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Prediction of the date, magnitude and affected area of impending strong earthquakes using integration of multi precursors earthquake parameters

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Abstract. Usually a precursor alone might not be useful as an accurate, precise, and stand-alone criteria for the earthquake parameters prediction. Therefore it is more appropriate to exploit parameters extracted from a variety of individual precursors so that their simultaneous integration would reduce the parameters's uncertainty.

In our previous studies, five strong earthquakes which happened in the Samoa Islands, Sichuan (China), L'Aquila (Italy), Borujerd (Iran) and Zarand (Iran) have been analyzed to locate unusual variations in the time series of the different earthquake precursors. In this study, we have attempted to estimate earthquake parameters using the detected anomalies in the mentioned case studies.

Using remote sensing observations, this study examines variations of electron and ion density, electron temperature, total electron content (TEC), electric and magnetic fields and land surface temperature (LST) several days before the studied earthquakes. Regarding the ionospheric precursors, the geomagnetic indices D_{st} and K_{p} were used to distinguish pre-earthquake disturbed states from the other anomalies related to the geomagnetic activities.

The inter-quartile range of data was utilized to construct their upper and lower bound to detect disturbed states outsides the bounds which might be associated with impending earthquakes.

When the disturbed state associated with an impending earthquake is detected, based on the type of precursor, the number of days relative to the earthquake day is estimated. Then regarding the deviation value of the precursor from the undisturbed state the magnitude of the impending earthquake is estimated. The radius of the affected area is calculated using the estimated magnitude and Dobrovolsky formula.

In order to assess final earthquake parameters (i.e. date, magnitude and radius of the affected area) for each case study, the earthquake parameters obtained from different earthquake precursors were integrated. In other words, for each case study using the median and inter-quartile range of earthquake parameters, the bounds of the final earthquake parameters were defined. For each studied case, a close agreement was found between the estimated and registered earthquake parameters.

1 Introduction

Although earthquake prediction is still a challenging task, recent studies have shown that numerous geophysical and geochemical parameters are closely associated with earthquakes (Pulinets and Boyarchuk, 2004; Molchanov and Hayakawa, 2008; Akhoondzadeh, 2011). Monitoring these parameters is one of the recent research activities with the aim of reducing the effects of natural hazards. Earthquake is a dynamic phenomenon and usually happens because of crust displacement. When the earthquake happens, an energy transfer due to a breakdown between source and environment is made. These changes prior to the earthquake or along with it may have different physical and chemical affects on the lithosphere, atmosphere and ionosphere, therefore making it detectable. These variations of lithosphere, atmosphere and ionosphere parameters before the main earthquakes are considered as earthquake precursors which are used as hints for impending earthquakes. Widespread research on earthquake prediction over the past decades has resulted in the recognition of many earthquake precursors in the lithosphere, atmosphere and ionosphere.

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Recently, various ground-based and satellite observations have shown the possibility of lithospheric, atmospheric and ionospheric disturbances generated by the earthquake preparation processes. There is a lack of extensive ground experiments to monitor geophysical and geochemical parameters in most areas. But satellite data, due to the vast coverage of the seismic zones of the Earth along with other sources of information, are regarded as a suitable means for earthquake study. They allow meaningful statistical studies with a much larger number of recorded events to be performed. Many papers and special reports have been published on satellite observation of perturbations associated with seismic activities (Hayakawa and Molchanov, 2002; Pulinets and Ouzounov, 2010, Akhoondzadeh et al., 2010a, b).

There exist hypotheses to explain the seismic electromagnetic mechanism based on geophysical and geochemical processes:

- Direct wave production in a wide band spectrum by compression of rocks close to earthquake epicenter could be likely related to piezo-electric and tribo-electric effects (Parrot, 1995);
- Rising fluids under the ground would lead to the emanation of warm gases (Hayakawa and Molchanov, 2002);
- Activation of positive holes that can reach the ground surface (Freund, 2002);
- Emissions of radioactive gas or metallic ions such as radon, which increase the Earth's surface potential (Pulinets et al., 2003);
- Penetration of atmospheric gravity waves (AGW), which are induced by the gas-water release from the earthquake preparatory zone into the ionosphere (Molchanov and Hayakawa, 2008).

A pre-seismic electric field and its polarity cause the electrons in the F-layer to penetrate to lower layers and therefore to create anomaly in the ionospheric parameters. The thin layer of particles created before earthquakes due to ions radiation from the earth has a main role in transferring electric field to the above atmosphere and then to the ionosphere.

2 Earthquake precursors

If it can be shown that earthquake perturbations are real and systematic, then they could be considered as short-term precursors, occurring between a few hours and a few days before the earthquake. Earthquakes as geophysical phenomena are irregular, non-linear, sophisticated and non-periodic events, such that the relations between their parameters are dynamic causing high uncertainties in their prediction. So, this necessitates finding proper methods to assess the trend of change in the relevant parameters. It should be noted that it is not expected that all precursors appear in any earthquake. Since not any individual precursor can be used as an accurate stand alone, for earthquake prediction this means that it is necessary to integrate different kinds of precursors. The precursors selected for analysis in this study include electron and ion density, electron temperature, total electron content (TEC), electric and magnetic fields and land surface temperature (LST) several days before some earthquakes.

2.1 Ionospheric precursors

The regional but substantially large-scale changes in atmospheric electricity over seismically active areas before the seismic shock are transformed into the ionosphere by means of a large-scale electric field. With the penetration of this electric field to the ionosphere, electron concentration anomalies are observed when the region affected has an area with a diameter greater than 200 km^2 (Dobrovolsky et al., 1979).

Pulinets et al. (2003) have shown that ionospheric anomalies have been observed in 73% of earthquakes with magnitudes greater than 5 M_s and 100% of earthquakes with magnitudes greater than 6 M_s within 5 days before the earthquake events. It should be noted that the ionospheric anomalies can be positive as well as negative.

The ionospheric anomalies usually happen in D-layer, E-layer and F-layer, and they may be observed 1 to 10 days prior to the earthquake and stay until 1 to 2 days after the earthquake. These ionospheric parameters may be monitored before earthquakes (Akhoondzadeh et al., 2010a, b).

2.1.1 The TEC precursor

GPS satellites with high time resolution measurements can be included as a supplementary tool to study ionospheric variations over the regions supported by GPS ground stations. TEC is the integrated number of the electrons within the block between the satellite and receiver or between two satellites. In this study, TEC variations data of GIM (Global Ionospheric Map) provided by NASA Jet Propulsion Laboratory (JPL) have been used. The GIM is constructed into $5^\circ \times 2.5^\circ$ (Longitude, Latitude) grid with a time resolution of 2 h. GIM data are generated on a daily basis using data from about 150 GPS sites of the IGS (International Gnss Service) and other relevant institutions. TEC data based on the date and geographic location of each earthquake from about 6 weeks before to 1 week after the main event have been processed in this research. Since the network for GPS measurements is only available at local scale in some regions, the TEC data extracted from GPS data is not an ideal tool for the wide extent of this study and therefore is used only in some cases.

2.1.2 Ionospheric precursors provided by DEMETER data

The French micro-satellite DEMETER was launched on 29 June 2004. The satellite's altitude is about 680 km and its measurements in the ionosphere are made within 65° N to 65° E. One of DEMETER's scientific objectives is to detect anomalous variations of electromagnetic waves, particle fluxes and thermal plasma parameters which could be related to seismic activity.

DEMETER has five instruments on board. They are ICE (Instrument Champ Eletrique), IMSC (Instrument Magnetic Search Coil), IDP (Instrument Detecteur de Particules), IAP (Instrument Analyseur Plasma), and ISL (Instrument Sonde de Langmuir). ICE measures the three components of electric field in a frequency range from DC up to 3.5 MHz, IMSC measures the three components of magnetic field in ELF and VLF frequency ranges, IDP measures ionospheric particles energy (electron and proton), IAP measures temperature, density and velocity of plasma ions, and ISL measures temperature and density of plasma electrons (Parrot et al., 2006).

With the data collected by ICE and IMSC experiments, it is possible to survey abnormal variations in recorded VLF transmitter signals during seismic activity when the signal path between the transmitter and the satellite goes through the top of an active seismic area (Akhoondzadeh et al., 2010b). Using the analysis of the DEMETER data, Molchanov et al. (2006) reported a drop of the VLF signals radiated by ground transmitters prior to large earthquakes. The electron density, electron temperature and ion composition (i.e. O^+, H^+ and He^+) measurements using IAP and ISL experiments can be used to reveal the nature of seismo-ionospheric variations (Akhoondzadeh et al., 2010a). In the present work, Demeter experimental data based on the date and geographic location of each earthquake from about 6 weeks before to 1 week after the earthquake have been processed.

2.2 Thermal anomaly precursor

Thermal anomaly is an unusual variation in surface temperature that occurs around 1–13 days prior to an earthquake with abrupt change in the temperature value of the order of 3–7 °C or more and disappears a few days after the event. The idea that the thermal anomalies may be connected with seismic activity was put to application in Russia, China and Japan. In 1980, Russian researchers detected thermal anomalies prior to an earthquake in central Asia using satellite images. Then, other researchers reported more observations on thermal anomalies before strong earthquakes (Qiang et al., 1999, Tronin, 2000, Tronin et al. 2002, Saraf and Choudhury, 2005a, b, Ouzounov and Freund, 2004, Choudhury et al., 2006 and Genzano et al., 2007).

Some remote sensing satellites can measure the radiations coming from the earth in thermal bands and provide useful information prior to earthquakes. Due to their suitable temporal and spatial resolutions, the thermal infrared bands of AVHRR and MODIS data have been used. However, when using optical satellite data in systematic and real-time monitoring of anomalies, cloud cover is occasionally a problem.

3 Proposed methods

The proposed methods in this study are presented in three sections. They include methods applied for (1) anomaly detection to be applied on every one of precursors, (2) earthquake parameters estimation from each single precursor showing anomaly, and (3) integration of estimated parameters to reach final earthquake parameters.

3.1 Method applied for anomaly detection

In order to detect anomaly in any dataset it is necessary to identify the normal and natural behavior state of the phenomenon. Using reported geographic latitude and longitude concerning the earthquake epicenter, we have analyzed earthquake precursors extracted from satellite data to observe the normal signals. The appropriate time period showing the normal behavior may be considered about 45 days before the event. This time period is long enough to show both normal and abnormal signals, where the latter are expected to appear almost close to the end of the period.

To look for earthquake anomaly from precursor variations, a reasonable range for regular variations should be specified. The varying signals with normal behavior belonging to any phenomenon can be fluctuating inside two specified upper and lower bounds. Then to detect anomalies, one should observe the signals appearing beyond these bounds. The median and the inter-quartile range of data are utilized in this study to construct the upper and lower bounds to separate seismic anomalies from the background of natural variations (Liu et al., 2004). In their study, the number of data elements (i.e. the number of days relevant to our study) is kept constant. In this study, the number of days is incremented in a dynamic and iterative manner, and for each varying time period, the varying upper and lower bounds are calculated (Akhoondzadeh, 2011). The varying upper and lower bounds are used for the detection of anomaly for the period of previous days to the present day when these bounds are calculated. This approach may have the advantage of excluding false detection triggered by some abnormally looking signals. In each time period, the bounds are calculated using the following equations.

$$x_{\text{high}} = M + k \times IQR \tag{1}$$

$$x_{\text{low}} = M - k \times IQR \tag{2}$$

Table 1. Estimation of the earthquake magnitude (Akhoondzadeh, 2011).

D_x value	Earthquake magnitude
$D_x \leq 1$	$M_\mathrm{w} < 6$
$1 < D_x \leq 2$	$6 < M_\mathrm{w} \leq 7$
$2 < D_x \leq 3$	$7 < M_\mathrm{w} \leq 8$
$3 < D_x$	$8 < M_\mathrm{w}$

$$x_{\mathrm{low}} < x < x_{\mathrm{high}} \quad \Rightarrow \quad -k < \frac{x-M}{IQR} < k \ ; \ D_\mathrm{x} = \frac{x-M}{IQR} \qquad (3)$$

where x, x_{high}, x_{low}, M, IQR and D_x are the parameter value, upper bound, lower bound, median value, inter-quartile range, and normalized deviation of x from median, respectively. According to this, if the absolute value of D_x is greater than k, ($|D_x| > k$), then the behavior of the relevant parameter (x) is regarded as anomalous. According to Eq. (3), $p = \pm 100 \times (|D_x| - k)/k$ indicates the percentage of parameter deviation from the undisturbed state. After calculation of median and inter-quartile range parameters, in each time period, the value of D_x for each day according to Eq. (3) is calculated. If the D_x value of a given day exceeds the defined relevant bounds, then it is considered as an anomaly (Akhoondzadeh, 2011).

It should be noted that some irrelevant anomalies may be detected too. In our previous studies (Akhoondzadeh et al., 2010a, b; Akhoondzadeh and Saradjian, 2010), it has been shown that these anomalies for which no successive occurrence of earthquakes is observed, are mainly related to geomagnetic activities and other unknown parameters. One of the main advantages of the present study is, by integrating earthquake parameters, to avoid misleading detected anomalies from concurrent analysis of many precursors.

3.2 Method applied for earthquake parameters estimation

The results from our previous studies indicate that the D_x value is relatively proportional to the earthquake magnitude (Akhoondzadeh et al., 2010a, b). For instance, in large earthquakes with a D_x value between 2 and 3, the magnitude value (M_w) is estimated to be around between 7 and 8. The earthquake magnitude estimation based on the D_x value is shown in Table 1.

The radius of the affected area can be estimated using the Dobrovolsky formula: $R = 10^{0.414M-1.696}$, where R is the radius of the earthquake preparation zone, and M is the earthquake magnitude (Dobrovolsky et al., 1989). Furthermore, studies show that the maximum of the affected area in the ionosphere does not coincide with the vertical projection of the epicenter of the impending earthquake and is shifted towards the equator in high and middle latitudes (Pulinets et al., 2003).

Based on previous studies on anomaly detection before strong earthquakes mentioned in Table 2, earthquake anomalies may be observed 1 to 13 days prior to the earthquake. If D_x value of a given day is greater than a predefined threshold, then, based on the type of precursor, the earthquake date is estimated according to the relation $\mu + 2.5 \times \sigma$, (i.e. the fourth column) where μ and σ are the mean and standard deviation of values of the anomaly observation day relative to the earthquake day (i.e. the third column)(Akhoondzadeh, 2011).

3.3 Method applied for earthquake parameters integration

In order to assess final earthquake parameters (which are date, magnitude and radius of the affected area) for each case study using the median and inter-quartile range of earthquake parameters obtained from different precursors, the approximate bounds of the final earthquake parameters are defined. For instance, the date of an impending earthquake is calculated based on $M \pm IQR$, where M and IQR are respectively the median and inter-quartile range of the predicted values of the earthquake date for all precursors (Akhoondzadeh, 2011).

4 Observations and case studies

In order to clear up uncertainty in earthquake anomaly detection, our study is based on a few types of precursors, sensors and case studies. Using visual inspection in seismic databases (http://earthquake.usgs.gov, http://www.emsc-csem.org, http://iiees.ac.ir and http://geophysics.ut.ac.ir), five earthquakes which happened in Samoa Islands, Sichuan (China), L'Aquila (Italy), Boroujerd (Iran) and Zarand (Iran) have been incorporated into this analysis. Table 3 indicates some characteristics of these earthquakes.

4.1 Samoa Islands earthquake

On the Samoa Islands, the largest earthquake so far took place at 06:48:11 LT on 29 September 2009 with a Magnitude $M_\mathrm{w} = 8.1$ (see Table 3). Table 4 illustrates the observed earthquake precursors concerning the Samoa earthquake.

As shown in Table 4, a strong enhancement of the TEC anomaly can be seen during several time intervals (Akhoondzadeh et al., 2010a). Anomalous TEC variations of the order of 2.55 began on 24 September 2009. Based on proposed method, this anomaly indicates that an earthquake with a magnitude between 7 and 8 would have happened between 25 September and 9 October 2009 and the radius of the affected area would have been between 15.92 and 41.30 km. The TEC anomaly on 28 September 2009 was expanded and amplified with a maximum value reaching 3.73 at 03:00 LT. For $D_\mathrm{x} = 3.73$ the magnitude of the impending

Table 2. Estimation of the earthquake date (Akhoondzadeh, 2011).

Precursor	Reference	Anomaly observation day relative to the earthquake day	Estimated earthquake day relative to the observation day
Ionospheric	(Zhao et al., 2008)	3	15
	(Liu et al., 2000)	4	
	(Pulinets et al., 2003)	5	
	(Akhoondzadeh et al., 2010a, 2010b)	11	
	(Akhoondzadeh and Saradjian, 2010)	8	
Thermal	(Ouzounov and Freund, 2004)	6	16
	(Saraf and Choudhury, 2005a)	13	
	(Choudhury et al., 2006)	7	
	(Pulinets et al., 2006)	7	
	(Saraf and Choudhury, 2005b)	8	

Table 3. List of the earthquakes selected in this study (reported by http://earthquake.usgs.gov/).

Case Study	Date yyyy/mm/dd	Time (UTC)	Longitude	Latitude	Magnitude (M_w)	Focal depth (km)
Zarand, Iran	2005/02/22	02:25:23	56.82 N	30.75 E	6.4	14
Borujerd, Iran	2006/03/31	01:17:01	48.78 N	33.50 E	6.1	7
Sichuan, China	2008/05/12	06:28:01.57	103.32 N	31.0 E	7.9	19
L'Aquila, Italy	2009/04/06	01:32:39.00	13.33 N	42.33 E	6.3	8
Samoa Islands	2009/09/29	17:48:10.99	172.10 W	15.49 S	8.1	18

earthquake, which would have occurred between 29 September and 13 October 2009, is estimated to have been greater than $M_w = 8.0$. Therefore, the radius of the affected area is estimated to have been greater than 41.30 km.

Table 4 also illustrates variations of different parameters extracted from DEMETER experimental data over the Samoa region. It concerns electron density (cm^{-3}) and electron temperature (K) from ISL, total ion density (cm^{-3}) from IAP, electric field from ICE and magnetic field from IMSC which were recorded when satellite orbits were close to the earthquake epicenter (i.e. less than 1500 km). An increase in total ion density is clearly observed at ∼10:30 LT on 25 September 2009. Variations of total ion density clearly exceed the upper bound of the order of 67% (Akhoondzadeh et al., 2010a). This precursor indicates that an earthquake with a magnitude greater than $M_w = 8.0$ would have occurred between 26 September and 10 October 2009. Similar to this, another unusual behavior is seen in electron density variations, when they reached a maximum value, at ∼10:30 LT, and exceeded the upper bound of the order of 67% on 25 September 2009. Because of the inverse relation between electron density and electron temperature, the observed anomaly in electron density can be acknowledged by the electron temperature variations. Table 4 indicates that the electron temperature had reached its minimum value ($D_x = -1.82$) at ∼10:30 LT, on 25 September 2009. This anomaly indicates that an earthquake with a magnitude between 6 and 7 would have happened between 26 September and 10 October 2009. Irregularities of electron density also occurred on ∼22:30 LT, 18, 21, 24 and 26 September 2009 and among them, the maximum irregularity intensity (i.e. 60.5%) was observed on 24 September 2009. According to this anomaly, an earthquake with a magnitude between 7 and 8 would have happened between 25 September and 9 October 2009 and the radius of the affected area could have been estimated to have been between 15.92 and 41.30 km.

Table 4 represents the intense appearance of the NPM transmitter waves in the VLF electric spectrogram on 21 September 2009. This strong electromagnetic enhancement of the VLF transmitter wave is due to the broadening of the spectral component at the transmitter frequency. This broadening was enhanced when the VLF wave crossed ionospheric irregularities (Bell and Ngo, 1988, 1990). This sharp appearance was also seen in the VLF magnetic spectrogram at the same time (Akhoondzadeh et al., 2010b). These earthquake precursors extracted using ICE and IMSC experiments indicate that an earthquake with a magnitude greater than $M_w = 7$, would have happened between 22 September and

Table 4. Different precursors concerning Samoa earthquake (Akhoondzadeh, 2011).

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (D_x)	Prediction of earthquake magnitude	Prediction of the radius of affected area (km)
TEC	28 Sep	29 Sep–13 Oct	+2.78	7–8	15.92–41.30
	28 Sep	29 Sep–13 Oct	+3.73	>8	>41.30
	28 Sep	29 Sep–13 Oct	+3.38	>8	>41.30
	28 Sep	29 Sep–13 Oct	+2.63	7–8	15.92–41.30
	27 Sep	28 Sep–12 Oct	+2.73	7–8	15.92–41.30
	27 Sep	28 Sep–12 Oct	+2.54	7–8	15.92–41.30
	26 Sep	27 Sep–11 Oct	+2.91	7–8	15.92–41.30
	25 Sep	26 Sep–10 Oct	+2.60	7–8	15.92–41.30
	25 Sep	26 Sep–10 Oct	+3.07	>8	>41.30
	24 Sep	25 Sep–9 Oct	+2.55	7–8	15.92–41.30
Electron Temperature	27 Sep	28 Sep–12 Oct	+3.24	>8	>41.30
O+ Density	26 Sep	27 Sep–11 Oct	+2.12	7–8	15.92–41.30
Total Ion Density	26 Sep	27 Sep–11 Oct	+2.08	7–8	15.92–41.30
Ion Density	26 Sep	27 Sep–11 Oct	+2.28	7–8	15.92–41.30
Total Ion Density	25 Sep	26 Sep–10 Oct	+3.0	>8	>41.30
O+ Density	25 Sep	26 Sep–10 Oct	+3.18	>8	>41.30
Ion Temperature	25 Sep	26 Sep–10 Oct	-2.87	7–8	15.92–41.30
Electron Density	25 Sep	26 Sep–10 Oct	+3.01	>8	>41.30
Electron Temperature	25 Sep	26 Sep–10 Oct	-1.82	6–7	6.14–51
Electron Density	24 Sep	25 Sep–9 Oct	+2.89	7–8	15.92–41.30
Ion Density	23 Sep	24 Sep–8 Oct	+1.96	6–7	6.14–15.92
Total Ion Density	21 Sep	22 Sep–6 Oct	+1.65	6–7	6.14–15.92
O+ Density	21 Sep	22 Sep–6 Oct	+2.24	7–8	15.92–41.30
O+ Density	21 Sep	22 Sep–6 Oct	+2.07	7–8	15.92–41.30
Total Ion Density	21 Sep	22 Sep–6 Oct	+2.04	7–8	15.92–41.30
Electron Density	21 Sep	22 Sep–6 Oct	+2.8	7–8	15.92–41.30
Ion Density	18 Sep	19 Sep–3 Oct	+2.07	7–8	15.92–41.30
The intense appearance of NPM transmitter waves in the VLF electric spectrogram	21 Sep	22 Sep–6 Oct	> 2.2	>7	>15.92
The intense appearance of NPM transmitter waves in the VLF electric spectrogram	21 Sep	22 Sep–6 Oct	> 2.2	>7	>15.92
The attenuation of NPM transmitter waves in the VLF electric spectrogram	24 Sep	25 Sep–9 Oct	>2.2	>7	>15.92
The most appearance of harmonic emissions above NPM transmitter in the HF electric spectrogram	27 Sep	28 Sep–12 Oct	>2.2	>7	>15.92
The intense appearance of harmonic emissions above NPM transmitter in the HF electric spectrogram	28 Sep	29 Sep–13 Oct	>2.2	>7	>15.92
Sea Surface Temperature	26 Sep	27 Sep–12 Oct	0.79	5–6	2.36–6.14

Table 5. Different precursors concerning Sichuan earthquake (Akhoondzadeh, 2011).

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (D_x)	Prediction of earthquake magnitude	Prediction of the radius of affected area (km)
TEC	11 May	12 May–26 May	−2.59	7–8	15.92–41.30
	10 May	11 May–25 May	−03.10	>8	>41.30
	10 May	11 May–25 May	−03.07	>8	>41.30
	9 May	10 May–24 May	−03.10	>8	>41.30
	9 May	10 May–24 May	−2.92	7–8	15.92–41.30
	9 May	10 May–24 May	−2.50	7–8	15.92–41.30
	8 May	9 May–23 May	−2.69	7–8	15.92–41.30
	8 May	9 May–23 May	−2.87	7–8	15.92–41.30
	8 May	9 May–23 May	−2.68	7–8	15.92–41.30
	2 May	3 May–17 May	−2.55	7–8	15.92–41.30
O+ Density	10 May	11 May–25 May	−2.18	7–8	15.92–41.30
Total Ion Density	10 May	11 May–25 May	−2.28	7–8	15.92–41.30
Ion Density	10 May	11 May–25 May	−2.05	7–8	15.92–41.30
Electron Temperature	10 May	11 May–25 May	+1.98	6–7	6.14–15.92
Electron Temperature	9 May	10 May–24 May	+1.73	6–7	6.14–15.92
Electron Density	9 May	10 May–24 May	−1.86	6–7	6.14–15.92
O+ Density	9 May	10 May–24 May	−2.40	7–8	15.92–41.30
Total Ion Density	10 May	11 May–25 May	−2.26	7–8	15.92–41.30
Electron Density	10 May	11 May–25 May	−1.70	6–7	6.14–15.92
Electron Density	3 May	4 May–18 May	+2.09	7–8	15.92—41.30
O+ Density	2 May	3 May–17 May	+2.37	7–8	15.92–41.30
Total Ion Density	2 May	3 May–17 May	+2.13	7–8	15.92–41.30
Electron Temperature	2 May	3 May–17 May	−3.22	>8	>41.30
Electron Temperature	1 May	2 May–16 May	+2.5	7–8	15.92–41.30

6 October 2009. Table 4 also represents the attenuation of the NPM transmitter signals when they crossed the disturbed ionosphere on 24 September 2009. This fading of the signal can be associated to an increase of the ionospheric density because during the ionospheric propagation the signal attenuation is directly proportional to the plasma density (Cannon and Bradley, 2003). The analysis of HF electric spectrogram shows the intense appearance of harmonic emissions above NPM transmitter on 28 September 2009 (Akhoondzadeh et al., 2010b).

The final earthquake parameters including the date, magnitude and radius of affected area are estimated using the earthquake parameters deduced from different precursors. The bounds of the final impending earthquake parameters are calculated using the median and inter-quartile range of earthquake parameters estimated using different precursors.

In this case study, it is predicted that an earthquake would have happened with a magnitude between 7 and 8, on a date between 29 September and 6 October 2009, and in an affected area of radius between 15.92 and 41.30 km. The Samoa earthquake actually happened on 29 September 2009 with a magnitude $M_w = 8.1$.

4.2 Sichuan, China earthquake

On 12 May 2008 at 14:28:01.57 LT a strong earthquake of magnitude $M_w = 7.9$ occurred in Southwest China (see Table 3). Some strong anomalies were observed on 2 May (06:00 LT), 8 May (02:00, 04:00, 06:00 LTs), 9 May (12:00, 14:00, 24:00 LTs), 10 May (12:00, 14:00 LTs) and 11 May (12:00 LT) 2009. Among all the above pre-earthquake anomalies, the anomalies observed on 9 and 10 May at 12:00 LT, were the strongest (the observed TEC exceeds the lower bound by −24%) (Akhoondzadeh et al., 2010a). These strong anomalies indicate that an earthquake with a magnitude greater than 8 would have happened between 10 and 24 May 2009. The corresponding data with total ion and electron density changes recorded by DEMETER IAP and ISL sensors are shown in Table 5. The transition in electron density value from lower bound occurred at ∼10:30 LT, on 9 May 2009 and was of the order of −24%. It reached its minimum value of −37%, 2 days before the earthquake (Table 5). This means that an earthquake with a magnitude greater than 8 would have happened between 10 and 24 May 2009. Such anomalies are also observed in electron temperature variations, when the magnitude of changes from the undisturbed state reaches 15% and 29%, on 9 and 10 May

Table 6. Different precursors concerning L'Aquila earthquake (Akhoondzadeh, 2011).

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (D_x)	Prediction of earthquake magnitude	Prediction of the radius of affected area (km)
TEC	4 Apr	5 Apr – 19 Apr	+1.92	6–7	6.14–15.92
	2 Apr	3 Apr – 17 Apr	+1.84	6–7	6.14–15.92
Total Ion Density	5 Apr	6 Apr–20 Apr	+2.58	7–8	15.92–41.30
Total Ion Density	5 Apr	6 Apr–20 Apr	+1.72	6–7	6.14–15.92
Electron Density	5 Apr	6 Apr–20 Apr	+2.21	7–8	15.92–41.30
Electron Density	4 Apr	5 Apr–19 Apr	+1.65	6–7	6.14–15.92
Total Ion Density	4 Apr	5 Apr–19 Apr	+2.64	7–8	15.92–41.30
Electron Density	4 Apr	5 Apr–19 Apr	+2.67	7–8	15.92–41.30
Electron Density	3 Apr	4 Apr–18 Apr	+3.35	>8	>41.30
Total Ion Density	3 Apr	4 Apr–18 Apr	+2.30	7–8	15.92–41.30
Electron Density	30 Mar	31 Mar–13 Apr	+1.93	6–7	6.14–15.92
Total Ion Density	30 Mar	31 Mar–13 Apr	+1.44	6–7	6.14–15.92

Table 7. Different precursors concerning Borujerd earthquake (Akhoondzadeh, 2011).

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (D_x)	Prediction of earthquake magnitude	Prediction of the radius of affected area (km)
LST	25 Mar	26 Mar–10 Apr	1.31	6–7	6.14–15.92
Total Ion Density	30 Mar	31 Mar–14 Apr	+1.54	6–7	6.14–15.92
Ion Temperature	29 Mar	30 Mar–13 Apr	+1.25	6–7	6.14–15.92

2009, respectively (Table 5). An unusual decrease of electron density (−13%) was seen at ∼22:30 LT, on 9 May 2009. The variations of electron density also indicated an increase of the order of 39% from the normal state on 3 May 2009, which is acknowledged by an anomaly in the total ion density of the order of 42%, at ∼22:30 LT, on 2 May 2009 (Table 5). According to this anomaly, an earthquake with a magnitude between 7 and 8 would have happened between 3 and 17 May 2009 and the radius of affected area varied between 15.92 and 41.30 km. The characteristics of other detected anomalies can be found in Table 5. The integration of earthquake parameters retrieved from different precursors indicates that an earthquake with a magnitude between 7 and 8 would have happened between 12 and 20 May 2009. The radius of affected area is estimated to be between 15.92 and 41.30 km.

4.3 L'Aquila, Italy earthquake

In Italy the deadliest earthquake (since the 1980 Irpinia earthquake) occurred ($M_\mathrm{w} = 6.3$) in the region of Abruzzo, in central Italy, at 03:32:39 LT on 6 April 2009 (see Table 3). The anomalous TEC corresponding to this event was of the order of 28% and 23% at 24:00 LT, on 2 and 4 April 2009, respectively. These anomalies indicate that an earthquake with a magnitude between 6 and 7 would have happened between 3 and 17 April 2009. The radius of affected area is estimated to have been between 6.14 and 15.92 km. The moderate geomagnetic activity around the date of this earthquake does not seem to modify the data recorded by DEMETER experiments. By inspection of electron density variations obtained from ISL, sharp increases of 123% and 78% from the unperturbed state at ∼22:30 LT, were observed on 3 and 4 April 2009 (Akhoondzadeh et al., 2010a), respectively. The observed anomalous variation on 4 April indicates that an earthquake with a magnitude between 6 and 7 would have happened between 5 and 19 April 2009. Simultaneously, the total ion density exceeded from the upper bound on 3 April 2009 and reached a maximum value of 76%, on 4 April 2009. This anomaly can be a hint of an earthquake with a magnitude between 7 and 8 which would have happened between 6 and 20 April 2009. The variations of daytime total ion density showed similar anomalies as that of nighttime. They showed an increase from the undisturbed state (15%) on 5 April 2009, which was accompanied by the electron density anomaly 47% observed at ∼10:30 LT, on 5 April 2009 (Akhoondzadeh et al., 2010a). The details of other detected anomalies and also predicted earthquake parameters can be seen in Table 6. In this case study, the earthquake parameters deduced from different precursors indicate that an earthquake with a magnitude between 6 and 7 would have happened between 7 and 15 April 2009. The radius of affected area is estimated to have been between 6.14 and 15.92 km.

Table 8. Different precursors concerning the Zarand earthquake (Akhoondzadeh, 2011).

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (D_x)	Prediction of earthquake magnitude	Prediction of the radius of affected area (km)
LST	21 Feb	22 Feb–9 Mar	0.92	5–6	2.36–6.14

Table 9. Case studies accompanied by the registered and estimated earthquake parameters.

Case study	Date		Magnitude (M_w)	
	Registered	Estimated	Registered	Estimated
Borujerd	31 Mar 2005	1–8 Apr 2006	6.1	6–7
Zarand	22 Feb 2005	22 Feb–9 Mar 2005	6.4	~ 6
Sichuan, China	12 May 2008	12–20 May 2008	7.9	7–8
L'Aquila, Italy	6 Apr 2009	7–15 Apr 2009	6.3	6–7
Samoa Islands	29 Sep 2009	29 Sep–6 Oct 2009	8.1	7–8

4.4 Borujerd, Iran earthquake

The occurrence of more than 130 strong earthquakes ($M_w > 7.5$) in the past centuries and almost daily earthquakes of magnitude 3.0 in Iran make it a severely earthquake-prone region. In Borujerd, an earthquake with a magnitude $M_w = 6.1$ took place at 01:17:01 LT on 31 March 2006 (see Table 3). The LST variations exceeded the predefind bounds on 25 March 2006 (Saradjian and Akhoondzadeh, 2010). This anomaly indicates that an earthquake of magnitude around 6 would have happened between 26 March and 10 April 2005. The IAP experiement measurements indicates that total ion density reached its maximum value on 30 March 2006 and that the ion temperature exceeded the lower bound on 29 March 2006 (Table 7) (Akhoondzadeh, 2011). By inspection of predicted parameters obtained from different precursors, it is predicted that an earthquake of magnitude between 6 and 7 would have happened between 1 and 8 April 2006.

4.5 Zarand, Iran earthquake

On 22 February 2005 at 2:25:23 UTC, an earthquake of magnitude $M_w = 6.4$ occurred in Zarand (see Table 3). The unusual variations of LST values on 21 February 2005 (Saradjian and Akhoondzadeh, 2010) indicate that an earthquake with a magnitude around $M_w = 6$ would have happened between 22 February and 9 March 2005 (Table 8).

5 Conclusions

Assuming that earthquake parameters estimation using any single precursor is associated with some uncertainties, this study is concerned with the integration of capabilities of different earthquake parameters extracted from the same earthquake precursors to better estimation of earthquake parameters. In order to detect disturbed states that might be associated with impending earthquake, the variations of different earthquake precursors regarding the five earthquakes have been analyzed in this study. For each precursor the date, magnitude and radius of the affected area parameters concerning the impending earthquake were estimated. By integrating the earthquake parameters resulting from all precursors, the final earthquake parameters were estimated more accurately (Akhoondzadeh, 2011).

For the Samoa and Sichuan earthquakes, the estimated earthquake parameters of impending earthquakes are close to the registered earthquake parameters (Table 9). This can be related to the different precursors (i.e. 14 and 6 precursors for Samoa and Sichuan cases, respectively) analyzed in these studied cases. This implies that the number and diversity of earthquake precursors lead to a precise estimation of earthquake parameters. Thus, fewer precursors such as for the L'Aquila, and Borujerd earthquakes with three precursors for each, have resulted in slightly less certain estimations.

It should be pointed out that earthquake anomalies can be hidden in the high magnetic activity periods. Therefore, excluding the geomagnetic activity periods, only the pre-seismic plasma anomalies in geomagnetic quiet periods have been investigated in this study. However, it is necessary to take into account that the ionosphere has complicated behavior, even under quiet geomagnetic conditions, and the measured parameters sometimes contain variations in a quiet seismic condition that can be associated to other unknown factors.

The seismic anomalies represented in this paper are promising for short term prediction, but attention has to be paid to the requirement for further investigation to obtain a very accurate regional model of quiet time for the lithosphere, atmosphere and ionosphere, in order to discriminate seismic precursors from the background of daily variations.

One of the advantages of the present study is to avoid misleading detected anomalies from concurrent analysis and integration of earthquake parameters extracted from many precursors.

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