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Pre-seismic Anomalies in Remotely Sensed Land Surface Temperature measurements: the Case Study of 2003 Boumerdes Earthquake

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Abstract

Detection of thermal anomaly prior to earthquake events has been widely confirmed by researchers over the past decade. One of the popular approaches for anomaly detection is the Robust Satellite Approach (RST). In this paper, we use this method on a collection of six years of MODIS satellite data, representing land surface temperature (LST) images to predict 21st May 2003 Boumerdes Algeria earthquake. The thermal anomalies results were compared with the ambient temperature variation measured in three meteorological stations of Algerian National Office of Meteorology (ONM) (DELLYS-AFIR, TIZI-OUZOU, and DAR-EL-BEIDA). The results confirm the importance of RST as an approach highly effective for monitoring the earthquakes.

Keywords: Thermal anomaly; Earthquake; RST; MODIS satellite data; LST; Ambient temperature

1. Introduction

Earthquake prediction is an area of intense scientific research; there have been many geophysical and geochemical phenomena that can be considered by the scientists as an earthquake precursor.

The current situation in earthquake space research assumes that this disastrous natural phenomenon highly correlates to Earth's deformation, surface temperature growth, gas and aerosol exhalation, and electromagnetic disturbances in the ionosphere (Tronin, 2006).

The available measurements of temperature and the applicability of remote sensing in monitoring temperature changes have increased the potential of their use as a precursor.

Using thermal detection to predict earthquakes was first proposed by scientists in the early eighties. The usages of satellite thermal Infrared measurements as earthquake predictors have been proposed. The correlations between solid Earth processes and atmosphere/ocean Dynamics prior to strong earthquakes was evident, specifically for a thermal anomaly LST pattern that is apparently related to pre-seismic activity (Ouzounov and Freund, 2004).

Many attempts to define the thermal anomaly and detect the pre-seismic anomalous thermal infrared signal were made. The connection between thermal fluctuations and seismic activity is not sure and other causes could be responsible for the observed thermal anomalies (metrological, observational), (Tramutoli et al., 2001, 2005, 2015).

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Remote sensing methods are widely used for investigations in seismo-active regions, principally through the application of satellite imagery of the Earth's surface in the visible- and near-infrared (IR) part of the spectrum with high spatial resolution (Ouzounov et al. 2006; Saraf et al. 2008; Panda et al. 2007; Akhoondzadeh 2012, 2013).Thus, Remote sensing and the use of thermal Infrared (TIR) sensors can play an important role as an appropriate technical solution for monitoring and measuring the change of the earth's surface temperature.

AVHRR (Advanced Very High Resolution Radiometer located on board NOAA satellite) data was firstly used to study the relationship between soil surface temperature increase "anomalies" and earthquake occurrence. Many studies have been done by using various types of Geo-Stationary and Polar Satellites data. Qiang et al. (1997), using METEOSAT TIR satellite data, began to study several earthquake occurred in China. Tronin et al. (2002, 2004) analysing a sequence of AVHRR TIR data, identifying the presence of positive pre-seismic TIR anomalies. (Huang et al. 2008), using thermal infrared data provided by MODIS sensor studied the relation between thermal anomalies and seismic activity around the epicentre of the Sichuan (China) earthquake (occurred on May 12, 2008: MS~8.0). The results showed that the temperature became higher 3-5 degree prior to the earthquake and the anomaly disappeared after the earthquake.

The RST approach proposed by Tramutoli et al. (1998) is described to identify space-time signal. A statistical definition of thermal infrared anomaly is given and proposed as a suitable tool for satellite thermal infrared surveys in seismically active regions (Tramutoli et al. 2005). This approach was used by a number of researchers to study the existence of space-time anomalies before the seismic events; RST was successfully applied for several earthquakes, in all continents of the world. 6th April 2009 Abruzzo earthquake (Italy) (Pergola et al. 2010), 20 September 1999 Chi-Chi earthquake (Taiwan) (Genzano et al. 2015). RST applications have been already successfully implemented by using validation/confutation approach, dedicated to determine existence of thermal infrared anomaly.

Many seismic events have been studied by applying the RST approach. Firstly, Tramutoli in the case of Irpinia-Basilicata earthquake (Novembre 23, 1980:M ~6.9) applied robust satellite technique with NOAA AVHRR Data. Filizzola et al. (2004) in the case of the Athens earthquake (Septembre 7, 1999), demonstrated the possibility to reach S/N ratios up to 1.5 by using daily analysis. Corrado et al. (2005) established the relation between TIR anomalies and earthquake of medium-low intensity occurred in Greece and Turkey. The connection between thermal anomaly and the earthquake was confirmed in several applications (Tramutoli et al., 2005; Genzano et al., 2007, 2015; Pergola et al., 2010; Eleftheriou et al., 2015).

Algeria is a North African country. It is situated in a seismically active region; there are eventually/in average five of moderately severe earthquake every year. The most severe earthquake occurred in recent twenty years was the Boumerdes earthquake of May 21st, 2003 (M=6.8). That disastrous event resulted in more than 2266 casualties. In addition, 10261 people injured, and 200000 homeless. The Reports indicate that more than 1243 buildings were completely or partially destroyed. Infrastructures were predictably damaged in Algiers, Boumerdes, Réghaia and Thénia (Curtis, 2004).

This event is addressed in (Aliano et al., 2007) with METEOSAT Data. In this paper, we apply the Robust Satellite Technique method to EOS MODIS (Moderate Resolution Imaging Spectroradiometer) data around the epicentre of Boumerdes earthquake in Algeria, in order to study the existence of thermal anomaly before the earthquake occurrence, and the connection with the seismic events. MODIS satellite data is characterized by its low spatial resolution (1 km), and MODIS products are all archived.

In this work, Six years (from 2000 to 2005) of daily MODIS land surface temperature have been analysed and pre-processed. In order to characterize the thermal infrared signal behaviour, the results will be discussed and completed with the analysis of the variations of air temperature measurements of three stations around the epicentre of earthquake of 21st May 2003 Boumerdes (Algeria).

2. Materials and Methods

2.1 Study area

Geographical location of the study area and sites considered in this study are presented in Figure (1).

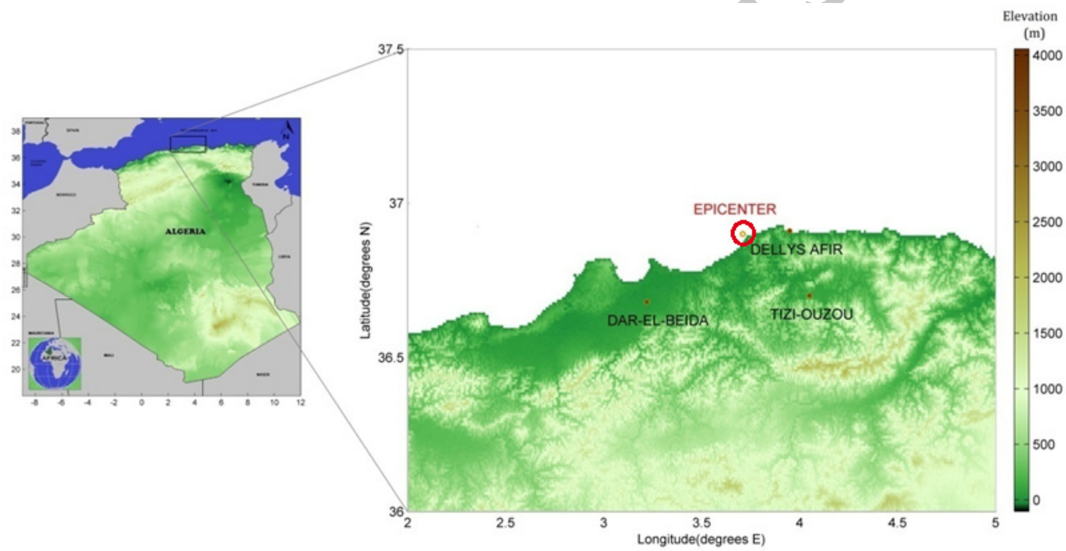


Fig. 1. Location of the main-shock epicentre (red circle) and meteorological stations

2.2 Data

Two kinds of data are used in this study: (i) Satellite data is obtained from MODIS satellite, and (ii) Observed data which consists of ambient temperature.

2.2.1 Satellite data

MODIS data for this work comes mainly from the website of NASA (http://earthexplorer.usgs.gov), MODIS image space resolution is 1 km x 1 km.

This research covers the event of 2003 Boumerdes Earthquake (Magnitude Mw= 6.8) which occurred on May 21 at 19:44:21 local time in northern Algeria. It was having its epicentre at 3.71 E 36.90 N.

We used daily night time LST (Land surface temperature) data for all north of Africa region, for the period (2000-2005), extracted from the 1 km spatial resolution gridded v.5 MOD11A1 LST product.

The tile is labelled from top to bottom and from left to right starting at 00. A tile contains 1200 x 1200 grids. Two tile (h17v05 and h18v05) neighbours are mosaicked together in order to study all the north of Algeria. Example of LST data used is represented in Fig. 2.

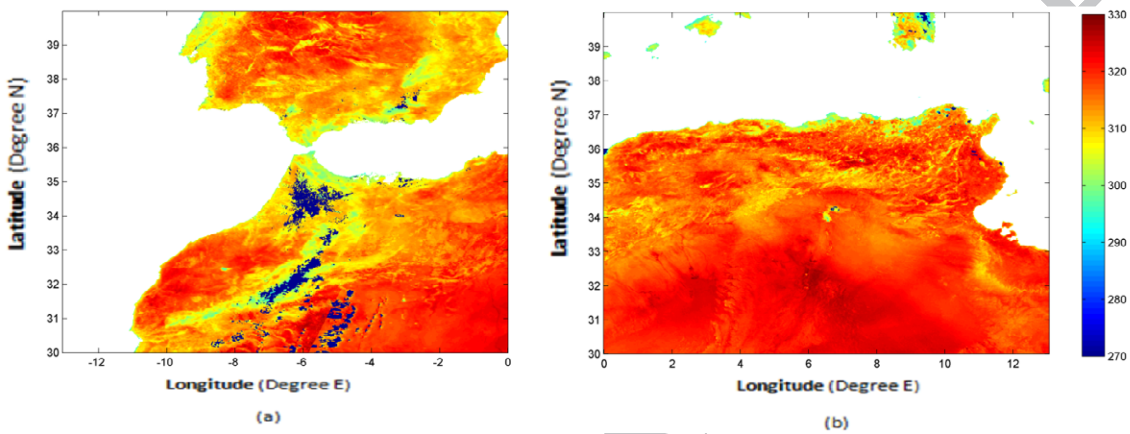


Fig. 2. LST image 30/06/2015 Algeria east tile (a) and west tile (b)

2.2.2 Observed Data

In order to study the connection between thermal anomaly and ambient temperature variations, the air temperature derived from meteorological stations around the earthquake epicentre has been taken into account.

Fig. 3, shows ambient temperature measurement of three meteorological stations (DELLYS AFIR, TIZI OUZOU, and ALGER DAR-EL-BEIDA) around earthquake epicentre (longitude 03.71, latitude 36.90) (Table 1).

Table 1
Meteorological stations around Boumerdés earthquake epicentre.

Station :	**Latitude**	**Longitude**
ALGER DAR-EL-BEIDA	36°41 N	03°13 E
DELLYS AFIR	36°55 N	03°57 E
TIZI OUZOU	36°42 N	04°03 E

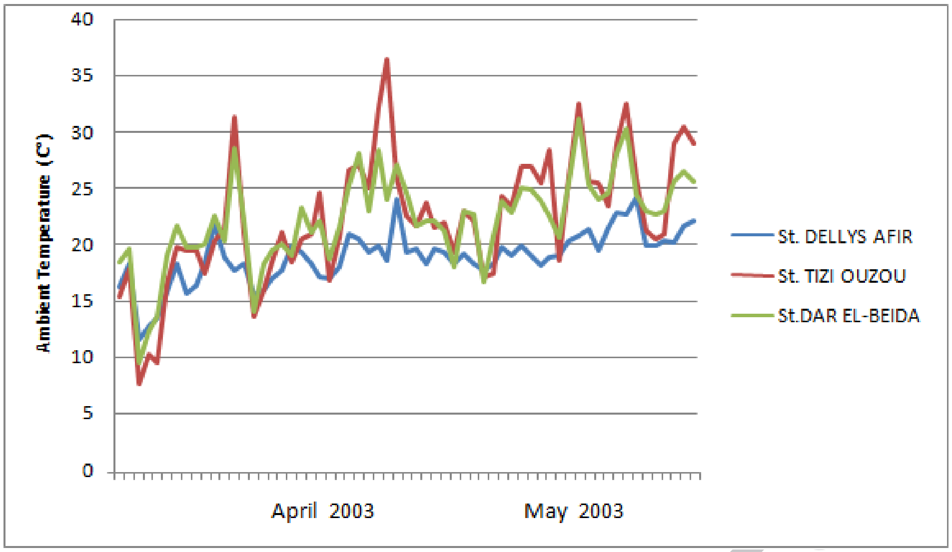


Fig. 3. Ambient temperature measurement variations of three meteorological stations

3. Methodology

3.1 Thermal anomaly definition

The Thermal infrared radiance is computed from satellite data using four parameters as follows (Tramutoli et al., 2005):

$$R_{TIR}(r,t) = f\ [\epsilon_{TIR}(r,t), \Im_{TIR}(r,t), T_S(r,t), \theta_{SAT}(r,t)] \qquad (1)$$

Where,

$\epsilon_{TIR}(r,t)$ is spectral emissivity, and $\Im_{TIR}(r,t)$ is Spectral transmittance, and $T_S(r,t)$ is surface temperature, and $\theta_{SAT}(r,t)$ is satellite zenithal angle.

3.2 Robust satellite technique (RST)

RST technique is an approach based on Robust AVHRR Technique (RAT). It was first proposed by Tramutoli (1998) and used for monitoring environmental disasters like volcanoes, floods, forest fires and seismic activities. Due to its simplicity and efficiency, this approach knew wide acceptance from the community. It has been used to detect thermal anomaly before earthquake by: (Tramutoli et al., 2005; Aliano et al., 2007; Pergola et al., 2010; Genzano et al., 2015; Pan Xiong et al., 2015; Eleftheriou et al., 2015).

The RAT (Robust AVHRR Technique) approach is an automatic change-detection scheme that identifies signal anomalies in the space-time domain as deviations from a normal state that has been preliminarily identified (and usually given in terms of time average and standard deviation) on the basis of satellite observations collected during several years, under similar observational conditions for each image pixel (Lacava et al., 2006). The RST approach is based on a multi-temporal analysis of historical data set of satellite observations acquired in similar observational conditions (e.g., same month of the year, same hour of the day, same sensor, etc.) (Eleftheriou et al., 2015).

Anomalous thermal infrared patterns are identified by using a specific index, RETIRA (Robust Estimator of TIR Anomalies) to be computed on the image at hand as in the equation below (Tramutoli et al., 2005; Genzano et al., 2015):

$$\otimes_V \ (r,t) = \frac{V(r,t) - \mu_V(r)}{\sigma_V(r)} \qquad (2)$$

Where r represents location coordinates on a satellite image, t is the acquisition time of image, and $V(r,t) = \mathrm{T(r,t)} - \mathrm{T(t)}$, is the value of the difference between the punctual value of the land brightness temperature $\mathrm{T(r,t)}$ At the location r (x,y) and acquisition time t, and its spatial average T (t) over the area of interest;

$\mu_V(r)$ and $\sigma_V(r)$ are the time average value and the standard deviation of $V(r,t) \equiv LST(r,t)$-$LST(t)$ obtained for each location r (x,y) using cloud free records belonging to a homogeneous data set of observations collected in different years in similar (same month, same time of the day, etc.) observational conditions.

$$\mu_V(r) = \frac{1}{N} \sum_{t\in\tau}^{N} V(r,t) \qquad (3)$$

$$\sigma_V(r) = \sqrt{\frac{1}{N} \sum_{t\in\tau}^{N} (V(r,t) - \mu_V(r))^2} \qquad (4)$$

For its application to seismic area monitoring, different variables have been used:

$$v(r,t) \equiv \left[\begin{array}{c} T(r,t) \\ \Delta T(r,t) \equiv \mathrm{T(r,t)} - \mathrm{T(t)} \\ \Delta LST(r,t) \equiv \mathrm{LST(r,t)} - \mathrm{LST(t)} \end{array} \right.$$

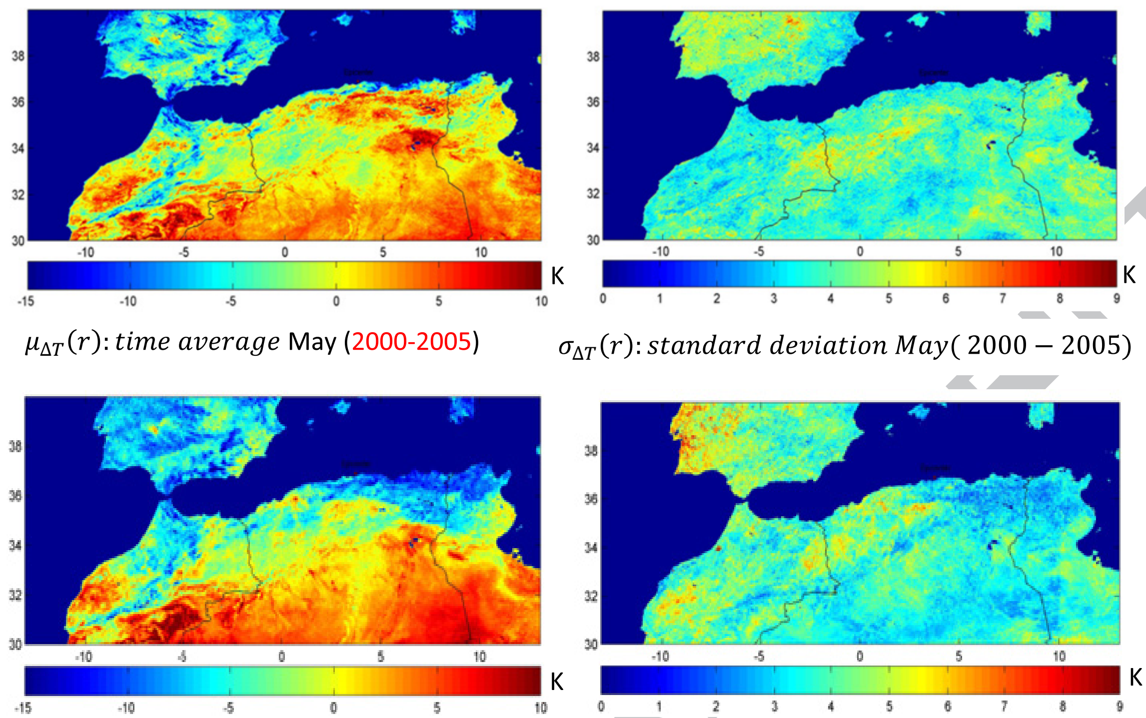
Where T(r,t) is simply the TIR radiance at the sensor, LST is a specific product of satellite data analysis, which is expected to give , an estimate of the surface temperature corrected by the variable contribute of water vapour in the atmosphere (Di Bello et al., 2004; Tramutoli et al., 2013).

T(t) and LST(t) are spatial averages of T(r,t) and LST(r,t) computed in place on the image at hand considering cloud- free pixel only.

4. Results and discussion

The different steps of process from data post-processing, to all computations and spatial mapping were performed via a proper computer program in MATLAB® software (Q uarteroni et al., 2014).

$\mu_{\Delta T}(r)$ And $\sigma_{\Delta T}(r)$ are computed at the same time and location of the day for all, both are two reference images, which represent the expected normal behaviour of the signal at each location (r) of the scene in the same observational conditions of the image. See Fig. 4.



$\mu_{\Delta T}(r): time\ average$ May (2000-2005) $\sigma_{\Delta T}(r): standard\ deviation\ May(\ 2000-2005)$

$\mu_{\Delta T}(r): time\ average$ April (2000-2005) $\sigma_{\Delta T}(r): standard\ deviation\ April\ (2000-2005)$

Fig. 4. Reference fields of investigated area for the month of May and April calculated during period 2000-2005.

$\Delta T(r,t) - \mu_{\Delta T}(r)$: Represent the signal to be investigated for its possible relation with seismic activity.

$\sigma_{\Delta T}(r)$: Local natural or observational variability of signal including all sources of variability as historically observed at the same site in similar observational conditions (sensor, time of day, month...etc).

RETIRA index $\otimes_{\Delta T}\ (r,t)$ was computed for all cloud free pixels using six years (2000-2005) of MODIS data.

4.1 Validation

We analysed the resulting images by applying RETIRA index to identify the correlation between time, location and magnitude of earthquake and existence of thermal anomalies.

In Fig. 5, we present the ratios of clouds in images during, the period of study. All very cloudy images were not included. (i.e. greater than 70% cloudy pixels in land surface of the image) .

In the validation period, all collected images are accepted because there is no image with more than 70% cloudy pixels. See Fig. 5.

Where $\otimes_V\ (r,t)$ >2.5, the pixel considered as anomalous, and coloured by blue.

For The distance of thermal anomalies about to the epicentre, we consider Dobrovolsky distance:

The zone of effective manifestation of the precursor deformation is a circle with the centre in the epicentre. The radius of the circle was calculated from the equation: where M is the magnitude (Dobrovolsky et al., 1979), see Fig. 6.

After observing and analysing the results, we identified many locations with RETIRA index and those pixels may be considered as thermal anomaly.

- Firstly the last week of April from 24, to 30 April 2003 (i.e one month before the main shock of Boumerdes earthquake) anomalous pixels around the epicentre earthquake, the anomalies detected are persistent in time (see, Fig. 7).
- The first four days of May, we identified a thermal anomaly in Bechar[†] region but, it is too far from the epicentre of the earthquake of 21st may 2003. Therefore, we don't take it into consideration because the distance is greater than Dobrovolsky distance.
- Two weeks before Boumerdes earthquake, appearance and disappearance of thermal anomalies were observed around the epicentre region on 6th, 8th, 11th, 12th and 15th of May (not persistent). Additionally they were observed also, two days before the earthquake, just close to the epicentre. See Fig. 9.
- After the shock, a new anomaly appeared in 24 and 29 May (three and eight days after the main shock respectively).This is depicted in Fig. 9.

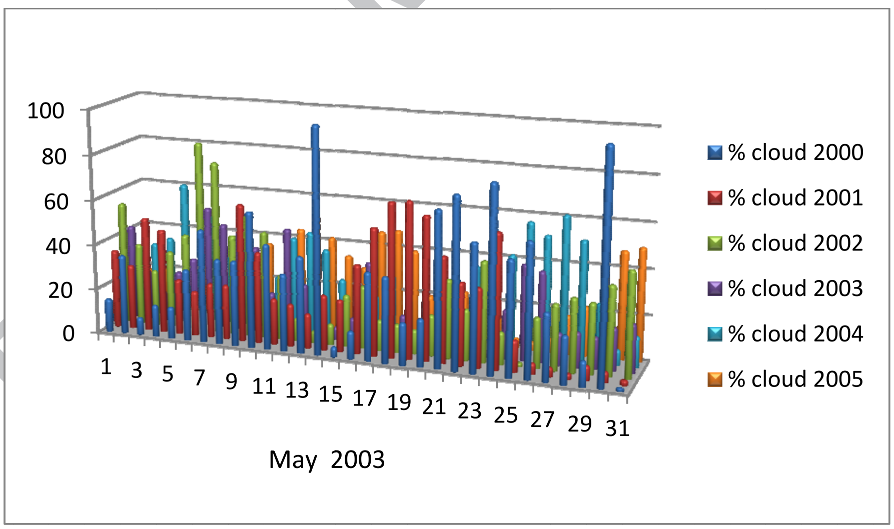


Fig. 5. Ratio of clouds in images during, the years: 2000-2005.

[†] Béchar is located in the north-western region of Algeria, roughly 800 kilometres of the epicentre.

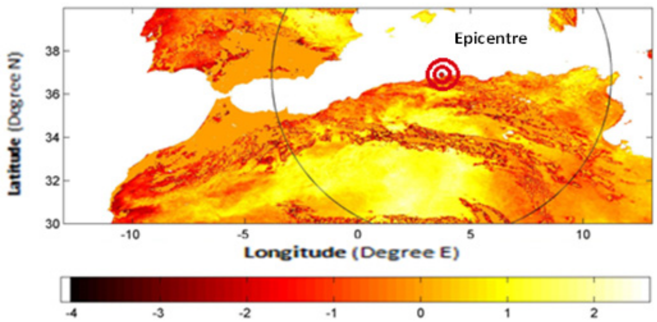


Fig. 6. Result of RETIRA index computation on the investigated area in 31 May 2003. The radius of the black circle represents Dobrovolsky distance. The epicentre is represented by tow red circles.

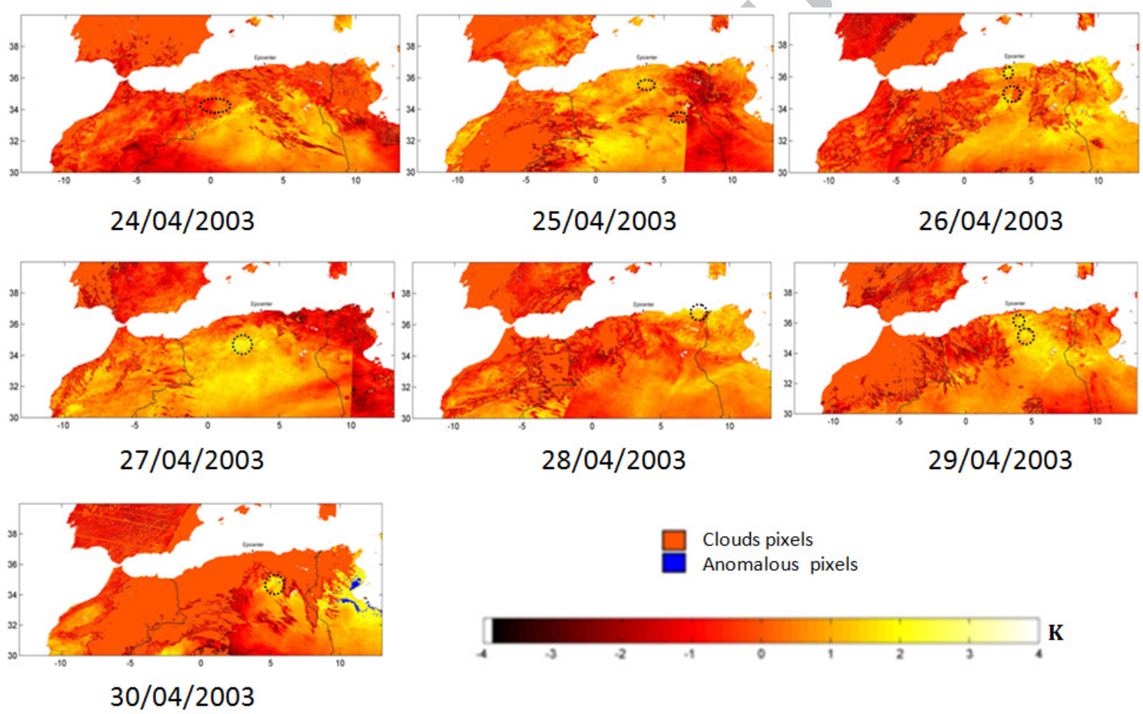


Fig. 7. Results of RETIRA index computation on the investigated area in April 2003. Anomalous pixels with $\otimes_V \ (r,t)$ > 2.5 depicted with blue and circled

All circled area in Fig. 7 are zoomed in for more details in the region of anomalous pixels, we can observe the variation of the values according to the colour palette (see Fig. 8).

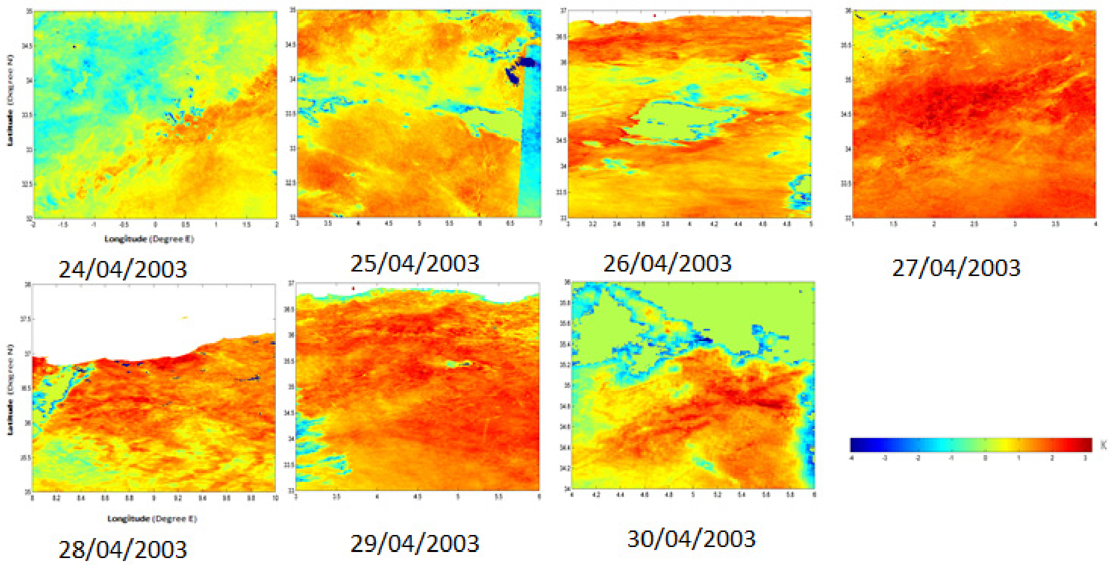


Fig. 8. Zoomed details in circled areas represented in the results of RETIRA index computed on the investigated area in April 2003.

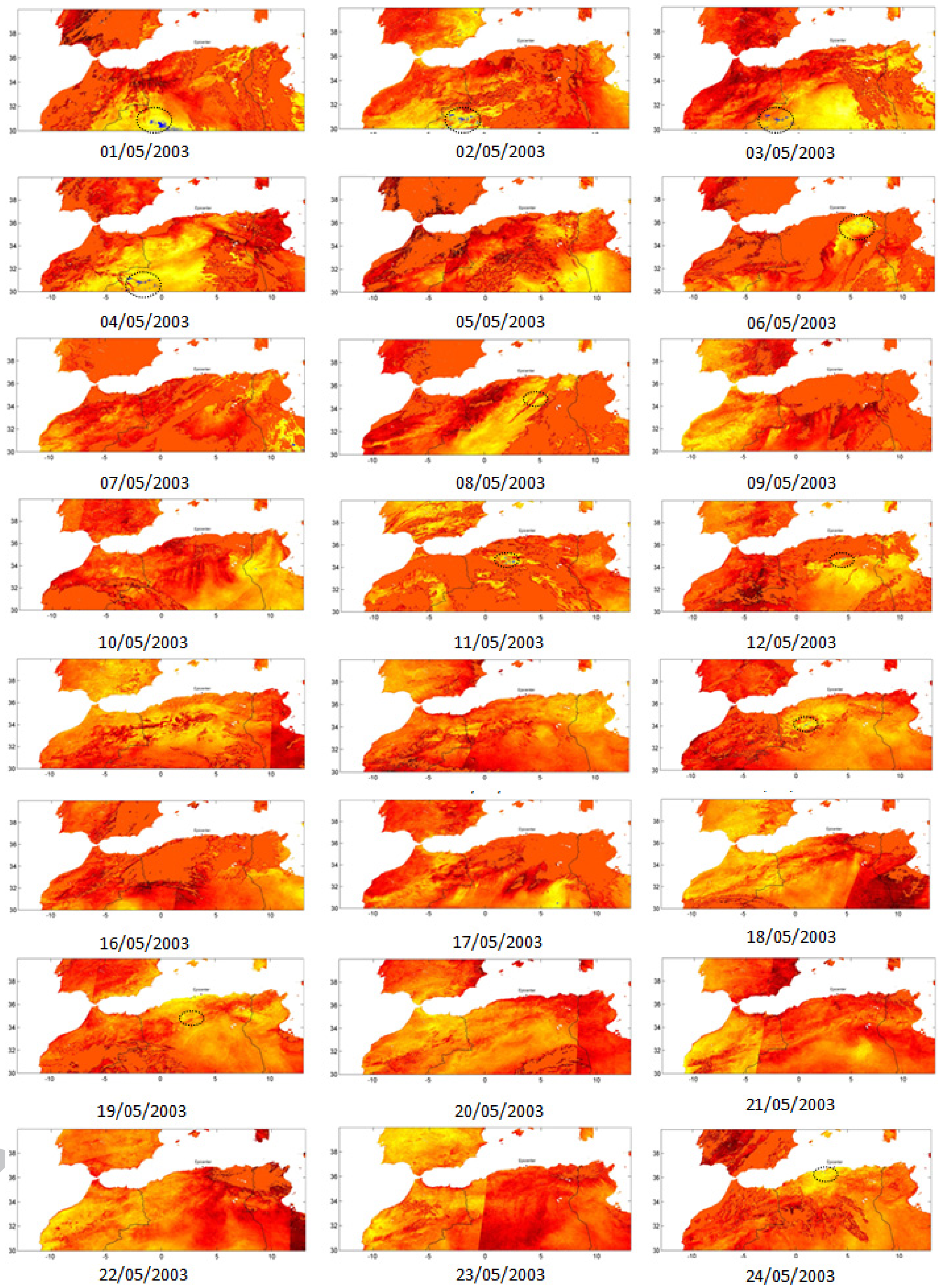


Fig. 9. Results of RETIRA index computation on the investigated area in May 2003. Anomalous pixels with $\otimes_V\ (r,t) > 2.5$ depicted with blue and circled.

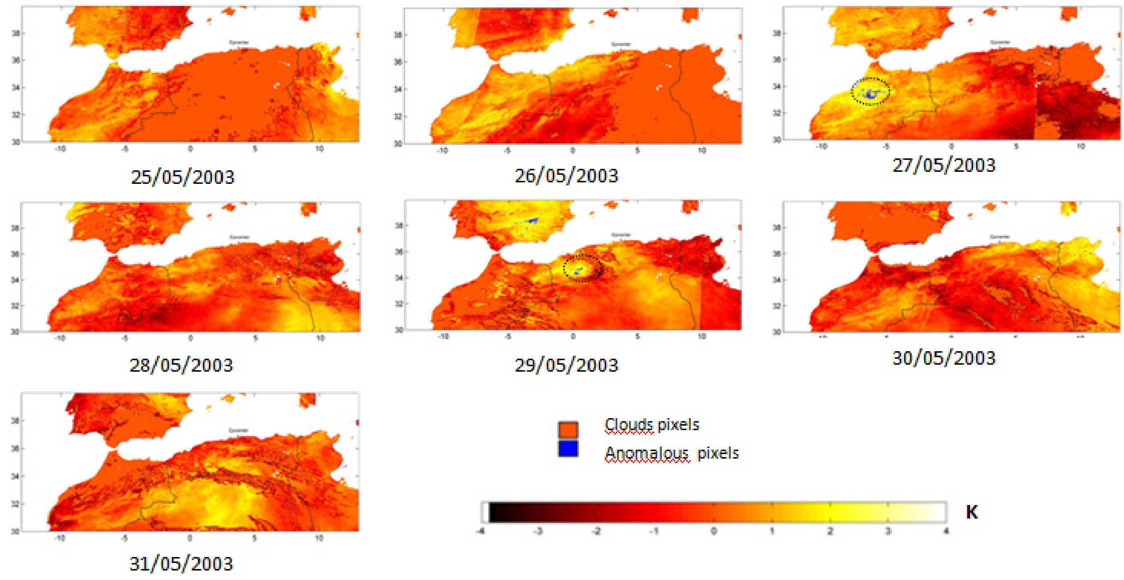


Fig. 9. Continued

The analysis of ambient temperature of three stations in the month of the earthquake occurrence, prior to the events shows that an augmentation in temperature in the same time of thermal anomaly was detected before the earthquake especially in Tiziouzou station, see Fig. 10.

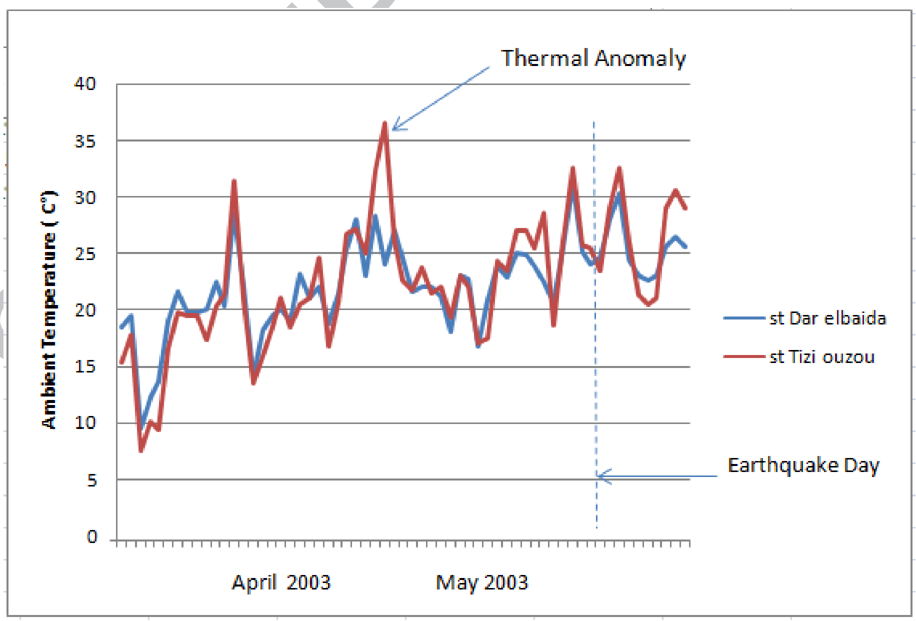


Fig. 10. Variations of ambient temperature in two meteorological station (Dar Al-Beida and Tizi ouzou) and abrupt temperature increases detected before 21st May 2003 earthquake Boumerdes (Algeria).

Fig. 10 represents the variations of ambient temperature in two meteorological stations during two months (April and May 2003). The measurement's values in TIZI OUZOU and Dar EL-beida station represented with red and blue curve respectively. The earthquake day is represented as vertical line. It should be mentioned that, this period of the year is not usually recognized by any increase in temperature. It can be seen that we have a surge in temperature three times before the earthquake day. From 11 to 13 April at the first time, secondly from 24 to 30 April and two days before the earthquake. In all cases recorded values were greater than 30 degrees.

These observations coincide with the results obtained by applying Robust Satellite Technique with MODIS satellite data. The same period of thermal anomaly detected by RST in the validation phase has been observed in ambient temperature variations.

4.2 Confutation phase

According to Table 2, no earthquake greater than 5 in magnitude was reported in the period 2001-2002. We analysed the result of RETIRA index to identify the existence of TIR anomalies in the seismic region of Boumerdes 21st May 2003 earthquake even in a relatively quite period.

5/2003

Table 2
Large and Moderate Earthquakes with Thrust Mechanism along the Tell Atlas (Belabbes et al., 2009).

location	Date	Longitude	Latitude(deg)	M_w
Orléansville	9 Sep 1954	1.47	36.28	6.7
El asnam	10 Oct 1980	1.36	36.18	7.3
Tipaza	29 Oct 1989	2.92	36.84	5.9
Mascara	18 Aug 1994	-0.03	35.40	5.7
Ain Temouchent	22 Dec 1999	-1.45	35.34	5.7
Beni ourtilane	10 Nov 2000	4.69	36.71	5.7
Zemmouri	21 May 2003	3.65	36.83	6.8

In order to examine the reliability of the analysed results for the Boumerdes earthquake, we used the same procedure to perform a confutation analysis on a relatively seismically unperturbed period: but in different years (April and May 2002)

- Two images (06/05/2002 and 07/05/2002) have been removed, a cause the cloud average percent is (>70%).

With the same conditions and RETIRA index $\otimes_V \ (r,t) > 2.5$ have been used to identify anomalous pixels in the images.

In Fig. 11, the appearance of anomalous pixels observed in four times:

- First, in 15/05/2002 we observe anomalies appear in the western region (Morocco) in the borders of Atlantic Ocean but they are not persistent (only one day).
- Second time, on 24/05/2002 in the same region.
- The third appearance of anomalies, in 27/05/2002 in the eastern region (Tunisia).

- Finally, the anomalies appear on May 30th 2002 in the region of epicentre earthquake of the 21st May 2003 Boumerdes (not persistent).

After the analysis of those results, we conclude that:

- Anomalies observed in the confutation phases are not persistent in time and are quite isolated in the spatial domain. So, it is possible that other causes contribute to form those anomalous pixels. The RETIRA index is not protected from the abrupt occurrence of signal outliers related to very *llocal*[‡] natural / observational conditions.

[‡] According to Tramutoli (1998) the double l is used to specify not only a certain place (r) but also a certain time (t).

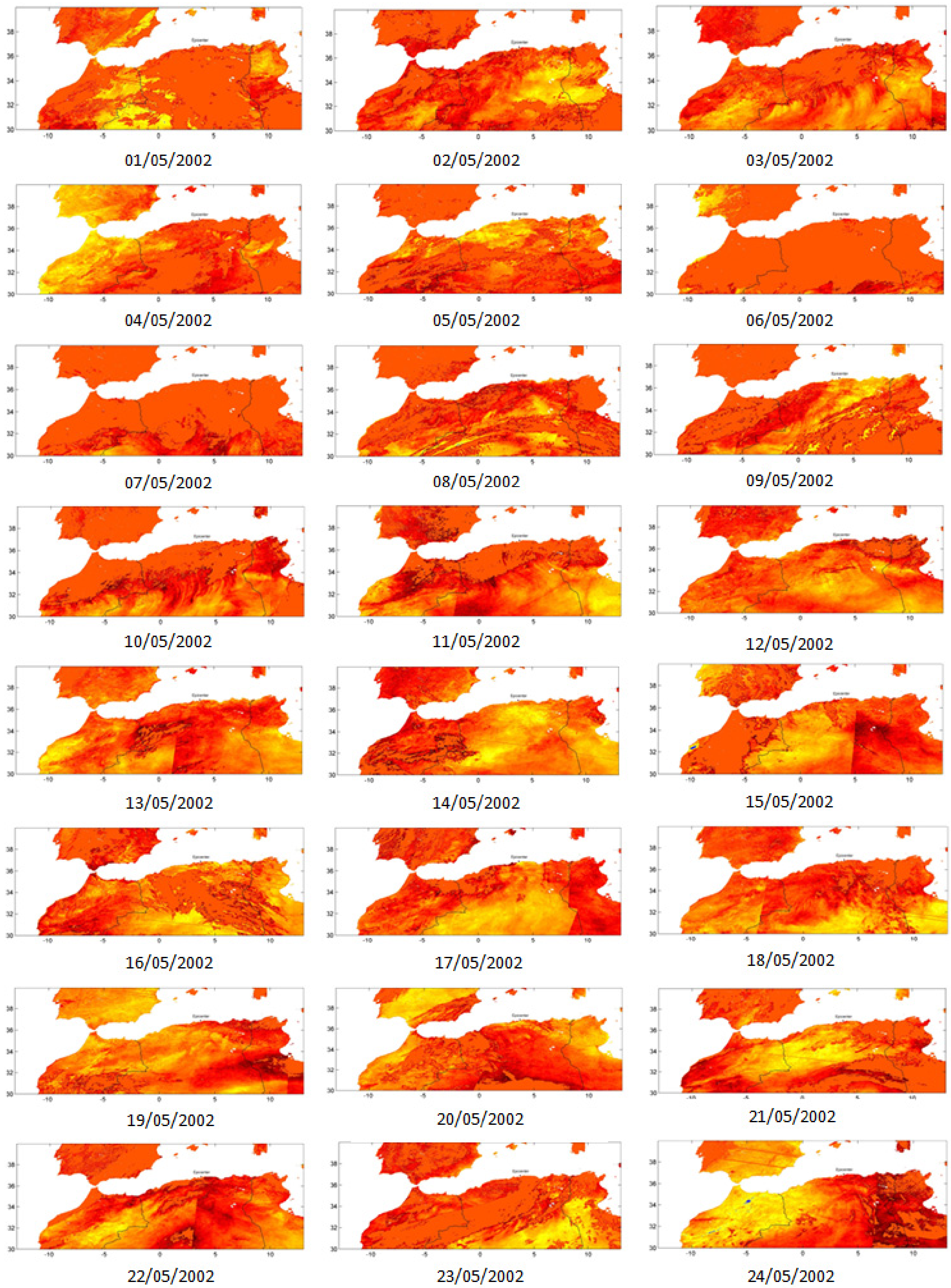


Fig. 11**.** Results of RETITA index computation on the investigated area in May 2002. Anomalous pixels with $\otimes_V \ (r,t) > 2.5$ depicted with blue and circled.

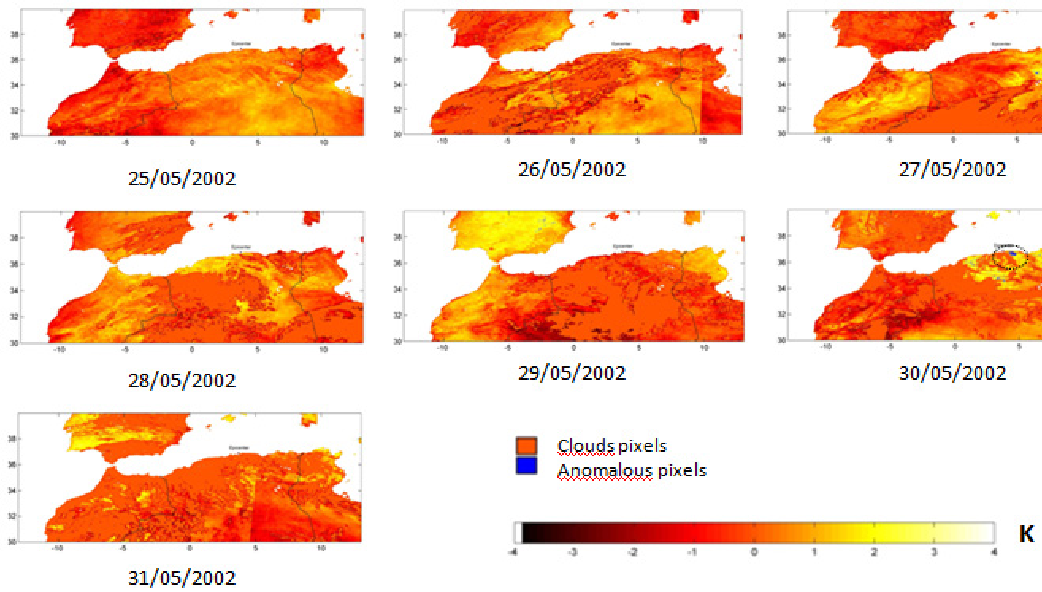


Fig. 11. Continued

5. Conclusion

In this paper, we used MODIS data from 2000 to 2005, to build a database of MODIS land surface temperature (LST) images. By using this data and a robust satellite data analysis approach, we seek to detect thermal anomalies before the 2003 Boumerdès earthquake. In the same context, the anomalies detected are completed by the analysis of the temperature evolution in neighbouring meteorological stations. The daily mean air temperatures in three nearest stations to the epicenter of Boumerdès earthquake were used.

In the validation phase, we detected a thermal anomaly persisting for a week during the month preceding the earthquake (from 24 April to 30 April) and in the month of earthquake, two days before the events, In the confutation phase the observed anomalies were not persistent in time and spatially isolated.

The analysis of the ambient temperature of three stations in the month of the earthquake occurrence and thermal anomalies detected with Robust Satellite Technique, prior to the earthquake, shows that augmentation in temperature in the same time of thermal anomaly was detected before the earthquake especially in Tiziouzou (Algeria) station.

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