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Thermal anomalies detection before earthquake using three filters (Fourier, Wavelet and Logarithmic Differential Filter), A Case study of two earthquakes in Iran

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Abstract

Earthquake is one of the most destructive natural phenomena which has human and financial losses. The existence of an efficient prediction system and early warning system will be useful for reducing effects of destroying earthquake. In this paper by applying three filters (Fourier, Wavelet and Difference Logarithmic Filter (LDF)) on soil temperature time-series, anomaly behavior before the major earthquakes was studied. Aforementioned methods were performed of the Bam (2003), and Zarand (2005) earthquakes in Iran. The results indicate thermal anomalies were detected before earthquake occurrence. Furthermore, the LDF filter detects thermal anomaly as well as the Fourier and Wavelet filters. For validation of the results, the soil temperature data of the Bam earthquake were considered from the Bam meteorological station and also from the Joroft meteorological stations that located in effective radius (Dobrolsky radius) and the same results was obtained. It states that there is a relation between temperature anomaly behavior and the major earthquakes.

Keywords: *Time Series,Thermal Anomaly, Prediction, Earthquake*

1. Introduction

Earthquake is one of the most unexpected and therefore the most destructive natural phenomena which has human and financial losses. For reducing effects of wrecking earthquake, existence of a robust and efficient prediction system and early warning will be useful. During last decades, many geophysical parameters such as ground deformations (uplift and tilt), abrupt changes in underground water level, gas emission rates (e.g. radon and CO_2), temperature and chemical composition, electrical properties of rocks, atmosphere and ionosphere, near surface air temperature and relative humidity, the Earth's thermal emission, variation in seismicity patterns, and changes in animal activity were proposed as possible earthquake precursors (Pulinets 1997; Ouzounov and Freund 2001; Cicerone et al. 2009; Crockett and Gillmore 2010; Kamali et al. 2012; Guangmeng and Jie 2013; Li and Parrot 2013; Eleftheriou et al. 2016).

The idea of the occurrence of thermal anomalies before the strong earthquakes was first presented by researchers from China, Japan and Russia. In 1980, some short-lived thermal infrared anomalies from satellite images were detected prior to an earthquake in central Asia by Russian researchers (Tronin 1996). After that, a large number of observations on thermal anomalies before strong earthquakes that cause fluctuations in the Land Surface Temperature (LST) were reported (Xu Xiudeng 1991; Tronin 2000; Tronin et al. 2002; Ouzounov and Freund 2004; Choudhury et al. 2006; Cicerone et al. 2009; Saraf et al. 2009; Saradjian and Akhoondzadeh 2011;Saber-Mahani 2016; Saber-Mahani et al. 2017; Bhardwaj et al. 2017; Khalili et al. 2019) These researches show that thermal anomaly occurs around 1–10 days prior to an earthquake with increases in the temperature of the order of 3–12 centigrade degrees or more and usually disappears a few days after the event. Although, the thermal anomalies may have origins other than earthquake, for example: emission of gases such as carbon dioxide, methane and hydrogen due to the opening and closure of micro pores upon induced stresses and also the changes of ground water regime have been offered as a possible cause for generation of thermal anomalies (Xu Xiudeng 1991; Tronin 1996; Hayakawa et al. 2007).

It seems that the precise anomalies detection in a nonlinear time series of earthquake precursors is a robust and efficient system for earthquake prediction.

Some researchers analyzed the LST time series to locate relevant anomalous variations prior to large earthquakes using Interquartile, Wavelet, Artificial Neural Network and Kalman filter methods (Saradjian and Akhoondzadeh 2010; Akhondzadeh 2012).

The main aim of this research is to detect the thermal anomalies of the soil temperatures time-series for the Bam and Zarand earthquakes in Iran, using the Fourier and Wavelet, and comparing two last filters with an innovative filter (Logarithmic Differential Filter (LDF)).

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2. Seismotectonic Setting

The Iranian plateau is one of the most seismically active areas in the world which tectonic activity of this region can be characterized by high topography, recent volcanism and many active faults along the Alpine-Himalaya orogenic belt (Zamani et al. 2012). Much of the shortening resulted by collision, has been expressed in earthquakes and mountain belts of the Zagros in the SW, the Kopeh-Dagh NE, the Alborz N and some has also been accommodated in central Iran that includes the Kerman-Bam plateau (Berberian and Yeats 2001; Walker and Jackson 2002; Walker and Jackson 2004).

The study area between 28°-32° North latitude and 56°-59° East longitude is a part of the Central-East Iran, Sanandaj-Baf, and Makran zones (Zamani et al. 2011) (Fig 1). The geology of the region is dominated by lithologies ranging from recent Quaternary alluvium to Precambrian basement which comprise igneous, sedimentary and metamorphic rock types.

The seismicity of the study area is connected with young and active faults of this region. The main faults are the Nayband, the Bam, the Lakar-Kuh faults with N-S trend and the Kuh-e-banan fault with NW-SE trend (Fig 2). The Kuh-e-banan fault is one of the most seismically active faults in Kerman province (Walker et al. 2010; Nemati 2015). The occurrence of many destructive earthquakes such as the Sirch earthquake, 1981; the Golbaf earthquake, 1998; the Bam earthquake, 2003 and the Zarand earthquake, 2005, show that the study area has a high seismicity rate.

3. Data

3.1. Seismicity Data

The Bam earthquake with a moment magnitude of 6.6 (USGS) occurred on December 26th, 2003 in the city of Bam (Kerman province, Iran), and caused to kill of thousands of people (Fig 1). On February 22th, 2005 a major earthquake with a moment magnitude of 6.4 (USGS) occurred near the Zarand city and caused to kill of tens people in the Zarand town. This major earthquake has two large aftershocks which occurred on May 1st (Mw=5.1), and May 14th (Mw=5.2), 2005 (Fig 2). In order to assess and detect the thermal anomalies before the mention earthquakes, the soil temperatures data were obtained from the nearest meteorological stations to them (Table 1).

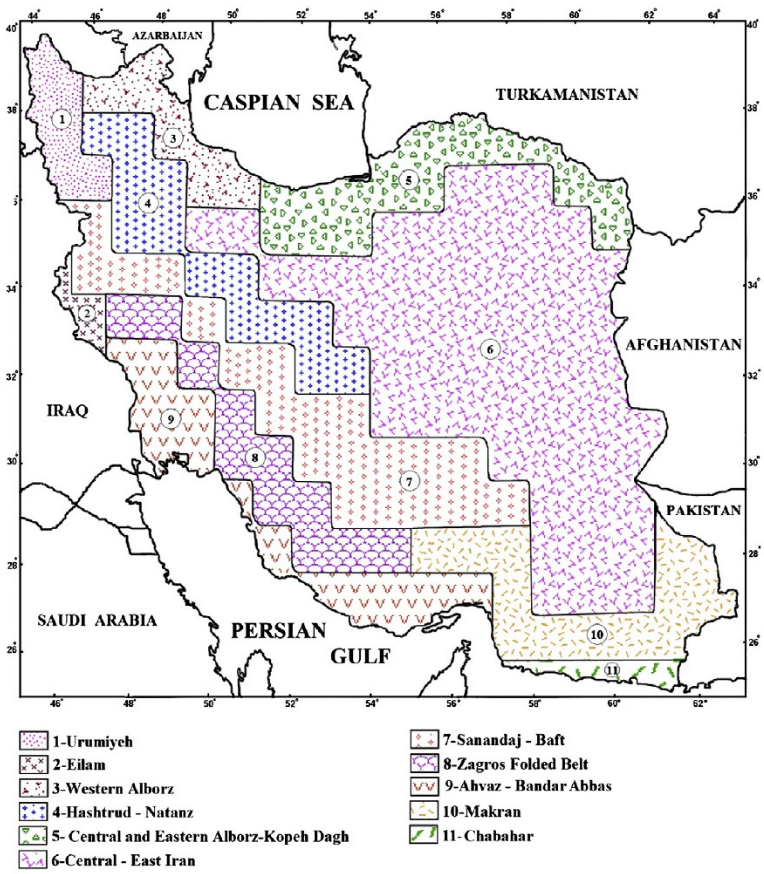

Fig 1. Automatic Integrated Self-Organized Optimum Zoning (AISOOZ) map of Iran that represents 11 optimum tectonic zones (Zamani et al. 2011).

3.2. Thermal Data

One of the most important earthquake precursors is temperature variation. It fluctuates several days before (and sometimes after) an earthquake. There are two types of thermal data. One of this is obtained from satellite sensors such as MODIS and AVHRR (that installed on TERRA, AQUA and NOAA satellites), and another type is obtained from thermometer which buried in the different depth of soil. In this research, we used the temperatures data which obtained from buried thermometers. Generally, the measured depth starts at 5 centimeter and ends at 100 cm which Deeper depth has a high validation for measuring thermal anomaly because deeper depth has lesser noise (atmospheric effects) than the other depth (Kamali et al. 2009). As the Fig 3 shows, soil temperature data from 100 cm depth has lower oscillation rate than the others. During a day, the solar energy stored, and after sunset it loses. It is expected that at the first hours of a day the energy storing in the lower soil layers, therefore, the thermal data were obtained from the 06:00 am.

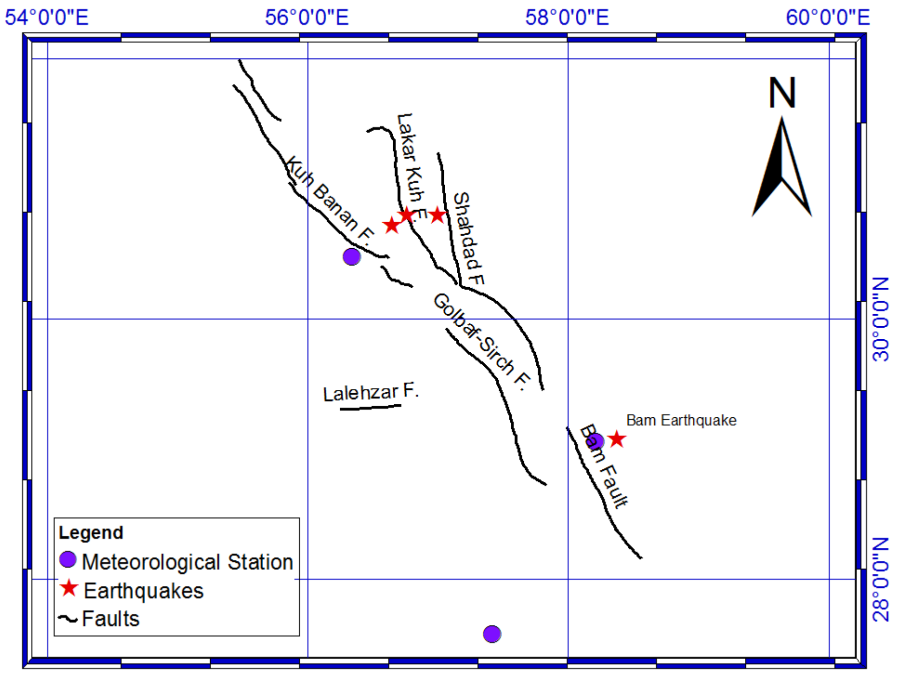

Fig 2. The Geographic map of the study area which is include the locations of the earthquakes and meteorological stations

Table 1. Information of the earthquakes and the nearest meteorological stations to them, where d is epicentral distance and r is the dobrolsky radius.

Earthquake Name	Date	Mag. (Mw)	Depth	Epicenter		Meteorology station		R (km)	D/R
				Lon.	Lat.	Lon.	Lat.		
Zarand	22/02/2005	6.4	14	56.76	30.80	56.34	30.48	565	0.06
Zarand	01/05/2005	5.1	14	57	30.80	56.34	30.48	156	0.41
Zarand	14/05/2005	5.2	14	56.65	30.72	56.34	30.48	172	0.11
Bam	26/12/2003	6.5	13	58.38	29.08	58.21	29.06	624	0.006
Bam	26/12/2003	6.5	13	58.38	29.08	57.48	28.35	624	0.18

When an earthquake occurs, some precursor appears in the specific radius from epicenter. Dobrovolsky calculated an experimental equation related to affected area of precursors (Eq.1) (Dobrovolsky et al. 1979):

$$R = 10^{0.41M} \qquad (1)$$

where R is Dobrovolsky radius, and M is earthquake magnitude. The soil temperature data of several months before and after main earthquakes were obtained from the Bam, Jiroft and Zarand meteorological stations for the Bam and Zarand earthquakes (Figs 4.a, 5.a and 6.a). For validating the method, the thermal data of Bam earthquake from Jiroft meteorology station which located in effective area were considered. In Fig 4 to 6, the green lines show the average values, and the red lines show upper and lower boundaries. It should be noted that time axis's are based on Julian days.

Based on this equation, distance between epicenter and meteorology station must be calculated and comprised with Dobrovolsky radius. Therefore, the D/R ration were calculated where D is the epicentral distance and R is Dobrolsky radius. The earthquakes had just D/R ratio less than 1 could be studied practically (Dobrovolsky et al. 1979).

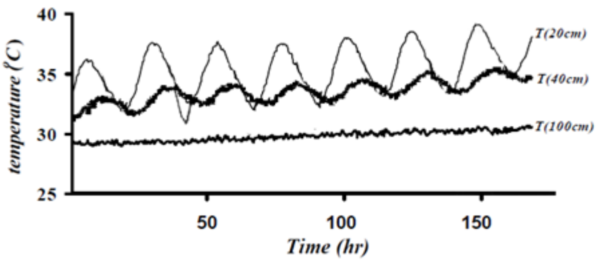

Fig 3. The soil temperature which records at the different depths (20, 40, and 100 centimeters) at the geophysics station (University of Tehran, Iran) 28 June 1995–11 July 1995 (Rezapour et al. 2010).

4. Method of Analysis

In order to extract meaningful statistics and other characteristics of the data time series analysis methods are used for analyzing time series data. Generally, time series analysis are used for two objectives in analyzing time series data; first, forecasting the future values of the data from the previous ones and the second, understanding the model creating the data (Lee and Coyne 2012). When a time-series model is created, it might be better applying a filter on it because in some cases, researchers want to eliminate noise from the time-series model and in some other cases researchers want to detect noise (it's useful for recognizing anomaly).

In this research, in order to detect thermal anomalies from the subsurface soil temperatures, before the earthquake occurrence, three types of filters (Fourier, Wavelet, and Logarithmic Differential Filter (LDF)) were conducted.

4.1. Fourier Transform

The Fourier transform is an integral transform that it converts any function such as f(t) to $F(\omega)$. A special case of this transform is Fourier series and it is useful when f (t) is periodic; f(t)=f(t+T). If function be not periodic or its period be unlimited ($T\rightarrow\infty$), the Fourier series converts to Eq.2. Aforementioned equation converts function from the time domain to the frequency domain. Furthermore, for transform inversely we can use Eq.3 (Chapra 2010):

$$F(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} f(t)\,e^{-i\omega t}\,dt \qquad (2)$$

$$f(t)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} F(\omega)\,e^{i\omega t}\,d\omega \qquad (3)$$

where and t are the frequency and time respectively.

In the Fourier filter, time-domain is converted to the frequency domain. In the frequency domain, low pass filter applied to time series, then time series is converted back to the time domain. The filtered time series is deducted from initial time series. By this method, anomalous behavior can be detected well.

4.2. Wavelet Transform

The wavelet transform's goal is to resolve problems in Short Time Fourier Transform (STFT), and it is an alternative method for STFT. For performing wavelet, signal convolves to wavelet function (as the same as STFT). The wavelet function plays the rule of the window function.

Wavelet is presented by $\psi(t)$. The function is known by shift factor "b" and dilation factor "a" that show signal in two axes time and scale (Fugal 1994). The wavelet transform is expressed in Eq. 4:

$$\psi(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} x(t)\,\psi^{*}\left(\frac{t-b}{a}\right)dt \qquad (4)$$

Baili et.al (2009) have shown that if the wavelet is more similar to the signal, the Signal to Noise Ratio (SNR) increase (Baili et al. 2009). The Daubechies wavelets are periodic like temperatures time series that we used. In this research the daubechies 5 wavelet used for filtering. The wavelet filter splits signals into two parts based on the frequency. It means that it creates two parts; the high frequency and the low frequency. The high-frequency part which consists of noises was converted to the time-domain.

4.3. Logarithmic Differential Filter (LDF)

In this paper, the Logarithmic Differential Filter (LDF) was used for the first time on thermal time series. One of the most important utility of this filter is this filter can convert constant distribution to normal distribution. At first, the LDF logarithmizes the time series, and categorizes data by applying the LOG10 on time-series. Then differential operator applies to the time-series, so data be closer to each other. Aforementioned procedure enable us to detect anomaly by using a normal range.

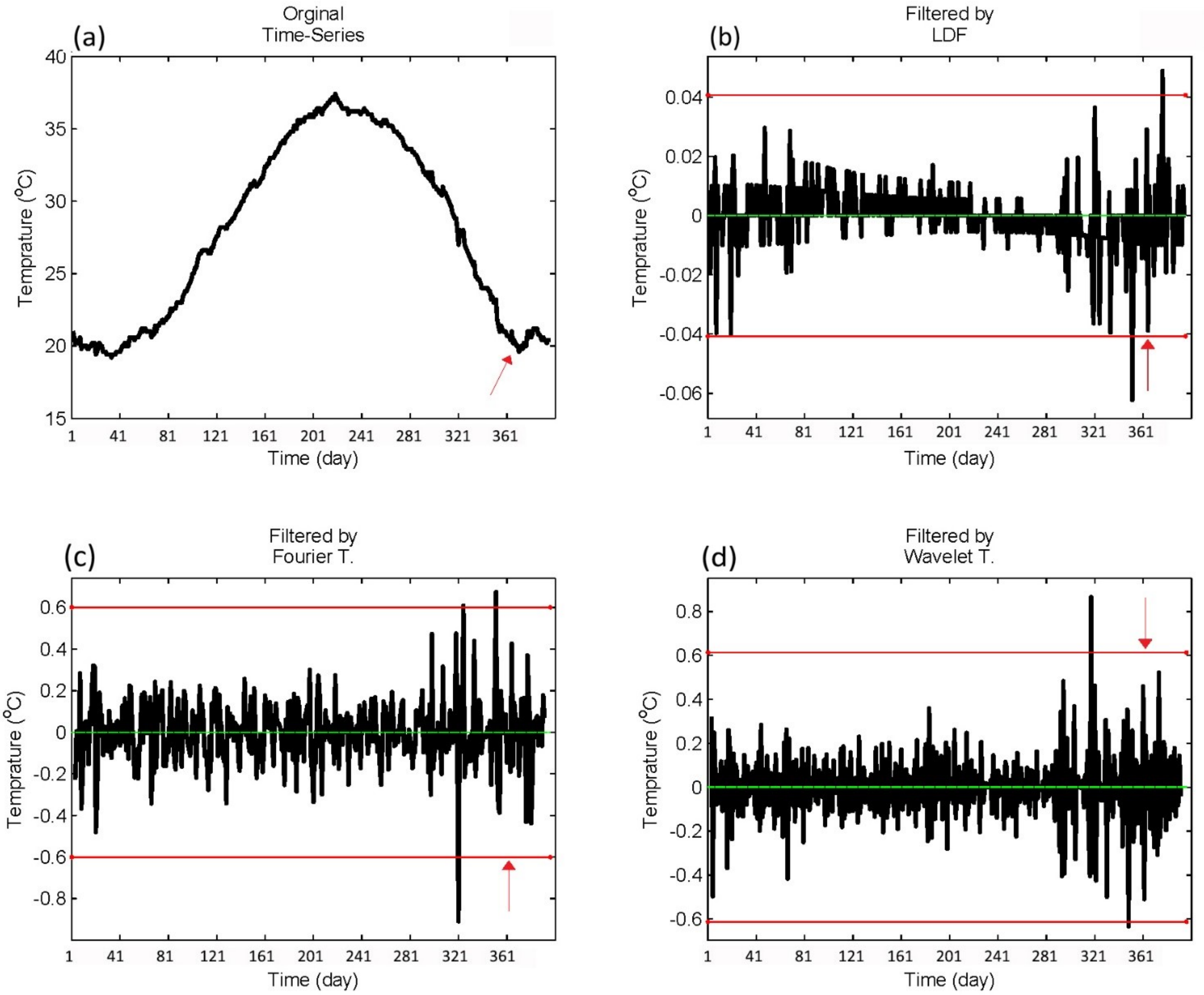

Fig 4. The Bam subsurface temperature time series from the Bam Meteorological station, a) original time-series, b) filtered by LDF, c) filtered by Fourier transform, and d) filtered by wavelet transform (1/1/2003 to 1/2/2004). Time label is based on Julian day.

5. Results and Discussion

In this research, in order to detect thermal anomalies before the earthquake occurrence from the soil temperatures, three types of filters (Fourier, Wavelet, and Logarithmic Differential Filter (LDF)) were applied on the time-series.

The results of all three filters were considered by statistical tendency methods such as the standard deviation and average. The range of normal behavior located between $\bar{S} + \tau\sigma$ (Saradjian and Akhoondzadeh 2010), where $\bar{S}$ is average of time-series, σ and τ are standard deviation and experimental constant respectively. τ is determined by try and error process, and it is a unit less value. This constant can be different in any case studies. In this paper, the τ were calculated 3.0 and 3.8 for the Bam (two stations) and the Zarand time-series correspondingly. The LDF time series are shown in the figures 4.b, 5.b and 6.b. As the figures 4.b and 5.b show in the Bam earthquake thermal anomalies were identified about 20 to 4 days before the earthquake. Furthermore, in the Zarand earthquakes (Fig 6.b), the abnormality appears in the one to five days before earthquakes. The results of the Fourier transform is shown in figures 4.c, 5.c and 6.c. As the figures 4.c and 5.c show, in The Bam earthquake thermal anomaly detected about 20 days before earthquake day. In The Zarand earthquake, the filtered time series (Fig 6.c) show thermal anomalies for two aftershocks but didn't show for the main shock. It should be noted that, in figure 4 to 6, the green lines show the average values, and the red lines show upper and lower boundaries.

The time series those filtered by wavelet transform are shown in the figures 4.d, 5.d, and 6.d. As it turns out form the Bam earthquake (Figs 4.d and 5.d), anomaly was be detected about 20 days before earthquake. Also in the Zarand earthquakes (Fig 6.d), the anomalous behaviors appear 6 to 14 days before earthquakes. Although, abovementioned methods could show temperature changes before some earthquake but the LDF filter can clearly show these changes in the all cases. Despite using the same data source, it can be seen that each method has different lead times and local time of the anomalies which might be related to nature of the methods. The Fourier and Wavelet methods are related to the frequency, so the results of these methods are similar to each other. In the both methods, the signals change to the frequency-domain, and the frequency divided into two group; high and low frequency. The high frequency is eliminated and the signals change back to the time-domain, but the LDF method does not related to the frequency directly. In this method, the signals are logarithmized, therefore the logarithm operator diminished range of data. After that, the derivation operator can make significant difference between the values with higher residuum than the other values, therefore the anomaly will be detected.

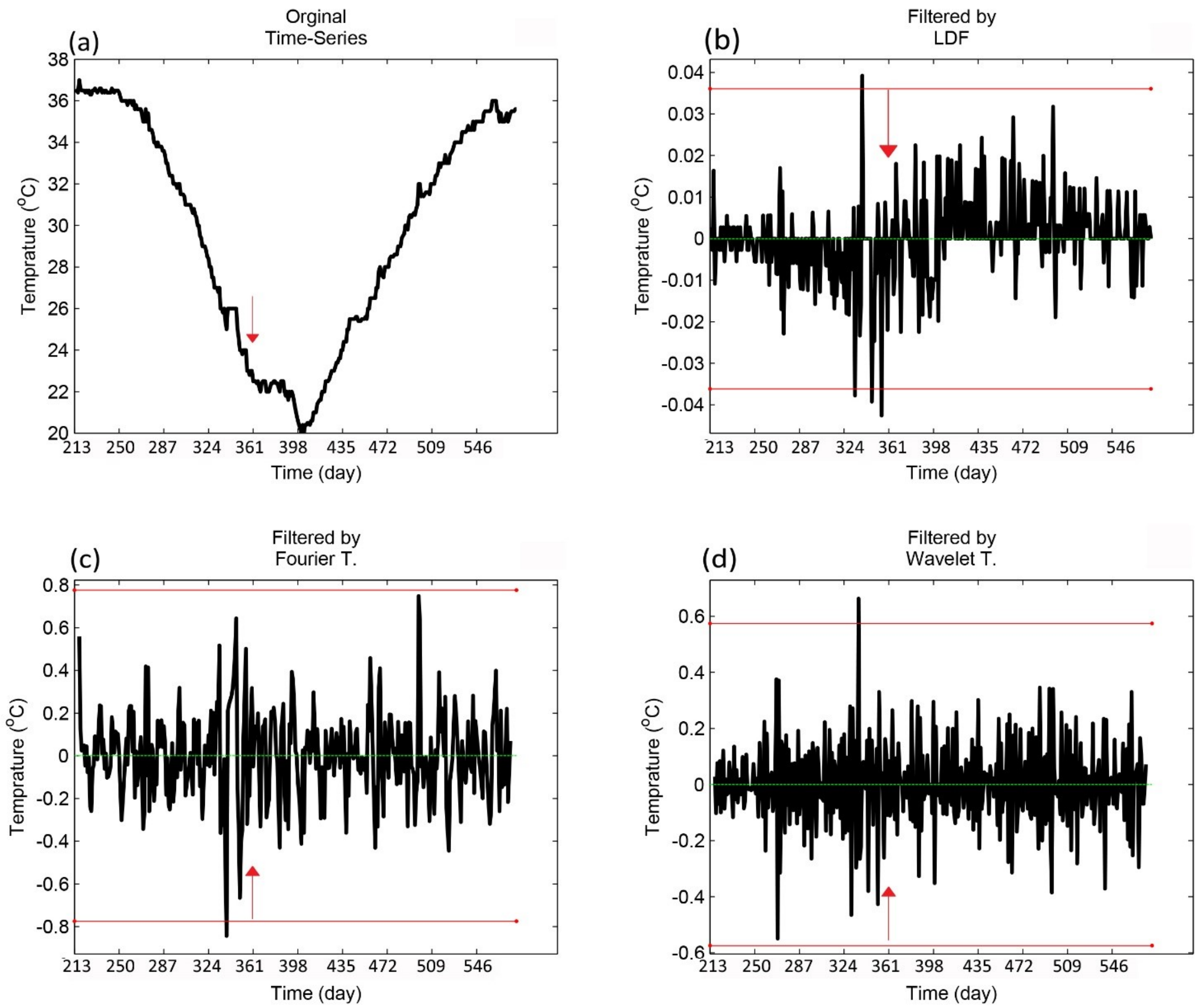

Fig 5. The Bam subsurface temperature time-series from the Jiroft Meteorological station a) original time-series, b) filtered by LDF, c) filtered by Fourier transform, and d) filtered by wavelet transform (1/8/2003 to 30/7/2004). Time label is based on Julian day.

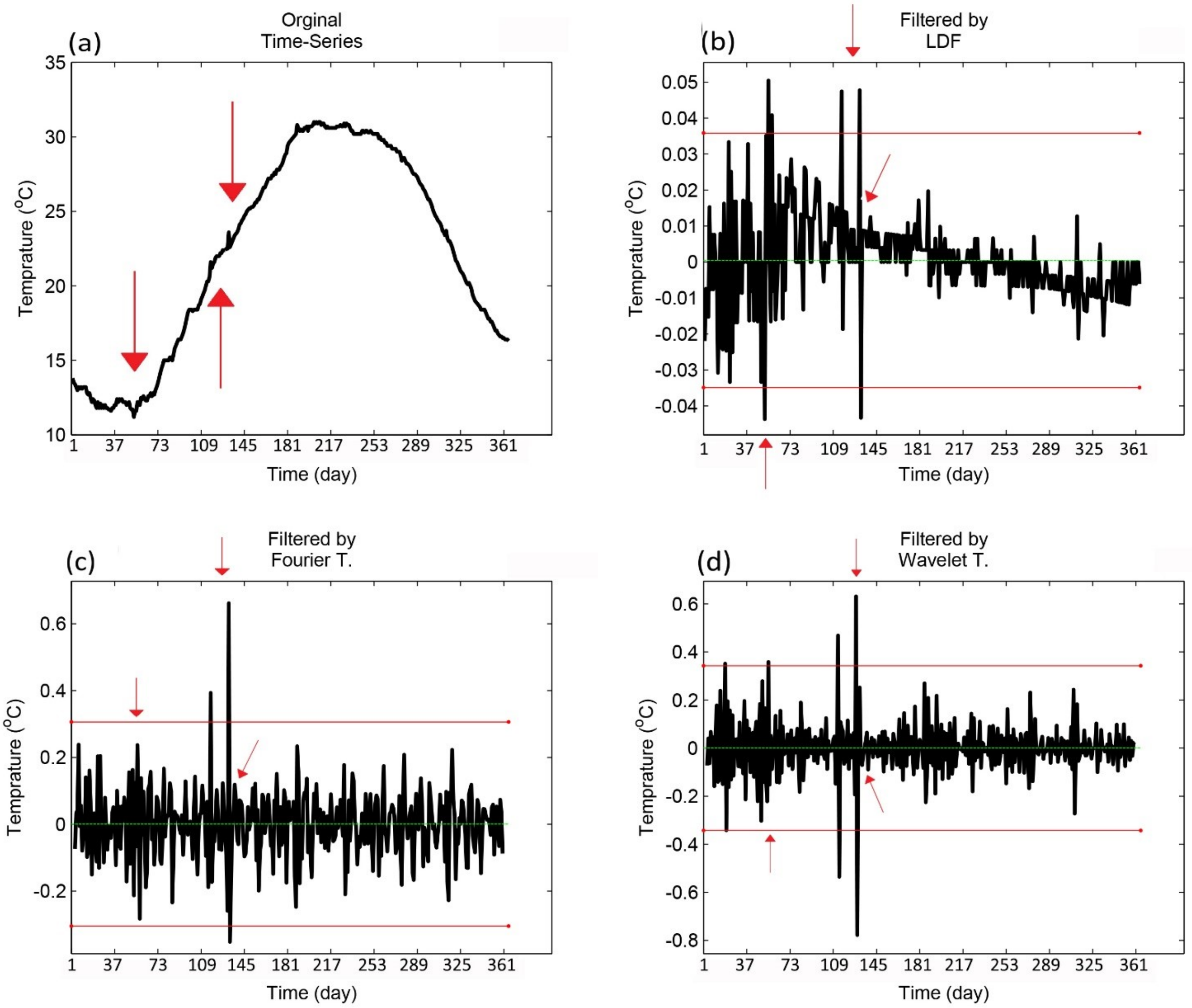

Fig 6. The Zarand subsurface temperature time-series from the Zarand Meteorological station. a) Original time-series, b) filtered by LDF, c) filtered by Fourier transform, and d) filtered by wavelet transform (1/1/2005 to 30/12/2005). Time label is based on Julian day.

6. Conclusion

In this research, the competence of 3 filters -the Fourier, Wavelet and LDF methods- to detect anomalies in soil temperature variations for the Bam and Zarand earthquakes has been shown. In all case studies, the discovered thermal anomalies derived from the buried thermometer in depth 100cm. For all events 3 methods can detect anomaly behavior. Also for the Bam earthquake, notice that Jiroft station there was in Dobrosky radius, the Jiroft meteorological station was considered and the appeared temperature anomaly behavior like the Bam station, and this point can validate the paper's results. The Results indicate that the LDF has high reliability. The LDF that could be considered such as a parameter, might be used in others precursors time-series.

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