during earthquake event and normal day.

Fig. 1, *b* shows latitudinal variation of electron temperature for 19 March, 1995 earthquake event. It may be seen from the contour map that electron

Table 1. Location of satellite and earthquake with their information

Earthquake date	Magnitude	Origin time of EQ (UT)	Satellite reaching time (UT)	Earthquake location	Satellite location
19/03/1995	4,9	04:20:56	12:36:03	8,08 N, 93,82 E	7,40 N, 91,30 E
19/03/1995	4,5	04:34:13	12:36:03	8,23 N, 94,01 E	7,40 N, 91,30 E
21/10/1995	4,9	19:39:39	10:27:1	31,43 N, 78,96 E	31,00 N,79,00 E
14/12/1995	4,6	04:09:32	10:50:11	18,13 N, 76,54 E	16,5 N, 77,4 E
24/09/1996	4,6	03:28:01	12:03:30	23,34 N, 88,59 E	24,8 N, 88,8 E
25/09/1996	5,0	17:41:17	11:48:15	27,43 N, 88,55 E	25,5 N, 87,5 E
21/05/1997	6,0	22:51:28	08:39:49	23,08 N, 80,04 E	20,02 N, 83,6 E

Table 2. Time difference between passes of satellite and earthquake occurrence andenhancement in electron temperature pre and post days of earthquake

Earthquake date	Time difference between satellite passes over EQ region and earthquake occurrence		Anomalies in SROSS C2 data over EQ day, %	
	Before	After	Pre EQ day	Post EQ day
19/03/1995	—	8 h 16 min	10	5
19/03/1995	—	8 h 16 min	10	5
21/10/1995	9 h 12 min	—	29	4
14/12/1995	—	6 h 41 min	28	11
24/09/1996	—	9 h 15 min	29	5
25/09/1996	6 h 33 min	—	29	5
21/05/1997	14 h 12 min	—	23	16

Table 3. Average electron temperature during normal day and earthquake day

Earthquake date	Average Electron Temperature, K	
	On normal day	On earthquake day
19/03/1995	~1400	~1563
21/10/1995	~1800	~2450
14/12/1995	~1280	~1700
24/09/1996 25/09/1996	~1500	~1850
21/05/1997	~1200	~1550

temperature gradually increases on earthquake day around the earthquake epicenter (8,23 °N) as compare to pre and post days of earthquake. Electron temperature value on pre earthquake day was ~1400 K and on earthquake day, it was ~1563 K. Electron temperature was greater at lower and higher latitude (~2000 K) as compared to earthquake epicentral latitude and it was about ~1563 K. Fig. 1, *c* shows 3D map of electron temperature as a function of geog. latitude and days. Fig. 1, *b*, *c* show that on earthquake day electron temperature gradually increased around the latitude of the earthquake epicenter from a low value ~500 K to about ~1563 K. Fig. 1, *c* shows similar results that are shown in Fig. 1, *b*, electron temperature gradually increased at 8,30 °N on earthquake day.

Fig. 1, *c* also shows that the electron temperature on the 19^{th} March was greater than on the

18th and 20th March around earthquake epicenter. From Fig. 1, *b*, *c*, it is clear that the electron temperature was low on earthquake day around latitude of the earthquake epicenter with respect to other latitudes; also electron temperature was high on the earthquake day as compared to pre and post earthquake days.

In the year 1995, two more earthquake events were recorded; on October 21, 1995 and on December 14, 1995 with magnitudes 4,9 and 4,6; and epicenters location (31,43 °N, 78,96 °E) and (18,13 °N, 76,54 °E), respectively. The satellite passed within 1° and 2° differences in longitude and latitude of earthquake longitude and latitude, in case of the 21st October and the 14th December earthquakes, respectively. Also satellite passed 9 hours 12 minute before and 6 hours 41 minute after occurrence of the earthquake, respectively. Fig. 2, *a* shows day to day variation in average electron temperature of SROSS C2 satellite data and it was 29 % greater than its pre earthquake day and 4 % greater than its post earthquake day for the October 21 earthquake event. Fig. 2, *b*, *c* show the contour map and 3D map for variation in electron temperature as a function of Geog. Latitude and days, respectively. Observed enhancement in electron temperature around earthquake epicenter (31,43 °N) on the earthquake day is shown in Fig. 2, *b*, c. Electron temperature increases from low value of ~1800 K in 28 °N to 31 °N latitude ranges to about ~2450 K at earthquake epicenter. Also both figures show that electron temperature on the earthquake day (21st October) was high (~2460 K) around earthquake epicenter latitude as compared to pre and post days of the earthquake day.

Fig. 3, *a* illustrates day to day variation in the average electron temperature derived from SROSS C2 satellite data and it was 28 % and 11 % greater than its pre and post earthquake day for the 14th December earthquake, respectively. ΣKp was observed to be around 30 during 19—23 October and 20 during 11—17 December as seen from the Fig. 2, *a*, 3, *a*, respectively. These figures show that the geomagnetic activity was quiet during the observation period for the 21st October and the 14th December, earthquakes.

Similar results were obtained for 14 December, 1995 earthquake event and these are shown in Fig. 3, *b*, *c*. Fig. 3, *b*, *c* show enhancement in electron temperature around the epicenter of the earthquake. Both Figs. shows that, on earthquake day, electron temperature gradually increases around latitude of earthquake epicenter (18,13 °N) from low value ~1280 K to about ~1700 K. Small enhancement in electron temperature was observed on main shock day at 15,5 °N latitude.

In the year 1996, two earthquake events were recorded on the 24th and the 25th September of magnitudes 4,6 and 5,0 with epicenter locations (23,34 °N, 88,59 °E) and (27,43 °N, 88,55 °E), respectively. The satellite passed within 2° differences in longitude and latitude respectively of earthquake. Also satellite passed around 9 hours 15 minute after and around 6 hours 33 minute before the earthquake occurrence time, respectively. For the 24th September earthquake electron temperature enhanced 29 % greater than its pre earthquake day. For the 25th September earthquake this enhancement was 5 % more than its pre earthquake day and these are shown in Fig. 4, *a*. ΣKp was around 30 during 24—25 September and it shows that all the days were geomagnetically quiet during the observation period. Fig. 4, *b*, *c* show contour map and 3D map respectively of variations in electron temperature as a function of geographical latitude and days. Both figures show enhancement in electron temperature at the earthquake epicenter for both earthquakes. Electron temperature on the 24th and the 25th September increased gradually from low value ~1500 K to about ~1850 K during latitude range 23 °N to 27 °N. Pre day of the 24th earthquake event was low value of electron temperature was observed as compared to both earthquake day, as shown in both the figures.

Similar effect was noticed in case of earthquake recorded on 21 May, 1997. Magnitude of this earthquake was 6 with an epicenter location at (23,08 °N, 80,04 °E). The satellite passed within 14 hours 12 minutes before and within 3° of the earthquake. Electron temperature value enhanced 23 % more than its pre and 16 % greater than its post day of the earthquake is shown in Fig. 5, *a*. ΣKp was below 10 during 19—23 May 1996. This also confirmed that all the days were geomagnetically quiet.

Similarly, Fig. 5, *b*, *c* show enhancement in electron temperature around the earthquake epicenter for earthquake days. Both Figs. show maximum enhancement in electron temperature was observed on earthquake day during 21 °N to 22,5 °N with maximum value about ~1550 K Electron temperature value ~1200 K for pre and post earthquake day was low as compared to earthquake day values ~1550 K.

The above discussion and analysis of electron temperature data shows the consistency between enhancement in electron temperature and seismo-electromagnetic emissions. Moreover the enhancement in electron temperature is dependant upon the magnitude of the earthquake. These results are good enough to predict the earthquake. The enhancement in average electron temperature varies from 29 to 10 % and 16 to 4 % as compared to pre and post earthquake day, respectively. It shows enhancement in electron temperature was observed maximum on pre earthquake day. Also it shows that enhancement in electron temperature observed, was maximum around earthquake epicentral latitude than at other latitudes.

5. Lithosphere-ionosphere coupling mechanism. The Earth's ionosphere is subjected to various man-made and natural influences. The well-known hypothesis of the mechanism of coupling between the lithospheric activity and ionosphere related to the seismic activity is through the channels such as — chemical, acoustic and electromagnetic. The influences of the seismic activity on the ionosphere occur over the periods

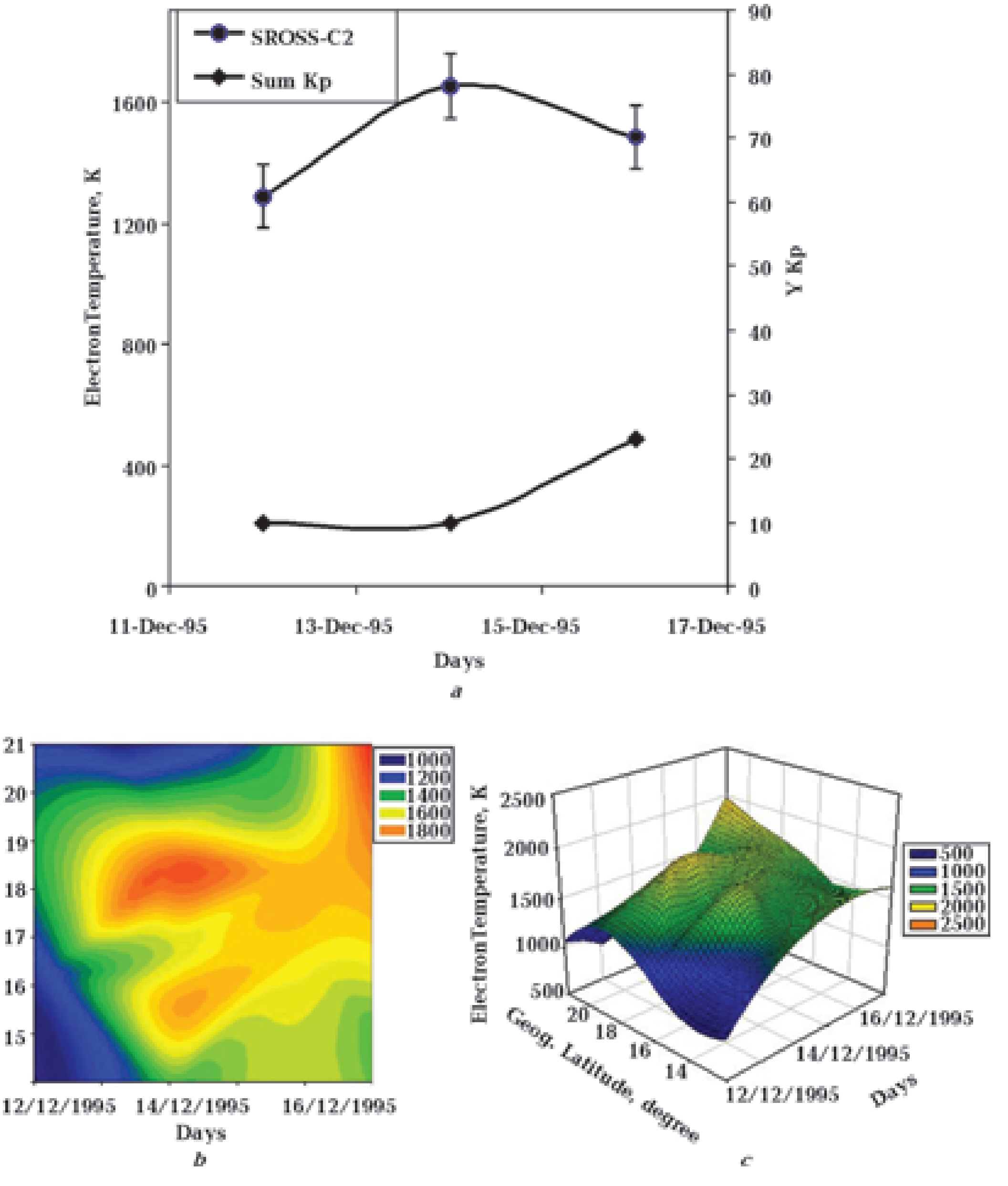

Fig. 3. Day to day variation in measured electron temperature and Kp index for 14 December 1995 earthquake (*a*), latitudinal variation of electron temperature as with geog. latitude and days for 14 December, 1995 earthquake (*b*), 3D plot of showing electron temperature as a function of geog. latitude and days for 14 December 1995 earthquake (*c*).

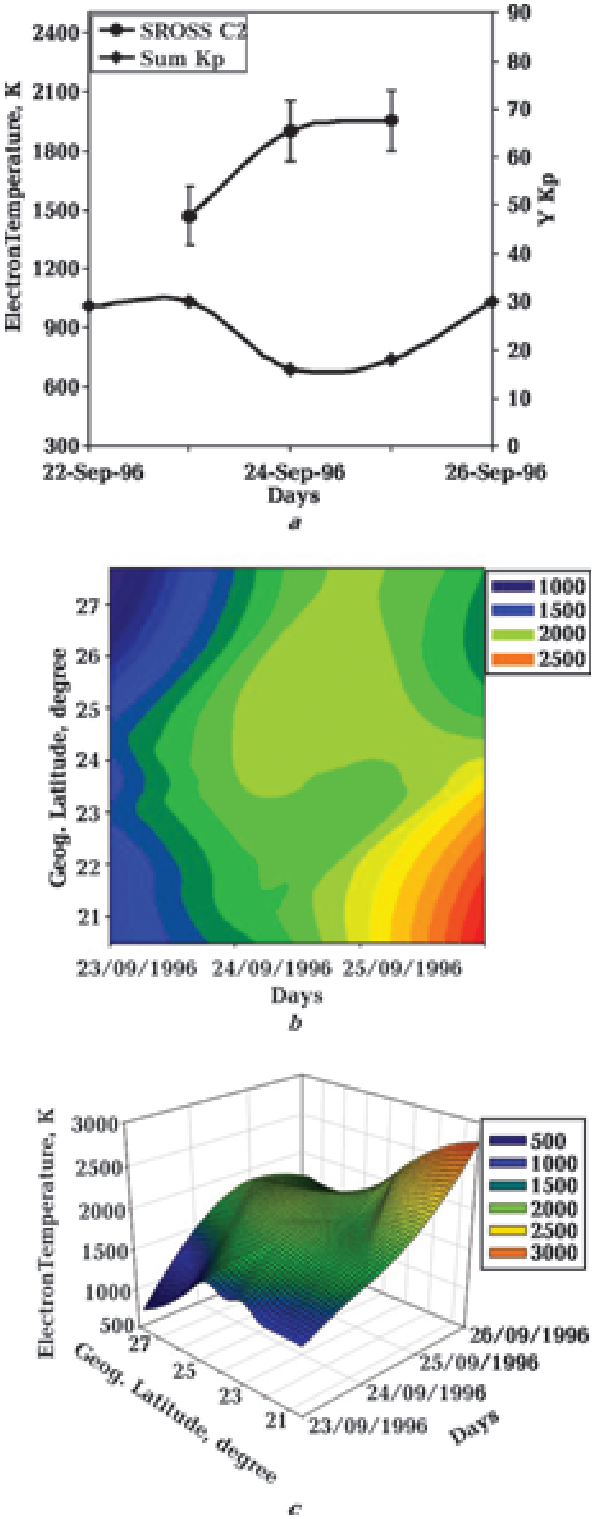

Fig. 4. Day to day variation in measured electron temperature and Kp index for 24 and 25 September, 1996 earthquake (*a*), latitudinal variation of electron temperature with geog. latitude and days for 24 and 25 September, 1996 earthquake (*b*), 3D plot of showing electron temperature as a function of geog. latitude and days for 24 and 25 September, 1996 earthquake (*c*).

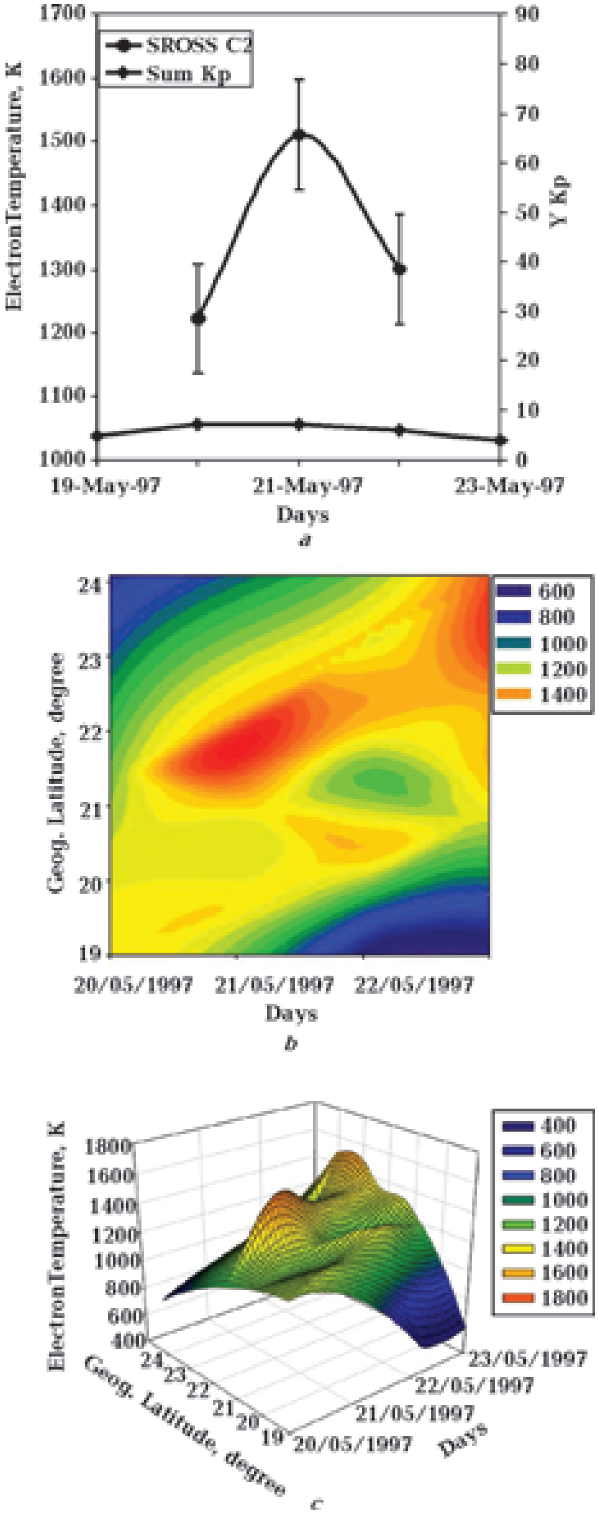

Fig. 5. Day to day variation in measured electron temperature and Kp index for 21 May, 1997 earthquake (*a*), latitudinal variation of electron temperature with geog. latitude and days for 21 May, 1997 earthquake (*b*), 3D of showing electron temperature as a function of geog. latitude and days for 21 May, 1997 earthquake (*c*).

from several hours to several days either during the preparatory phase or during the post-seismic relaxation phase.

In case of chemical channel, the geochemical quantities such as surface temperature, radon emanation induce the perturbation in the conductivity of the atmosphere, leading to the ionospheric modification through the atmospheric electric field [Pulinets and Boyarchuk, 2004; Sorokin et al., 2006 *a*, *b*, Hayakawa, 2007].

The acoustic channel is based on the atmospheric oscillations in the lithosphere-atmosphere-ionosphere coupling and the perturbations in the Earth's surface such as temperature, pressure in a seismo-active region excite the atmospheric oscillations traveling up to the ionosphere [Miyaki et al., 2002; Shvets et al., 2004; Hayakawa, 2007].

The electromagnetic channel is the one through which radio emissions (DC to VHF) generated in the lithosphere propagate up to the ionosphere, and modify the ionosphere thereby leading to heating or ionization [Molchanov et al., 1995; Hayakawa, 2007]. The intensification of precipitating high-energy electrons with simultaneous excitation of electromagnetic waves above the earthquake epicenter was previously registered in the top side ionosphere as well.

Electromagnetic waves were generated during earthquake preparation phase due to different mechanisms. These SEM waves propagate towards ionosphere and reach the ionosphere. When the SEM waves collide with neutrals, positive ions and electrons having energies of few tens of electron volts are produced. The free electrons can travel long distances along magnetic field lines within the ionosphere. Again more and more ion-electron pairs are produced when the electrons collide with neutrals. This process continues until the electrons thermalise and attain energy of a few electron volts. In other word, it seems that changes in the magnetic flux tube topology can lead to increased precipitation of energetic electrons. There occur collective oscillations in electrons and then collision among electron, ion and neutrals. And during the collision whole volume oscillates. Then the change in density and temperature of ionospheric parameters such as ion and electron causes the change in collision frequency and modified ionospheric conductivity [Grimalsky et al., 2003]. By this process ionosphere temperature increases.

6. Conclusions. SROSS C2 satellite data have been analyzed for finding out the relation between seismic activity and the ionosphere perturbation under quiet geomagnetic activity. Enhancement in average electron temperature on earthquake day has been observed to be 29 % to 10 % greater than its pre and 16 % to 4 % more than its post earthquake day. It shows enhancement in electron temperature was observed maximum on pre earthquake day. Also enhancement in average electron temperature has been observed to be maximum 14 hours before and 9 hours after of the main shock. Also enhancement in electron temperature was observed high within 1 to 2° around earthquake epicentral latitude than the other latitude. From this study; one can conclude that ionospheric perturbations were observed on earthquake days as compared to pre and post days. And F2 region of ionosphere gets perturbed because of seismic activity and it is relate to the Seismo-electromagnetic emissions associated with earthquake during earthquake time, before and after the earthquake time.

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