Ion density and temperature variations at altitude of 500 km during moderate seismic activity

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ABSTRACT

Ionospheric ions (O^+ and H^+) and temperature (T_i) as precursory parameters to seismic activity have been analysed from year 1995 till 1998, using SROSS-C2 (average altitude range of ~ 500 km) satellite measurements for moderate magnitude earthquakes. The details of seismic events during this period are downloaded from United State Geological Survey (USGS) and National Earthquake Information Centre (NEIC) website. 13 seismic events of moderate magnitude ($M = 4 - 5.5$) from 1995-1998, using SROSS-C2 satellite measurements have been analyzed. During seismic affected period, considerable decrease in the density of heavier ion - O^+ and increase in the ion temperature (T_i) is observed during all the selected events. Lighter ion - H^+ doesn't show any significant change. Electric field and electromagnetic emissions generated due to seismogenic activity could be the plausible initializing agents responsible for change in ion concentration and temperature values during these events.

Keywords: ion density, ion temperature, seismic activity, moderate magnitude earthquakes, satellite measurements

1. Introduction

The seismo – ionospheric coupling is probably one of the most complex and interesting areas of research involving interactions starting from earth's interior to magnetosphere. Different physical precursory indicators – earth degassing (King, 1986), metallic aerosols emanation (Alekseev, 1995), ground water uplift and geoelectric potential change (Rikitake, 1976), increase in P- wave velocity (Bolt, 1993), anomalous vertical electric field (Kondo, 1968), ionospheric precursors (Gokhberg et al., 1983; Larkina et al., 1983) etc can be found reported

in literature. Among these precursory indicators, probably the ionospheric precursors are the youngest.

The first publications discussing ionospheric effects due to earthquakes were reported just after the Alaska “Good Friday” earthquake in 1964 (Bolt, 1964; Donn and Posmetier, 1964; Row, 1966). The wave movements of ground, before and after the earthquake, were associated with acoustic gravity waves. The acoustic gravity wave – ionosphere coupling was the first proposed theory of seismo – ionospheric coupling (Yuen et al., 1969; Birkfeld, 1974). Variations in foE parameter before the Tashkent earthquake in 1966 were studied by Antselevich (1971). Datchenko et al., (1972) analysed electron variations before Tashkent earthquake. These papers mainly used observations by ground based ionosondes.

Installation of local probes onboard satellites; gave an opportunity to study the variations of near – earth plasma parameters in connection with preparing earthquakes. Initial reports on satellite measurements of ionospheric precursors of earthquakes can be found in early eighties (Migulin et al., 1982; Larkina et al., 1983; Gokhberg et al., 1983). Precursors registered by satellites can be divided into three categories: electromagnetic field and noises, plasma parameter variations and particle flux.

Present work concentrates on ionospheric plasma variations during seismic affected time as measured by satellite. One of the earliest reports existing in literature, which observed variations in ionospheric plasma densities as precursory indicators of seismic activity, goes back in 1983. Gokhberg et al., (1983) measured onboard AE-C and ISIS – 2 satellite data to report variations in local plasma density and temperature before earthquakes. Pulnits et al., (1991) observed large scale plasma irregularities over earthquake preparation zone using topside sounders. Afonin et al., (1999) and Hayakawa (2000) statistically analysed larger database of plasma densities using Intercosmos – 24. This report by Hayakawa serves as a reliable report, co – relating global distribution of seismic activity and ion density variations as it includes larger database (3000 orbits of intercosmos-24 satellite). Afonin et al., (2000) reported precursory type significant changes in ion density distribution pattern over earthquake epicentres at night over ~ 500 km satellite altitude. They found anomalous behaviour in ion density pattern within ± 7 days of strong earthquake. Pulnits and Boyarchuk (2004) studied variations in ion concentrations before earthquakes using AE-C satellite data over the middle latitudes. They observed decrease in mean ion mass. Electron

and ion temperature variations have also been studied by Sharma et al., (2013). They registered ~ 1.2 times increase in T_e and T_i as an effect of earthquakes.

To make ionospheric precursors as real time prediction technique, more contributions by researchers in this direction is required. Present work aims to analyse the variation of ion density (O^+ and H^+) and ion temperature (T_i) as a precursory parameter to seismic activity from year January 1995 till December 1998, using Retarding Potential Analyser (RPA) payload aboard SROSS - C2 (Stretched Rohini Series Satellite) satellite at an average altitude range of ~ 500 km over the Indian region. Previous studies concentrate only on case studies of large magnitude earthquakes. But present report discusses variation of ionospheric parameters (ion density and temperature) during 13 moderate magnitude earthquake events.

2. Data collection, selection and analysis

2.1 Data Collection

The ion density (O^+ and H^+) and temperature (T_i) data during the period from January 1995 to December 1998, used for the present study, have been obtained using a RPA payload aboard the SROSS-C2 satellite, which was launched by Indian Space Research Organization (ISRO) on May 4, 1994 at 420X620 km altitude. The RPA payload consisted of two sensors, (i.e. electron and ion sensors) and associated electronics (Garg and Das, 1995). In addition, a spherical Langmuir probe is included which acts as a probe to estimate the spacecraft potential as the satellite spins. The electron and ion sensors have a planar geometry and consist of multi – grid Faraday cups with a collector electrode. These mechanically identical sensors are mounted on the top deck; they move in the cartwheel mode perpendicular to the spin axis of the spacecraft. Both sensors have different grid voltages as suitable for the collection of electrons and ions in the earth's ionosphere. The temperature data (T_e and T_i) is obtained by analysing one complete electron and ion I–V plot through linear and nonlinear curve fitting techniques, respectively. The ion density (O^+ , O_2^+ , H^+ , He^+) is obtained by the curve fitting to a composite I–V curve using a nonlinear curve method of iteration to the observed characteristics. Although RPA sensor measurements were made throughout the spin cycle of the satellite, data taken only within $\pm 30^\circ$ and $\pm 60^\circ$ (angle between sensor normal and velocity vector) for ion and electron sensors are considered for the analysis (after including the empirical corrections for spin modulation for density calculations) as mentioned by Garg et al., (2003) . The measurements outside the mentioned angle between sensor normal and velocity vector could not be used for ion density calculations as the correction for spin

modulation outside the said limit could not be applied (Garg and Das, 1995). Hence the ion density data is not continuous and is scattered with some data points taken within the specified limits and a loss for the rest of the spin cycle i.e. for about 80 km in space there are no data points and again some data points with 170 m interval and so on.

The information about earthquakes was downloaded from USGS website during the period from January 1995 to December 1998. The data for magnetic activity (K_p), during seismic events, were downloaded from website of National Space Science Data Center (NSSDC) <http://omniweb.gsfc.nasa.gov/>. The standard K_p values look like 0, 0+, 1-, 1, 1+, 2-, ... but are stored as $K_p = 0, 3, 7, 10, 13, \dots$ in the OMNI data set which are mapped as 0+ to 3, 1- to 7, 1 to 10, 1+ to 13, 2- to 17, etc.

2.2 Data Selection and analysis

Data selection and analysis is the most crucial part of the present work. The satellite passes rarely correspond to earthquake preparation zone. Total of 13 moderate magnitude events from year 1995 till 1998 using SROSS-C2 measurements were analyzed for present study. The ionospheric ion parameters (ion concentration – O^+ and H^+ and temperature - T_i) during normal time were compared with seismic affected days. 5 days prior and after the event day i.e. a total of 11 days were considered as seismic affected period. ± 20 days excluding seismic affected period were considered as normal days. Days which experienced higher magnetic activity ($K_p > 3$) in the above selection criteria have been excluded from the analysis. Thus all the selected days during seismic events and normal days are free from magnetic disturbances. Data selection ensures that the perturbation due to diurnal, latitudinal, longitudinal and altitude effects are negligible. The recorded ionospheric ion parameters (O^+ and T_i) values during particular event have been compared with normal days during the same time interval to minimise diurnal effects. Considering the fact that effect of seismic activity prolongs for quite a longer period and keeping in mind the availability of satellite passes, time window of minimum possible hours from the event time have been considered for analysis. A 5° window of latitude and longitude around the geographic location of the epicenter of the seismic events has been employed to minimize the latitudinal and longitudinal effects. To reduce the altitudinal effects, it has been also taken into account that the altitudinal variations are well within the limit of 50 km range during selection of satellite passes for a particular seismic event.

3. Results and discussions

Natural disasters, in particular earthquakes cause lots of damage to life and property and have emerged as a challenge to mankind. Common man expects from science and technology to progress in a way that could increase the level of protection. Earthquake preparation is a real physical process but our failures to predict earthquakes; only show our inability to understand its real mechanism. Earthquake prepares itself from days before an earthquake and ionospheric precursors get registered during this period. For better understanding and to make earthquake prediction as a real time prediction and warning system, more statistical; analytical; experimental and theoretical work on short and long term spatial and temporal scale needs to be done. Present work is an attempt to analyze short term ionospheric ion parameter's anomalies during moderate magnitude earthquakes at an average altitude of ~ 500 km.

The 13 moderate magnitude earthquakes ($M = 4 - 5.5$ on Richter scale) have been considered from year 1995-1998 for the present study. All the selected events have hypocentre ≤ 30 km from the epicentre. The shallow depth of the origin of an earthquake intensifies the devastation. The nearer is the hypocentre to the epicentre, higher is the devastation on the ground surface. Total of 13 events, which satisfied the selection criteria, from hundreds of earthquake events over the low latitudinal/equatorial regions have been used for the study. The majority of seismic locations lie in northern slope of the trough region. Table 1 gives detailed information of each event. Figure 1 shows the spatial location of the chosen 13 moderate magnitude earthquakes. These seismic event locations are spread over the sea and land. The solid circle shows the event location and open circle shows the earthquake preparation zone around it. Earthquake preparation zone is the area where local deformations associated with future earthquake is observed. The earthquake preparation zone is calculated as per the equation $\rho = 10^{0.43M}$, where ρ is radius of earthquake preparation zone and M = magnitude of earthquakes. The equation is applicable for spherical surfaces and has been evaluated by Doborsky et al., (1979). From the above equation area under the earthquake preparation zone have been evaluated. Table 1 lists the area under the earthquake preparation zone for the chosen 13 events. Figure 2 shows average values of Kp during seismic (black bars) and normal times (red bars). All values are less than 30, thus indicating that the selected normal and seismic affected days are not affected by high magnetic activity.

3.1 Variation of O^+ ion density during earthquakes

Figure 3, represents variation of O^+ ions during seismic (black circle) and normal time (red star) during all the 13 earthquakes. All the events show decrease in O^+ ion density during seismic affected time as compared to normal days. Magnitude of O^+ ion densities are in $/m^3$. Epicentres of earthquakes that occurred on 17.01.1995 ($M = 4.9$), 20.07.1995 ($M = 5$), 05.09.1997 ($M = 4$) and 05.01.1998 ($M = 5.5$) shared nearby geographical locations. Average O^+ ion density on these earthquakes on normal days were $1.68E+11$, $5.65E+10$, $5.37E+10$, $6.25E+10$ and seismic affected times were $8.53E+10$, $3.79E+10$, $3.56E+10$, $4.02E+10$ respectively. Normal day's densities were ~ 1.5 to 2 times higher compared to seismic affected time. Two earthquakes on 03.08.1995 ($M = 4.8$) and 07.08.1995 ($M = 4.5$) had coinciding epicentres. Average O^+ ion density during normal days were $7.49E+10$, $1.09E+11$ and seismic affected days were $4.98E+10$, $5.55E+10$ respectively, showing ~ 1.5 to 2 times increase over seismic time. Five earthquakes that occurred on 25.02.1995 ($M = 4.8$), 10.06.1995 ($M = 4.9$), 08.07.1995 ($M = 5.5$), 09.12.1995 ($M = 5.1$) and 15.12.1996 ($M = 4.7$) had epicentres in the sea area. These earthquakes recorded average O^+ ion density on normal days as $5.71E+11$, $1.48E+10$, $1.09E+11$, $2.61E+11$ and $1.44E+10$, while during seismic affected days as $4.60E+11$, $6.50E+09$, $5.55E+10$, $1.31E+11$ and $6.82E+09$ respectively. Normal day's densities during these events were 1.2 to 2.3 times higher than seismic affected days. Two more earthquake events on 26.04.1996 ($M = 4.6$) and 09.03.1998 ($M = 4.7$) also showed similar trend as above earthquake events. The average densities during normal days were $1.39E+11$ and $1.04E+12$, while during seismic affected days were $5.87E+10$ and $5.18E+11$ respectively. Thus, showing increase in densities during normal days by 2 to 2.4 times over seismic affected days respectively. All the 13 moderate magnitude earthquake events which had epicentres on land and sea showed similar kind of variations.

H^+ ion densities during all the earthquake events were also analyzed and the changes observed were small. H^+ ions are light ions and can get transferred even under the influence of weak winds. Moreover, at the altitudinal range under consideration (~ 500 km) O^+ is only the dominant ion, H^+ is not sufficient in number density to give any kind of conclusive results. Bhorogain and Bhuyan (2010) also reported insufficient density of H^+ ions.

3.2 Variation of ion temperature (T_i) during earthquakes

During these moderate magnitude earthquakes, corresponding ion temperatures (T_i) were analysed. Figure 4, represents variation of ion temperature (T_i) during seismic (black circle)

and normal time (red star) during all the 13 earthquakes. All the earthquakes show increase in T_i during seismic affected time as compared to normal days. Magnitude of ion temperatures (T_i) are in K. Epicentres of earthquakes that occurred on 17.01.1995 ($M = 4.9$), 20.07.1995 ($M = 5$), 09.05.1997 ($M = 4$) and 05.01.1998 ($M = 5.5$) shared nearby geographical locations. Average ion temperatures (T_i) on these earthquake affected period were 1280, 1850, 1540, 1310 and on normal days were 1050, 1520, 1160, 1100 respectively. T_i - ion temperature, during seismic affected days were almost ~ 1.2 times higher compared to normal days. Two earthquakes on 03.08.1995 ($M = 4.8$) and 07.08.1995 ($M = 4.5$) had coinciding epicentres. Average T_i during seismic affected days were 1450, 1410 and normal days were 1210, 1130 respectively, showing ~ 1.2 times increase over normal time. Five earthquake events that occurred on 25.02.1995 ($M = 4.8$), 06.10.1995 ($M = 4.9$), 08.07.1995 ($M = 5.5$), 09.12.1995 ($M = 5.1$) and 15.12.1996 ($M = 4.7$) had epicentres in sea. These earthquakes recorded average ion temperatures (T_i) as 1160, 1120, 1410, 1180 and 2250 during seismic period while on normal days as 970, 820, 1130, 990 and 1900 respectively, showing an increase of ~ 1.2 to 1.4 times over normal days. Two more earthquakes on 26.04.1996 ($M = 4.6$) and 09.03.1998 ($M = 4.7$) also showed similar trend as above earthquake events. The average ion temperatures (T_i) during seismic affected days were 1300 and 1000, while during normal days were 1010 and 830 respectively. Thus, showing increase in T_i during normal days by ~ 1.2 times over normal days. All the selected moderate magnitude earthquakes show ~ 1.2 times enhancement in T_i during seismic time over normal time. All the temperature data recorded by RPA payload aboard on SROSS-C2 satellite are within the error limits of ± 50 K (Garg et. al, 1995).

Enhancement in ionospheric temperatures due to seismic activity has been reported (Sharma et al., 2013; Ho et al., 2013; Sarkar et al., 2012). However, Oyama et al., (2008) used Hinotori satellite data and observed decrease in T_e during pre and post seismic events. The ionospheric plasma density (N_e and N_i) as precursory indicators of earthquakes have been main focus of majority of studies. The statistical analyses of ionospheric temperatures (T_e and T_i) are comparatively less rich (Shen et al., 2015).

3.3 Average variation of O^+ ion density and ion temperature T_i

Figure 5, shows variation of Average O^+ ion density (upper panel) and average ion temperature T_i (lower panel) during seismic affected and normal days during moderate magnitude earthquakes. Table 2 lists variation of O^+ ion density and ion temperature – T_i

during seismic and normal times. Variation of average O^+ ion density during seismic affected time shows a good co-relation ($R^2 = 0.92$) with normal time. It shows an increase of ~ 1.7 times during normal days compared to seismic affected days. Similarly, variation of average ion temperature T_i during seismic affected time shows a good co-relation ($R^2 = 0.97$) with normal time. The increase, in ion temperature is ~ 1.14 times higher during seismic times over normal time. During all the moderate magnitude earthquake events, decrease in O^+ ion density and increase in T_i was observed. The relationship is highly correlated, direct and linear in nature. The graphical analysis is almost in agreement with calculated values. As the analysis of these events are devoid of all the other perturbing effects – latitudinal, longitudinal, altitudinal, diurnal, and magnetic disturbance. The anomalies in ionospheric parameters can be solely attributed to seismic effect.

Anomalous observations in ionospheric parameters due to seismic activity have brought lots of questions which are still part of discussions and research. The road to understanding of the nature of the seismic originated ionospheric perturbations is a far ahead task because the morphology of seismic originated ionospheric perturbations is not well established. Lots of statistical work still needs to be done in this direction. The moderate magnitude earthquakes analysed in the present work suggests decrease in O^+ ion density at an average ~ 500 km during seismic affected time. Many reports suggest results the other way i.e plasma density increases as an effect of seismic activity (for example Oyama et al., 2016; Ho et al., 2013; Sarkar et al., 2012). However, these studies were conducted using DEMETER and DMSP satellite having an average altitude of 700 and 800 km respectively. Anomalous electric field due to seismic activity is considered as most probable cause for variations in ionospheric parameters (Oyama et al., 2011). The direction of electric field determines increase or decrease of plasma density. And, the process of generation of electric field is still not well established (Oyama et al., 2016). If the electric field enhances in the eastward direction in day time and westward direction daytime, we can expect decrease in plasma density between the normal time's crests. It should be noted that lot of energy is required to diminish the imposed electric field developed during the normal days, and then reverse it's affects. Oyama et al., 2011 reported the decrease in density of the atomic oxygen ion using DE- 2 satellite at an average altitude ~ 400 km. As per Oyama et al., 2011 the direction of electric field was simply enhanced and same over the entire disturbed area. That is the usual eastward electric field during the day and the westward electric field at night time in the ionosphere simply enhances. Hasbi et al., (2011) investigated variations in TEC before some large earthquakes

over Sumatra. They observed significant increase and decrease in TEC before 26 Dec 2004 earthquake. The earthquake that took place on 28 March 2005 observed sudden decrease in TEC. They also used DEMETER satellite observations and have reported plasma depletions around the magnetic equator. Aggarwal et al., (2016) observed anomalous depletions in GPS-TEC during 3-4 days before the seismic event. Present work analysis indicates reduction in O^+ ion density during seismic affected times compared to normal times.

Ion temperature (T_i) increases as an effect of seismic activity. The elevation in ion temperature can be attributed to Joule heating (Sharma et al., 2013). The seismogenic electric field within the ionosphere is modulated by daily variations of plasmaspheric electric fields that cause the daily variations of the sign of seismo-ionospheric variations. The detailed theoretical calculations and further experimental observations strengthen the hypothesis of temperature enhancement due to earthquake over the epicenter zone of ionospheric region which may be considered as a short term precursor in future.

The coupling mechanisms between lithosphere – ionosphere related to seismic activity can be through acoustic, chemical, electric field or electromagnetic channel. In the region of the present study ~ 500 km, electric field and electromagnetic emissions play a vital role in perturbing ionospheric parameters. The vertical fields penetrate into the ionosphere where, due to anisotropic conductivity of ionosphere they transform into horizontal fields (Kim et al., 1994). Moreover the vertical electric field developed is time varying (Vershinin et al., 1999; Hao et al., 2000), so magnetic field would also get into play resulting in electromagnetic emissions. Thus, the forces developed due to disturbed dynamo movement; electromagnetic emissions in ELF, VLF range could restrict the motion of ions but neutral particles are free to move generating new set of chemical reactions and change concentration of ions compared to normal time. VLF/ELF emissions and anomalous electric field can bring plasma in motion. And hence, an increase in ionospheric temperatures can be expected. VLF/ELF emissions reach the Earth's surface and enter into the near-Earth space, where they cause perturbations (TEC changes, ionospheric motions, joule heating, etc.) in the atmosphere and ionosphere (Molchanov et al., 1995; Ohta et al., 2001).

Even though magnitude of anomalous electric field is still a question (Devi et al., 2004), the other kind of phenomena generated due to even low magnitude of earthquakes can seriously perturb ion density and concentration values.

Conclusions

Ionospheric parameters (O^+ and H^+ ion density and ion temperature T_i) variability due to earthquakes $M \leq 5.5$ have been analysed using data retrieved from RPA payload of SROSS-C2 satellite from year January 1995 till December 1998 over the Indian region. In all the selected earthquake events it has been observed that heavier ion (O^+ ion) density decreases and ion temperature T_i increases as an effect of seismogenic activity. The decrease in O^+ ion density is ~ 1.8 times and increase in ion temperature T_i is ~ 1.2 times respectively during seismic event affected times. It has been also found that light ion - H^+ show negligible changes in concentration. The change in ion concentration and ion temperature can be attributed to combined interaction of anomalous electric field and electromagnetic emissions. All the earthquake events selected are of moderate magnitude intensity and could interact differently with anomalous electric field, giving rise to different dynamics compared to interactions observed during high magnitude earthquake events.

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Table 1 - Details of Earthquake events

Sl. No	Date	Latitude (°geog N)	Longitude (°geog E)	Time (UTC)	Magnitude	Depth (km)	Area under earthquake preparation zone (km²)
1	17.01.1995	34.65	70.76	07:15:50	4.9	27	51442.8
2	25.02.1995	3.02	64.94	09:21:36	4.8	10	42201.9
3	10.06.1995	1.20	67.52	13:40:48	4.9	10	51442.8
4	08.07.1995	4.32	62.43	06:44:43	5.5	10	168781.4
5	20.07.1995	29.84	69.52	07:26:24	5	19	62708.2
6	03.08.1995	29.96	81.53	03:05:44	4.8	27	23298.3
7	07.08.1995	29.86	81.53	18:28:48	4.5	30	42201.9
8	09.12.1995	15.44	88.43	10:04:44	5.1	10	76440.7
9	26.04.1996	17.16	73.55	12:19:33	4.6	23	28400.4
10	15.12.1996	2.18	65.44	01:47:31	4.7	10	34619.8
11	05.09.1997	33.83	72.81	15:41:51	4	17	8656.1
12	05.01.1998	29.01	64.35	06:57:36	5.5	18	168781.4
13	09.03.1998	22.48	78.01	07:41:18	4.7	10	34619.8

Table 2 - Variation of average O⁺ ion density and ion temperature during earthquake events

Sl. No	Date	Average O ⁺ ion density (m ⁻³)		Ratio (O ⁺ Normal time/ Seismic time)	Average Ti ion temperature (K)		Ratio (Ti Seismic time/ Normal time)
		Seismic time	Normal time		Seismic time	Normal time	
1	17.01.1995	8.53E+10	1.68E+11	2	1280	1050	1.2
2	25.02.1995	4.60E+11	5.71E+11	1.2	1160	970	1.2
3	10.06.1995	6.50E+09	1.48E+10	2.3	1120	820	1.4
4	08.07.1995	5.55E+10	1.09E+11	2	1410	1130	1.2
5	20.07.1995	3.79E+10	5.65E+10	1.5	1850	1520	1.2
6	03.08.1995	4.98E+10	7.49E+10	1.5	1450	1210	1.2
7	07.08.1995	5.55E+10	1.09E+11	2	1410	1130	1.2
8	09.12.1995	1.31E+11	2.61E+11	2	1180	990	1.2
9	26.04.1996	5.87E+10	1.39E+11	2.4	1300	1010	1.3
10	15.12.1996	6.82E+09	1.44E+10	2.1	2250	1900	1.2
11	05.09.1997	3.56E+10	5.37E+10	1.5	1540	1160	1.3
12	05.01.1998	4.02E+10	6.25E+10	1.6	1310	1100	1.2
13	09.03.1998	5.18E+11	1.04E+12	2	1000	830	1.2

FIGURE CAPTIONS

Figure 1: Representation of spatial locations of the seismic events

Figure 2: Representation of Kp during seismic and normal times

Figure 3: Representation of variation of O^+ ion density (black – seismic time, red – normal time) during all the seismic events

Figure 4: Representation of variation of Ti ion temperature (black – seismic time, red – normal time) during all the seismic events

Figure 5: Representation of relationship of average O^+ ion density (upper panel) and ion temperature (lower panel) during seismic and normal times

Figure-1

Figure-2

Figure 2

Figure-3

Figure 3

Figure-4

Figure 4

Figure-5

Figure 5