Reducing atmospheric noise in RST analysis of TIR satellite radiances for earthquakes prone areas satellite monitoring.

Manuscript Number: JPCE-D-14-00121R2

Article Type: SI: EQS precursors/prediction

First Author: Mariano Lisi.

Order of Authors:Mariano Lisi[1,3]; Carolina Filizzola[2]; Nicola Genzano[1]; Rossana Paciello[2]; Nicola Pergola[2];Valerio Tramutoli[1,2,3]

Abbreviation: M. Lisi[1,3], C. Filizzola[2], N. Genzano[1], R. Paciello[2], N. Pergola[2], V. Tramutoli[1,2,3]

(1) University of Basilicata, School of Engineering; via dell'Ateneo Lucano, 10, 85100 Potenza-Italy;
(2) IMAA-CNR Institute of Methodologies for Environmental Analysis, National Research Council, Tito Scalo (Potenza), Italy; C.da S. Loja, 85050 Tito Scalo-Italy;
(3) International Space Science Institute, Bern Hallerstrasse 6, 3012 Bern Switzerland.

Corresponding Author: Dr. Valerio Tramutoli,e-mail address: valerio.tramutoli@unibas.it
Corresponding Author's Institution: University of Basilicata, via dell'Ateneo Lucano, 10, 85100 Potenza-Italy

Abstract

Space-time fluctuations of the Earth's emitted Thermal Infrared (TIR) radiation observed from satellite from months to weeks before an earthquake are reported in several studies. Among the others, a Robust Satellite data analysis Technique (RST) was proposed (and applied to different satellite sensors in various geo-tectonic contexts) to discriminate anomalous signal transients possibly associated with earthquake occurrence from normal TIR signal fluctuations due to other possible causes (e.g. solar diurnal-annual cycle, meteorological conditions, changes in observational conditions, etc.). Variations in satellite view angle depending on satellite's passages (for polar satellites) and atmospheric water vapour fluctuations were recognized in the past as the main factors affecting the residual signal variability reducing the overall Signal-to-Noise (S/N) ratio and the potential of the RST-based approach in identifying seismically related thermal anomalies. In this paper we focus on both factors for the first time, applying the RST approach to geostationary satellites (which guarantees stable view angles) and using Land Surface Temperature (LST) data products (which are less affected by atmospheric water vapour variability) instead of just TIR radiances at the sensor.
The first results, obtained in the case of the Abruzzo earthquake (6 April 2009, M_W~6.3) by analyzing 6 years of SEVIRI (Spinning Enhanced Visible and Infrared Imager on board the geostationary Meteosat Second Generation satellite) LST products provided by EUMETSAT, seem to confirm the major sensitivity of the proposed approach in detecting perturbations of the Earth's thermal emission a few days before the main shock. The results achieved in terms of increased S/N ratio (in validation) and reduced "false alarms" rate (in confutation) are discussed comparing results obtained by applying RST to LST products with those achieved

by applying an identical RST analysis (using the same MSG-SEVIRI 2005-2010 data-set) to the simple TIR radiances at the sensor.

Keywords: Abruzzo seismic sequence, thermal anomalies, TIR satellite radiances, RST, LST.

1. Introduction

Over the last two decades several studies (see, for example, Gorny et al., 1988; Qiang and Dian, 1992; Tronin, 1996; Qiang et al., 1997; Tronin et al., 2002; Ouzounov and Freund, 2004) reported the appearance of space-time anomalies in TIR (Thermal Infra-Red) satellite imagery before (from weeks to days) severe earthquakes. Such anomalies, observed near the place and time of an earthquake, were attributed to different genetic causes like the increase of green-house gas (such as CO_2, CH_4) emission rates (e.g. Qiang et al., 1991; Tronin, 2000; Tramutoli et al., 2001a, 2009, 2013, and references therein), the modification of ground water regime (e.g. Hamza, 2001), and more complex phenomena (e.g. Pulinets et al., 2002, 2006, 2007; Ouzounov and Freund, 2004) all including, among the others, pre-seismic effects, increased near surface temperature and TIR emission.

Despite numerous studies reporting pre-seismic TIR anomalies, rigorous definitions of TIR anomaly have only recently been given (e.g. Tramutoli et al., 2001a, Ouzounov and Freund, 2004, Piroddi and Ranieri, 2012). In the last decade more attention was paid to other (e.g. meteorological) possible causes of TIR anomalies and to their possible occurrence also in the absence of significant seismic activity (confutation). Among other methods, the Robust Satellite Technique (RST, Tramutoli et al., 2005, 2007) – formerly RAT (Robust AVHRR[1] Technique, Tramutoli, 1998) – was successfully applied to investigate possible relations between earthquake occurrence and space-time fluctuations of the Earth’s emitted TIR radiation observed from satellite.

The RST approach is based on a statistical definition of “TIR anomalies” and on a suitable method for their identification even in very different natural (e.g. related to atmosphere and/or surface) and observational (e.g. related to the time/season of a satellite pass) conditions. Since its first application to the study of earthquakes the RST approach has been used with a validation/confutation method to verify the presence/absence of anomalous space-time TIR transients in presence/absence of seismic activity.

Several earthquakes in different continents (Europe, Asia, America and Africa), in various geo-tectonic settings (compressive, extensional, and transcurrent) and with a wide range of magnitudes (from 4.0 to 7.9) were analyzed applying the RST approach to different satellite TIR sensors (e.g. Tramutoli et al., 2001b, 2005, 2009; Di Bello et al., 2004; Filizzola at al., 2004; Corrado et al., 2005; Genzano et al., 2007, 2009a; Aliano et al., 2007, 2008a, b, c; Lisi et al., 2010; Pergola et al., 2010).

Variations in satellite view angle depending on satellite's passages (for polar satellites) and atmospheric water vapour fluctuations were recognized in those previous works as the main factors limiting the Signal-to-Noise (S/N) ratio and the possibility for the RST-based approach to more clearly identify seismically related thermal anomalies.

The use of a sensor on board geostationary satellites allowed us to overcome the first problem (as a geostationary attitude guarantees stable view angles). The second could be dealt with using LST data products (which are less affected by atmospheric water vapour variability) instead of just TIR radiances at the sensor.

LST estimations from remotely sensed data are generally obtained from one or more channels within the thermal infrared atmospheric window from 8 to 13 µm (Dash et al., 2002). Operational LST retrievals often make use of split-window algorithms (see, e.g., Prata, 1993; Wan and Dozier, 1996), where LST is obtained through a semi-empirical regression of top-of-

---

[1] AVHRR (Advanced Very High Resolution Radiometer) is a sensor flying on board NOAA (Nationaland Oceanic Atmospheric Administration) satellites.

the-atmosphere (TOA) brightness temperatures of two pseudo-contiguous channels (i.e., the split-window channels). The Land SAF (Satellite Application Facility on Land Surface Analysis) LST algorithm is based on the generalized split-window (GSW) formulation initially developed for AVHRR and MODIS[2] by Wan and Dozier (1996) and later adapted to SEVIRI split-window channels by Madeira (2002).

The GSW algorithm mainly exploits the direct proportionality between the atmospheric Total Columnar Water Vapour Content (TCWVC) and the brightness temperature difference measured in two adjacent TIR spectral bands centred at 11.0 and 12.0 µm (split-window bands). In fact, the atmospheric attenuation is greater in the 12.0 µm channel than in the 11.0 µm channel and, as the attenuation increases (primarily as a result of increasing atmospheric water vapour content), the difference in the radiance measured in the two bands increases.

The error of LST retrievals via GSW mostly depends on:

1) the residual uncertainty about the surface emissivity;

2) the representativeness of atmospheric profiles used to determine calibration coefficients when applied at a local scale;

3) the satellite view angle, which also determines the total optical path. LST estimations are often limited to satellite zenith angles (SZAs) below $\sim 60^{\circ}$, where retrieval errors are still acceptable (see, e.g., Wan and Dozier, 1996; Sun and Pinker, 2003).

LST products are generated by Land SAF through the application of a generalized split-window algorithm to data acquired by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board Meteosat Second Generation (MSG) satellites.

We used the algorithm proposed by Trigo et al. (2008a) on the basis of the formulation first developed by Wan and Dozier (1996) for AVHRR and MODIS data. Thus, LST is estimated as a linear function of clear-sky TOA brightness temperatures measured by SEVIRI split-window channels centred respectively at 10.8 µm and 12.0 µm.

The Land SAF LST product (operationally retrieved, archived and disseminated since February 2005) provides an estimation of the ground surface temperature corrected for the variable contribution of water vapour in the atmosphere (see Filizzola et al., 2004; Di Bello et al., 2004), thus reducing the natural noise associated with simple TIR brightness temperature analyses.

In this paper we present the results of the first application of the RST approach to Land Surface Temperature products (LST) obtained from geostationary satellite data. The approach was used to study the L’Aquila earthquake (6 April 2009, MW ~6.3).

As usual, the results obtained by the RST analysis at the time of this earthquake (validation) are compared with those obtained by an identical analysis performed over the same area, in similar observational conditions and same period of the year but in a seismically unperturbed (i.e. without earthquakes of a similar magnitude) period of a different year (confutation).

2. The RST methodology for a robust estimation of thermal anomalies

The RST approach is a general change detection method for satellite data analysis. It has already been successfully applied to monitor major natural and environmental hazards related to: flood risk (Tramutoli et al., 2001a; Lacava et al., 2005, 2006, 2010); volcanic activity (Pergola et al., 2001, 2004a, b; Tramutoli et al., 2001c; Di Bello et al., 2004; Bonfiglio et al., 2005; Marchese et al., 2006; Filizzola et al., 2007); forest fires (Cuomo et al., 2001; Mazzeo et al., 2007), etc. Since its first application to the 1980 Irpinia-Basilicata’s earthquake (Di

---

[2] MODIS (or Moderate Resolution Imaging Spectroradiometer) is a sensor on board Terra (EOS AM) and Aqua (EOS PM) satellites.

Bello et al., 2004; Tramutoli et al., 2001b), the RST has been applied to seismically active areas while monitoring several other major (M>5) earthquake events: Athens on 7 September 1999 (Filizzola et al., 2004), Izmit on 17 August 1999 (Tramutoli et al., 2005), Gujarat on 26 January 2001 (Genzano et al., 2007), Boumerdes/Thenia on 21 May 2003 (Aliano et al., 2007), Hector Mine on 16 October 1999 (Aliano et al., 2008a), Umbria – Marche in October 1997 (Aliano et al., 2008b), Mestia Tianeti (Georgia) on 23 October 1992 (Genzano et al., 2009a), and various seismic events (with $4 < M_b < 5.5$) occurred in Greece and Turkey in May and June 1995–1996 (Corrado et al., 2005).

The RST methodology is based on the following logic: space-time transient anomalies can be defined and identified only by comparison with a normal behaviour of the measured signal that has to be preliminarily defined. Since such "normal" behaviour is variable in the space–time domain, it is impossible to establish any *a-priori* fixed threshold suitable to establish when a signal has to be considered anomalous independently from the observation time and location. A signal, which is normally observed at a specific time and place, could in fact prove to be anomalous when observed in a different time and/or place.

To accomplish this, RST exploits all the information contained in long-term series of homogeneous satellite records, collected at a location (x,y) under similar observational conditions (*i.e.* same month of the year, same hour of the day, same satellite sensor) in order to characterize the signal behaviour $T(x,y,\tau)$ measured at time t, in terms of its expected (mean) value $\mu_T\ (x,y)$ and variability (standard deviation) $\sigma_T\ (x,y)$, historically observed in unperturbed conditions (reference fields).

On this basis, anomalous TIR patterns are identified as a deviation from those "normal" conditions, using a specific index, RETIRA (Robust Estimator of TIR Anomalies, Filizzola et al., 2004; Tramutoli, 2005, belonging to the ALICE – Absolutely Local Index of Change of the Environment) class of indexes, computed on the image at hand as in Eq. (1):

$$\otimes_{\Delta T}\ (x,y,t) = \frac{\Delta T(x,y,t) - \mu_{\Delta T}(x,y)}{\sigma_{\Delta T}(x,y)} \qquad (1)$$

where:

- $\Delta T(x,y,t) \equiv T(x,y,t) - T(t)$ is the difference between the current TIR signal value $T(x,y,t)$ and its spatial average $T(t)$ at the instant t of a satellite acquisition;
- $T(t)$ is the spatial average of $T(x,y,t)$ computed in place on the image at hand considering only cloud-free pixels, all belonging to the same, land or sea, class in the investigated area. In this way $\Delta T(x,y,t)$ is computed separately considering only sea pixels if (x,y) is located on the sea and considering only land pixels if (x,y) is located on the land;
- $t \in \tau$ is the time of acquisition of the satellite image at hand;
- τ defines the homogeneous domain of satellite images selected during the same year, the same period (month or season) and the same hour of the day (time slot); those restrictions on the time-series are useful in order to reduce the signal variability connected to both seasonal and daily cycles;
- $\mu_{\Delta T}\ (x,y)$ is the historical mean value at a considered location (x,y), calculated on the image time-series at hand considering only cloud-free pixels, all belonging to the selected data-set $(t \in \tau)$;
- $\sigma_{\Delta T}\ (x,y)$ is the historically observed signal variability at a considered location (x,y), calculated considering only cloud-free pixels within the same data-set $(t \in \tau)$.

This way $\otimes_{\Delta T}\ (x,y,t)$ gives the local excess of the current $\Delta T\ (x,y,t)$ signal compared with its historical mean value and weighted by its historical variability at the considered location. Both $\mu_{\Delta T}\ (x,y)$ and $\sigma_{\Delta T}\ (x,y)$ are computed, once and for all for each location (x,y), processing several years of historical satellite records acquired in similar observational conditions. $\mu_{\Delta T}\ (x,y)$ and $\sigma_{\Delta T}\ (x,y)$ are two reference images describing the normal behaviour of the signal and its variability at each location (x,y) in observational conditions as similar as possible to those of the image at hand. The difference $\Delta T(x,y,t) - \mu_{\Delta T}\ (x,y)$ then represents the

Signal (S) to be investigated because of its possible relation with seismic activity. It is always evaluated by comparison with the corresponding natural/observational Noise (N), represented by $\sigma_{\Delta T}$ (x,y), which describes the overall (*llocal*[3]) variability of S including all (natural and observational, known and unknown) sources of its variability, as historically observed at the same site in similar observational conditions (sensor, time of day, month, etc.). This way, the relative importance of the measured TIR signal (or the relative intensity of anomalous TIR transients) can naturally be evaluated in terms of S/N ratio by the RETIRA index.

Being independent from whatever *a priori* model/assumption, RST can easily be exported on different (satellite/sensor) data, geographic areas and observation period (day/season). For instance, the RST approach has already been implemented on TIR radiances collected both by polar (NOAA/AVHRR and EOS/MODIS) and geostationary (MSG/SEVIRI) satellite sensors (Lisi et al., 2010; Genzano et al., 2010, 2009b; Pergola et al., 2010) to study the Abruzzo seismic event.

In this paper, the Abruzzo seismic event is analyzed by applying, for the first time, the RST approach to LST products obtained from geostationary satellite data.

Water vapour is one of the most variable components of the atmosphere, partly absorbing the outgoing Earth-emitted TIR radiation. Variations of the atmospheric water vapour content contribute to further increase the variability of the measured TIR signal.

Moreover, even though images collected by a polar platform are precisely navigated and co-located (in order to permit the computation of reference images, $\langle \Delta T(x,y,t) \rangle$ and $\sigma_{\Delta T}(x,y)$ by a multi-temporal analysis), at each revisiting time t the same location (x,y) is observed at different satellite zenith angles (which also means different ground-resolution cells). This circumstance may produce a further spurious temporal variation of the measured signal. It should be noted, however, that all the residual «noisy» contributions to the TIR signal (including those related to the variability of atmospheric conditions and view angles mentioned above) are intrinsically taken into account by the RST approach, as they generally increase the *llocal* value of $\sigma_{\Delta T}(x,y)$ reducing corresponding $\otimes_{\Delta T}(x,y,t)$ values and, consequently, false anomaly proliferation. However, by this way, sensitivity toward lower intensity signal variation is also reduced.

Variations in satellite view angle (for polar satellites) and atmospheric water vapour fluctuations were already recognized in the past as the main factors affecting the residual signal variability reducing the overall Signal-to-Noise (S/N) ratio and the potential of the RST-based approach in identifying seismically related thermal anomalies.

The use of a sensor on board geostationary satellites demonstrated (e.g. Filizzola et al., 2004) to overcome the first problem (as a geostationary attitude guarantees stable view angles), while the latter could be faced using LST data products (which are less affected by atmospheric water vapour variability) instead of just TIR radiances at the sensor (Tramutoli et al, 2001).

In this work, the LST products generated by the Land SAF are used instead of TIR radiances at the sensor in order to provide an estimation of near surface temperatures corrected for the variable contribution of water vapour in the atmosphere (see Filizzola et al., 2004 and Di Bello et al., 2004). This way, a reduction of the natural noise associated with the most important cause of the atmospheric transmittance variability is expected.

The same index already applied by Di Bello et al. (2004) and Filizzola et al. (2004) to radiances measured from sensors (like AVHRR) aboard polar satellites:

$$\otimes_{\Delta LST}(x,y,t) = \frac{\Delta LST(x,y,t) - \mu_{\Delta LST}(x,y)}{\sigma_{\Delta LST}(x,y)} \qquad (2)$$

is applied for the first time to a sensor (SEVIRI) aboard a geostationary satellite.

---

[3] According to Tramutoli (1998) the double *l* will be hereafter used to highlight a reference not only to a specific place (x,y) but also to a specific time t.

The only difference with expression (1) is the use of a land surface temperature, LST (x,y,t) SEVIRI product instead of the simple TIR signal $T(x,y,t)$ around 11 μm (e.g. channel 9 centred at10.8 μm for SEVIRI). In fact, in this case:

- $\Delta LST(x,y,t) = LST(x,y,t) - LST(t)$ is the difference between the current LST value $LST(x,y,t)$ and its spatial average $LST(t)$ at the instant t of a satellite acquisition;
- $LST(t)$ is the spatial average of $LST(x,y,t)$ computed in place on the image at hand considering only cloud-free pixels over land;
- $t \in \tau$ is the time of acquisition of the satellite image at hand;
- τ defines the homogeneous domain of satellite images selected during the same year, the same period (month or season) and the same hour of the day (time slot);
- $\mu_{\Delta LST}$ (x,y) is the historical mean value at a considered location (x,y), calculated on the image time-series at hand considering only cloud-free pixels, all belonging to the selected data-set ($t \in \tau$);
- $\sigma_{\Delta LST}(x,y)$ is the historically observed signal variability at a considered location (x,y), calculated considering only cloud-free pixels within the same data-set ($t \in \tau$).

In addition to the reduction expected by the use of geostationary data, the utilization of the variable ΔLST (instead of ΔT) has the advantage of reducing natural noise associated with the variability of the atmospheric water vapour content.

It should also be mentioned that, as already recognized in previous works (Filizzola et al., 2004; Tramutoli et al., 2005; Aliano et al., 2008a), since the $\otimes_{\Delta LST}$ (x,y,t) index is based on time averaged quantities, it is intrinsically not protected from the abrupt occurrence of signal outliers related to particular natural (e.g. a local warming due to night-time cloud passages) or observational (e.g. errors in image navigation/co-location process) conditions. Examples of such known effects are given, for instance, in Filizzola et al., 2004, Aliano et al., 2008a, Genzano et al, 2009b). However, such conditions have to be effectively sporadic in time (otherwise they will be controlled and vanished by the time averaging process used to build reference fields) and relatively isolated in the space domain (otherwise they will be controlled and vanished by the spatial average process used to build the $\Delta_{LST}(x,y,t)=LST(x,y,t) - LST(t)$ variable, starting from $LST(x,y,t)$ data, e.g. Tramutoli et al., 2005).

For those reasons, spatial extension and persistence in time are additional requirements to be satisfied (together with the relative intensity) in order to preliminarily identify Significant Sequences of LST Anomalies (SSLAs).

Moreover, it should be mentioned that, although the comparison with ground measurements associated with LST satellite retrievals shows quite significant biases (2-9°C r.m.s., Freitas et al., 2010; Trigo et al., 2008b, Cuomo et al., 2002), the correlation with near-surface thermal conditions has nevertheless proved to be quite high (>0.9) in the temporal domain (Cuomo et al., 2002). However such bias, which could strongly affect the absolute values of LST estimates, is not expected to affect the values of the RETIRA (and ALICE) indexes (computed following the RST methodology) as they are based on signal variations (both in space and time domains) and not on its absolute values.

This paper investigates S/N improvements achievable by applying the index (2) (based on LST products) instead of the index (1) (based on raw TIR brightness temperatures) to SEVIRI LST observations (covering years 2005– 2010) for the case of the L'Aquila earthquake (M_W~6.3) which occurred on 6 April 2009.

To this aim, Land SAF-LST data, generated by using the GSW algorithm of Trigo et al. (2008b), were used. Such data are made available by EUMETSAT only for cloud-free pixels being cloud removal performed on the basis of the NWC-SAF (2007) approach.

3. The study case of the Abruzzo earthquake

The Abruzzo earthquake (M_W ~6.3) occurred on 6 April 2009 at 01:32:39 UTC. The exact coordinates are 42.334 N and 13.334 E (INGV, 2010), which correspond to a point at 95 km northeast of Rome. This earthquake was the main shock in a series of pre-seismic events, which started in February and continued through March 2009 (Fig. 1). According to Dobrovolsky's equation (Dobrovolsky et al., 1979; Pulinets et al., 2004)

$$r = 10^{0.43M} \text{ km}$$

where M is the magnitude of the earthquake and r is the radius (in km) of the circle around the epicentre, the radius of the earthquake preparation area could be estimated in 511 km.

Several scientific studies carried out after the event occurrence focus on the Abruzzo earthquake. For example, local crustal deformations were monitored by laser strain meters (Amoruso and Crescentini, 2010), by DInSAR satellite interferometry (Anzidei et al., 2009) and by GPS stations.

Di Luccio et al. (2009) and Plastino et al. (2009) detected pre-seismic fluid-related signals consistent with a strain occurrence at depth.

A gas geochemical survey carried out in the L'Aquila area confirmed the deep crustal origin of the anomalous gas emission detected by ground measurements and suggested by satellite observations (Martinelli et al., 2009). Anomalous V_P/V_S ratios were recorded some days before the main shock in apparent relation with underground fluid movements (Lucente et al., 2010) and crust deformation processes associated with the seismic sequence.

In this work, the Abruzzo seismic sequence considered as a test case to investigate possible relations between the earthquake occurrence and significant (space-time persistent) fluctuations of LST measurements obtained from a geostationary satellite.

On this basis, the RST methodology was applied to all LST data collected from 2005 to 2010, at the same time of the day (00:00 GMT), in March and April, to perform a validation/confutation analysis. We considered the months of March and April 2009 for validation purposes, while in the confutation phase the analysis was performed considering March and April 2007, which were relatively seismically unperturbed within the considered dataset.

4. The validation phase: from 15 March until 15 April 2009

On the basis of the reference fields $\mu_{\Delta LST}(x,y)$ and $\sigma_{\Delta LST}(x,y)$, computed following the RST prescriptions, LST anomaly maps (calculated on the basis of Eq. 2) were generated for all LST night-time (00:00 GMT) images in the period 15 March– 15 April 2009 (validation phase). Each scene of the data-set was processed, but pixels previously declared as affected by clouds (using the cloud mask product provided by EUMETSAT, NWC-SAF, 2007) as well as pixels corresponding to data missing were excluded from whatever further processing and analysis according to the RST prescriptions.

Figure 2 shows the maps of the $\otimes_{\Delta LST}(x,y,t)$ index from 15 March until 15 April 2009. Pixels with $\otimes_{\Delta LST}(x,y,t) > 3.5$ (i.e. $\Delta LST(x,y,t) - \mu_{\Delta LST}(x,y)$ excess greater than $3.5 > \sigma_{\Delta LST}(x,y)$) are depicted in red and hereafter, only for the sake of simplicity, we will refer to them as "LST anomalies".

Looking at the sequence of pictures in figure 2, it is possible to note that higher intensity LST anomalies (i.e. pixels with $\otimes_{\Delta LST}(x,y,t) > 3.5$) appear in the maps affecting the Northern Africa on 21 and 28 March, while Central Italy (the Abruzzo region) and Balkan region are affected by persistent (in the space/time domain) LST anomalies (SSLAs) beginning on 30 March until 1 April. Another high intensity SSLA appears in the northern part of the scene (North-East of the Italian peninsula and Croatia region) on 4 and 5 April 2009.

On the basis of this analysis, if we consider lower intensity LST anomalies (pixels with $\otimes_{\Delta LST}(x,y,t) > 3$ and $\otimes_{\Delta LST}(x,y,t) > 2.5$) we can better appreciate (Figure 3) the space/time evolution of the LST anomalies observed before. Generally, low intensity anomalies follow those of higher intensity noticeably enlarging the anomaly area and filling gaps both in the space (among isolated anomalous pixels) and time domains.

On the basis of such considerations and looking at Figure 1 showing the seismic events with M>3.5 occurred in the period March–April 2009, it is possible to note that two main SSLAs are clearly visible:

- the first in Central Italy (black circle in figure 3) from 30 March to 1 April (7 days before the main shock of the Abruzzo earthquake) located near the main tectonic lineaments (green lines) and seismic epicentres of the earthquakes occurred in the area.
- the second in the Balkan region (blue circle in Figure 3) where an earthquake with M_L~4.2 occurred on 31 March 2009.

The appearance of two SSLAs in Central Italy and in the Balkan region, both in a possible relation with the strong seismic events occurred there, seems to be consistent with the idea of a strict seismic correlation among Southern Dinarides–Albanides and Central Apennines zones already argued by Mantovani et al. (2010).

Two other SSLAs could be identified in Figure 3 (in fact, they appear sufficiently spatially persistent only when lower intensity anomalies with $\otimes_{\Delta LST} > 2.5$ are also considered):

- one near tectonic lineaments of the Padania plain and in the North-East of the Italian peninsula on 21 and 31 March and 4 and 5 April 2009 (purple circle in figure 3). The regions have been affected by an earthquake (Forlì earthquake) on 5 April 2009 (M_L~4,6)
- another in the Northern part of Africa on 21 and 28 March 2009 (green circle in figure 3)**,** probably related to the residual local warming effect due to the night time passage of a cloudy system (Filizzola et al., 2004, Aliano et al., 2008a).

5. The confutation phase: from 15 March until 15 April 2007

The confutation analysis for the Abruzzo earthquake was performed by considering the same period as the validation step (15 March–15 April) but in a different year, in order to verify the absence of SSLAs in a relatively seismically unperturbed period. The selection of the year 2007 for confutation purposes was done consulting the INGV (2010) seismic catalogue in the period 2005-2010 (according to LST data used in the analysis): no seismic event with M≥5 is reported over the investigated area during the months of March and April 2007 (Figure 4). As for the validation step, the same cut at 3.5σ (i.e. $\otimes_{\Delta LST}(x,y,t) > 3.5$) was used in order to identify high intensity SSLAs on the images.

Figure 5 shows the result of the RST analysis for the year 2007 performed using the same LST data employed in the validation phase. It is possible to note that no SSLA is present and that only isolated, not time persistent (disappearing just in 1 day) LST anomalies are detectable (being the area overcast for most of the time) on 6 April 2007 on the same area (Eastern Calabria Region) where about 10 days before the only seismic event with M>4 (26 March 2007, M=4.1) occurred in the considered period over the whole Italian peninsula.

6. Conclusion

The RST approach built on a statistically based definition of TIR anomalies was used in this work together with a space-time persistence analysis to investigate possible relations between an earthquake occurrence and space-time fluctuations of the Earth’s emitted TIR radiation observed from satellite.

The Abruzzo earthquake (6 April 2009, M_W ~6.3) was analyzed by applying, for the first time, the RST approach to LST products obtained by geostationary satellite data. Previous works of the same authors had suggested that an increase of signal-to-noise ratio could be achievable by using geostationary (rather than polar) data (see Filizzola et al., 2004) or LST products (instead of simple TIR radiance at sensor, e.g. Tramutoli et al. 2001, Di Bello et al., 2004). The use of geostationary satellite sensors operating with time-invariant satellite view angles contributes to reduce observational noise, while LST data, providing an estimation of the ground surface temperature corrected for the variable contribution of water vapour in the atmosphere, lead to a reduction of natural noise. An additional increase of signal-to-noise ratio is expected when considering a combination of the two conditions, i.e. applying the RST approach to LST products derived by geostationary data. To this aim, the results obtained with the use of LST products (generated by the Land SAF through the application of a generalized split-window algorithm to SEVIRI images) were analyzed in the case of the Abruzzo earthquake.

The period (15 March–15 April 2009) around the time of the Abruzzo earthquake was considered as a test case for validation purposes, while a relatively unperturbed period (no earthquakes with M>5) was taken for the confutation analysis in the same months (March–April) of a different year (2007).

The validation/confutation approach highlights that high intensity (with $\otimes_{\Delta LST}>3.5$) Significant Sequences of space-time persistent LST Anomalies (SSLAs) appear in Central Italy seven days before the main shock of the Abruzzo earthquake (6 April 2009, M_W~6.3). In particular, very intense and extended LST anomalies were observed near tectonic lineaments from 30 March until 1 April. No SSLA and no similar anomalies were observed in absence of earthquakes in similar observation conditions in the period (March–April 2007) considered for confutation purposes.

Moreover, the results obtained using LST products confirm and improve those obtained by using the simple TIR radiances at the sensor collected both by polar (NOAA/AVHRR and EOS/MODIS) and geostationary (MSG/SEVIRI) satellite sensors (Lisi et al., 2010; Genzano et al., 2010, 2009b; Pergola et al., 2010), and demonstrate that such results were not due to atmospheric effects (i.e. changes in the atmospheric transmittance).

In conclusion, some critical points should be highlighted such as the existence of some factors that can *limit* the *applicability* of this *technique* in particular observational conditions, as in presence of persistent cloudy bodies that take up the scene.

In fact, clouds reduce the amount of satellite records usable within the historical reference data-set, producing a data lack in the historical series of observations and this way influencing the multi-temporal analysis. Moreover, if the presence and persistence of cloudiness is wide, the scene can be so “obfuscate” that it will be hard to observe the space-time continuity of possible thermal anomalies over the selected area test.

In addition, the geographic distribution of clouds over an heterogeneous thermal scene can significantly influence the computation of spatial means. In fact, as emerged after the analysis of a large number of satellite images processed, if clouds mostly insist over the “usually warmer part” of the scene, the spatial average $LST(t)$ will result lower than the expected value in clear sky conditions. Consequently, it is possible to have higher values of the signal $\Delta LST(x,y,t) = LST(x,y,t) - LST(t)$ over the quite entirety of the clear portion of the scene that are related to an anomalous cooling of $LST(t)$ (named *cold spatial average effect* in Aliano et al. 2008a, Genzano et al. 2009b) due only to an anisotropic distribution of clouds along the north-south direction.

In this sense, taking advantage from the intrinsic exportability of the RST approach, the use of microwave sensors could help to overcome such limitations. In fact, this kind of electromagnetic radiation, which penetrates (not raining) clouds, allows us to observe the Earth’s surface in any weather conditions. Even though the spatial resolution of MW passive sensors (10-50 km nadir view) is much lower than that of TIR sensors (1-5 km), it remains largely sufficient to monitor the thermal anomalies usually observed at a wide scale around the earthquake preparation zone.

Acknowledgments
The research leading to these results has been supported by INGV-DPC S3 project "*Short Term Earthquake prediction and preparation*". It has been also supported by the European Commission through the FP7 Programme – PRE-EARTHQUAKES project "*Processing Russian and European EARTH observations for earthQUAKE precursors Studies*" (Grant Agreement n° 263502) and by the FSE Basilicata (2007/2013) Project SESAMO (*Sviluppo E Sperimentazione di tecnologie integrate Avanzate per il MOnitoraggio della pericolosità sismica*). The authors would like to also thank the support given by the International Space Science Institute (ISSI) in the framework of the Project "*Multi-instrument Space-Borne Observations and Validation of the Physical Model of the Lithosphere-Atmosphere-Ionosphere-Magnetosphere Coupling*". This study has been performed using LST data provided by Land Surface Analysis SAF co-funded by EUMETSAT. The content of this document is the sole responsibility of the authors and it does not represent the opinion of the INGV-DPC, ISSI and European Commission who are not responsible for any use that might be made of the information contained herein.

References:

Aliano, C., Corrado, R., Filizzola, C., Genzano, N., Pergola N., Tramutoli V., 2007. From GMOSS to GMES: Robust TIR Satellite Techniques for earthquake active regions monitoring. In Global Monitoring for Security and Stability (GMOSS), Activity EU-Report 2007.

Aliano, C., Corrado, R., Filizzola, C., Pergola N., Tramutoli V., 2008a. Robust Satellite Techniques (RST) for seismically active areas monitoring: the case of 21st May, 2003 Boumerdes/Thenia (Algeria) earthquake. In Proceedings of International Workshop on the Analysis of Multi-temporal Remote Sensing Images; IEEE, pp. 1–6. Multitemp doi: 10.1109/MULTITEMP. 2007. 4293042.

Aliano, C., Corrado, R., Filizzola, C., Genzano, N., Pergola N., Tramutoli V., 2008b. TIR Satellite Techniques for monitoring earthquake active regions: limits, main achievements and perspectives. In Annals of Geophysics, 51(1), 303–317.

Aliano, C., Corrado, R., Filizzola, C., Genzano, N., Pergola N., Tramutoli V., 2008c. Robust Satellite Techniques (RST) for seismically active areas monitoring: the case of 1997-1998 Umbria-Marche seismic sequence. In Volume speciale Annals of Geophysics Colfiorito 1997-2007.

Amoruso A. and Crescentini L., 2010. Limits on earthquake nucleation and other pre-seismic phenomena fromcontinuous strain in the near field of the 2009 L'Aquila earthquake. In Geophys. Res. Lett., 37, L10307, doi:10.1029/2010GL043308.

Anzidei, M., Boschi, E., Cannelli, V., Devoti, R., Esposito, A., Galvani, A., Melini, D., Pietrantonio, G., Riguzzi, F., Sepe, V., Serpelloni, E., 2009: Coseismic deformation of the destructive April 6, 2009 L'Aquila earthquake (central Italy) from GPS data. In Geophys. Res. Lett., 36, L17307, doi: 1029/2009GL039145.

Bonfiglio, A., Macchiato, M., Pergola, N., Pietrapertosa C., Tramutoli, V., 2005. AVHRR automated detection of volcanic clouds. In International Journal of Remote Sensing, 26 (1), 9–27.

Corrado, R., Caputo, R., Filizzola, C., Pergola, N., Pietrapertosa, C., Tramutoli, V., 2005. Seismically active area monitoring by robust TIR satellite techniques: a sensitivity analysis on low magnitude earthquakes in Greece and Turkey. In Natural Hazards and Earth System Sciences, 5, 101–108.

Cuomo, V., Lasaponara, R., Tramutoli, V., 2001. Evaluation of a new satellite-based method for forest fire detection.Iin. J. Remote Sens., 22(9), 1799–1826.

Cuomo, V., Afflitto, N., Blumetti, M., Bonfiglio, A., Candela, O., Carone, T., 2002. Pollino project action D: A multi-scale approach, in the space– time domain, to environmental risk monitoring. In Manfred Ehlers (Eds.), Remote sensing for environmental monitoring. GIS Applications and Geology, vol. 4545. pp. 13– 23 SPIE.

Dash, P., Göttesche, F. M., Olesen, F.S., 2002 Potential of MSG for surface temperature and emissivity estimation: considerations for real-time applications. In J. remote sensing, vol. 23, no. 20, 4511–4518.

Di Bello, G., Filizzola, C., Lacava, T., Marchese, F., Pergola, N., Pietrapertosa, C., Piscitelli, S., Scaffidi, I., Tramutoli, V., 2004. Robust Satellite Techniques for Volcanic and Seismic Hazards Monitoring, in Ann. Geophys., 47 (1), 49 – 64.

Di Luccio, F., Ventura, G., Di Giovambattista, R., Piscini, A., Cinti, F.R., 2010. Normal faults and thrusts reactivated by deep fluids: the 6 April 2009 Mw6.3 L'Aquila earthquake, Central Italy. Journal of Geophysical Research, 115, B06315, doi:10.1029/2009JB007190.

Dobrovolsky, I. R., Zubkov, S. I., Myachkin, V. I., 1979. Estimation of the size of earthquake preparation zones”. Pure Appl. Geophys., 117, 1025–1044.

Filizzola, C, Lacava, T., Marchese, F., Pergola, N., Scaffidi I., Tramutoli, V., 2007. Assessing RAT (Robust AVHRR Techniques) performances for volcanic ash cloud detection and monitoring in near real-time: The 2002 eruption of Mt. Etna (Italy), in Remote Sensing of Environment 107 440–454.

Filizzola, C., Pergola, N., Pietrapertosa, C., Tramutoli, V., 2004. Robust satellite techniques for seismically active areas monitoring: a sensitivity analysis on September 7, 1999 Athens’s earthquake, in Phys. Chem. Earth, 29, 517–527.

Freitas, S. C., Trigo, I. F., Bioucas-Dias, J. M., Göttsche, F.-M., 2010. Quantifying the uncertainty of Land Surface Temperature retrievals from SEVIRI/Meteosat, in IEEE Transaction on Geoscience and Remote Sensing, vol. 48, n. 48, no.1, January.

Genzano, N., Aliano, C., Filizzola, C., Pergola N., Tramutoli, V., 2007. A robust satellite technique for monitoring seismically active areas: The case of Bhuj-Gujarat earthquake, in Tectonophysics, 431, 197–210.

Genzano, N., Aliano, C., Corrado, R., Filizzola, C., Lisi, M., Paciello, R., Pergola, N., Tsamalashvili, T., Tramutoli, V., 2009a. Assessing of the Robust Satellite Techniques (RST) in areas with moderate seismicity, in Multitemp 2009, Fifth International Workshop on the Analysis of Multitemporal Remote Sensing Images, Connecticut, USA, 28-30 July 2009: 2009, pp. 307-314.

Genzano, N., Aliano, C., Corrado, R., Filizzola, C., Lisi, M., Mazzeo, G., Paciello, R., Pergola N., Tramutoli, V., 2009b. RST analysis of MSG-SEVIRI TIR radiances at the time of the Abruzzo 6 April 2009 earthquake, in Natural Hazards and Earth System Sciences, vol. 9, pp. 2073-2084.

Genzano, N., Corrado, R., Coviello, I.,. Grimaldi, C. S. L, Filizzola, C., Lacava, T., Lisi, M., Marchese, F., Mazzeo, G., Paciello, R., Pergola N., Tramutoli, V., 2010. A multi-sensors analysis of RST based thermal anomalies in the case of the Abruzzo earthquake, in Proceedings of the 2010 IEEE International Geoscience and Remote Sensing Symposium.

Gorny, V. I., Salman, A. G., Tronin, A. A., Shilin, B. B., 1988. The Earth outgoing IR radiation as an indicator of seismic activity in P. Acad. Sci. USSR, 301, 67–69.

Hamza, V. M., 2001 Tectonic leakage of fault bounded aquifers subject to non-isothermal recharge: A mechanism generating thermal precursors to seismic events In Phys. Earth Planet. In., 126, 163–177.

Lacava, T., Cuomo, V., Di Leo, E. V., Pergola, N., Romano, F., Tramutoli, V., 2005. Improving soil wetness variations monitoring from passive microwave satellite data: the case of April 2000 Hungary flood, in Remote Sens. Environ., 96/2, 135–148.

Lacava, T., Di Leo, E. V., Pergola, N., Tramutoli, V., 2006. Spacetime soil wetness variations monitoring by a multi-temporal microwave satellite records analysis, in Phys. Chem. Earth, 31, 1274– 1283.

Lacava, T., Filizzola, C., Pergola, N., Sannazzaro, F., Tramutoli, V., 2010. Improving flood monitoring by RAT (Robust AVHRR Technique) approach: the case of April 2000 Hungary flood. International Journal of Remote Sensing 31: 8, 2043 — 2062. DOI: 10.1080/01431160902942902.

Lisi, M., Filizzola, C., Genzano, N., Grimaldi, C. S. L., Lacava, T., Marchese, F., Mazzeo, G., Tramutoli, V., 2010. A study on the Abruzzo 6 April 2009 earthquake by applying the RST approach to 15 years of AVHRR TIR observations, in Natural Hazards and Earth System Sciences, vol. 10 p. 395–406.

Lucente, F.P., De Gori P., Margheriti L., Piccinini D., Di Bona M., Chiarabba, C., Agostinetti, N. P., 2010. Temporal variation of seismic velocity and anisotropy before the2009 MW 6.3 L’Aquila earthquake, Italy”. In Geology 2010;38;1015-1018 doi: 10.1130/G31463.1.

Madeira, C., (2002): “Generalised Split-Window Algorithm for Retrieving Land-Surface Temperature from MSG/SEVIRI Data, SAF on Land Surface Analysis Training”. Workshop, Lisbon, Portugal, July 8-10.

Mantovani E., Viti M., Babbucci D., Albarello D., Cenni N., and Vannucchi A., (2010): “Long-term earthquake triggering in the Southern and Northern Apennines”. J Seismol (2010) 14: 53–65 DOI 10. 1007/s10950-008-9141-z.

Marchese, F., Pergola, N., Telesca, L., 2006. Investigating the temporal fluctuations in satellite Advanced Very High Resolution Radiometer thermal signals measured in the volcanic area of Etna (Italy) in fluctuations and noise, in letters 6, (3) 305-316.

Martinelli, G., Heinicke, J., Italiano, F., 2009. Variazioni nel flusso di CO2 osservate nel marzo-aprile 2009 in Italia centrale, Atti del GNGTS 2009, Trieste, Italy, available at: http://www2.ogs.trieste.it/gngts/gngts/index.php?option= com content\&task=view&id=71\&Itemid=163, 16–19 November 2009.

Mazzeo, G., Marchese, F., Filizzola, C., Pergola, N., Tramutoli, V., 2007. A multi-temporal Robust Satellite Technique (RST) for forest fire detection, in: Multitemp 2007, Louven, Belgium, 1-6, doi:10.1109/MULTITEMP.2007.4293060, 18–20 July.

NWC-SAF, 2007. Algorithm Theoretical Basis Document for Cloud Products”. (CMa-PGE01,CT-GE02 and CTTH - PGE03 v1. 4). AF/NWC/CDOP/MFL/SCI/ATBD/01, Issue 1, Rev. 4, 7.

Ouzounov, D., Freund, D., 2004. Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data in Adv. Space Res., 33, 268–273.

Pergola, N., Pietrapertosa, C., Lacava, T., Tramutoli, V., 2001. Robust Satellite Techniques For Monitoring Volcanic Eruptions, in Annals Of Geophysics 44 (2), 167–177.

Pergola, N., V. Tramutoli and F. Marchese (2004a). Automated Detection of Thermal Features Of Active Volcanoes By Means Of Infrared AVHRR Records, in Remote Sensing Of Environment 93, 311–327.

Pergola, N., Tramutoli, V., Scaffidi, I., Lacava, T., Marchese, F. 2004b. Improving Volcanic Ash Clouds Detection By A Robust Satellite Technique, in Remote Sensing Of Environment 90 (1), 1–22.

Pergola, N., Aliano, C., Coviello, I., Filizzola, C., Genzano, N., Lacava, T., Lisi, M., Mazzeo, G., Tramutoli, V., 2010. Using RST approach and EOS-MODIS adiances for monitoring seismically active regions: a study on the 6 April 2009 Abruzzo earthquake. Natural Hazards and Earth System Sciences 10, 239–249.

Piroddi, L., Ranieri, G., 2012. Night Thermal Gradient: A New Potential Tool for Earthquake Precursors Studies. An Application to the Seismic Area of L’Aquila (Central Italy). IEEE Journal Of Selected Topics In Applied Earth Observations And Remote Sensing, 2012, 5(1), 307-312.

Plastino, W., Povinec, P.P., De Luca, G., Doglioni, C., Nisi, S., Ioannucci, L., Balata, M., Laubenstein, M., Bella, F., Coccia, E., 2010. Uranium groundwater anomalies and

L'Aquila earthquake, 6 April 2009 (Italy). Journal of Environmental Radioactivity, 101, 45-50.

Prata, A. J., Barton, I. J., 1993. A multichannel, Multiangle method for the determination of infrared optical depth of semitransparent high cloud from an orbiting satellite. Part I: Formulation and simulation. In Journal Appl. Meteorol., 32(l), 1623-1637.

Pulinets, S. A., Boyarchuk, K. A., Hegai, V. V., Karelin, A. V., 2002. Conception and model of seismo-ionospheremagnetosphere coupling, in Seismo-Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling, edited by: Hayakawa, M. and Molchanov, O. A, Terra Scientific Publishing Co., Tokyo, 353–361.

Pulinets, S. A., 2004. Ionospheric Precursors of Earthquakes; Recent Advances. In Theory and Practical Applications, Terr. Atmos. Ocean. Sci., 15, 413–435.

Pulinets, S. A., Ouzounov, D., Karelin, A. V, Boyarchuk, K. A., Pokhmelnykh, L.A, 2006. The physical nature of thermal anomalies observed before strong earthquakes, in Phys. Chem. Earth, 31, 143–153.

Pulinets, S. A., Biagi, P., Tramutoli, V., Legen’ka, A. D., Depuev, V. K., 2007. Irpinia earthquake 23 November 1980 – Lesson from Nature reviled by joint data analysis, in Ann. Geophys., 50(1), 61–78.

Quiang, Z. J., Xu, X. D., Dian, C.-G., 1991. Thermal infrared anomaly-precursor of impending earthquakes, in Chin. Sci. Bull., 36 (4), 319-323.

Qiang, Z. J. and Dian, C. G., 1992. Satellite thermal infrared impending temperature increase precursor of Gonghe earthquake of magnitude 7.0, Qinghai Province, in Geoscience, 6 (3), 297–300.

Qiang, Z. J., Xu, X. D., Dian, C. G., 1997. Thermal infrared anomaly precursor of impending earthquakes, in Pure Appl. Geophys., 149, 159–171.

Sun, D., Pinker, R. T., 2003. Estimation of land surface temperature from a Geostationary Operational Environmental Satellite (GOES-8). In J. Geophys. Res., 108(D11), 4326, doi:10.1029/2002JD002422.

Tramutoli, V., 1998. Robust AVHRR techniques (RAT) for environmental monitoring: theory and applications, Earth surface remote sensing II, in Proceedings of SPIE, 3496, 101–113.

Tramutoli, V., Di Bello, G., Pergola, N., Piscitelli, S., 2001a. Robust satellite sensing of seismically active areas”. In Annals of Geophysics, vol. 44, n. 2, 295-312.

Tramutoli, V., Claps, P., Marella, M., Pergola, N., Pietrapertosa, C., Sileo, C., 2001b. Hydrological implications of remotely sensed thermal inertia, in Remote Sensing and Hydrology 2000, vol. 267, edited by: Owe, M., Brubaker, K., Ritchie, J., and Rango, A., IAHS Publ., 207–211.

Tramutoli, V., Pergola, N., Pietrapertosa, C., 2001c. Training on NOAA/AVHRR of Robust Satellite Techniques for next generation of weather satellites: an application to the study of space–time evolution of Pinatubo’s stratospheric volcanic cloud over Europe, in Smith, W.L., Timofeyev, Yu.M. 189 (Eds.), IRS 2000: Current Problems, in Atmospheric Radiation. VA’ Deepak Publishing, Hampton, 36–39.

Tramutoli, V. 2005. Robust Satellite Techniques (RST) for natural and environmental hazards monitoring and mitigation: ten years of successful applications, in ISP MSRS 2005 Conference Proceedings, Beijing, China.

Tramutoli, V., 2007. Robust Satellite Techniques (RST) for Natural and Environmental Hazards Monitoring and Mitigation: Theory and Applications, in Proceedings of Multitemp 2007, 1–5, doi: 10. 1109/MULTITEMP. 2007. 4293057.

Tramutoli, V., Aliano, C., Corrado, R., Filizzola, C., Genzano, N., Lisi, M., Lanorte, V., Tsamalashvili, T., Pergola, N., 2009. Abrupt change in greenhouse gases emission rate as a possible genetic model of TIR anomalies observed from satellite in Earthquake active regions, in Proceedings of 33rd International Symposium on Remote Sensing of Environment (ISRSE33), Stresa, Lago Maggiore, Italy, 4–8 May.

Tramutoli, V., Aliano, C., Corrado, R., Filizzola, C., Genzano, N., Lisi, M., Martinelli, G., Pergola, N., 2013. On the possible origin of Thermal Infrared Radiation (TIR) anomalies in earthquake-prone areas observed using Robust Satellite Techniques (RST). Chemical Geology, 339, pp 157 -168.

Trigo, I. F., Peres, L. F., DaCamara, C. C., Freitas, S. C., 2008a. Thermal Land Surface Emissivity Retrieved From SEVIRI/Meteosat, in IEEE Trans. Geosci. Remote Sens., vol. 46, doi: 10. 1109/TGRS. 2007. 905197.

Trigo, I. F., Monteiro, I. T., Olesen, F., Kabsch, E., 2008b. An assessment of remotely sensed Land Surface Temperature, in Journal Geophys. Res., vol. 113, D17108, doi: 10. 1029/2008JD010035.

Tronin A. A., 1996. Satellite thermal survey a new tool for the study of seismoactive regions, in. J. Remote Sens., 41(8), 1439–1455.

Tronin, A. A., 2000. Thermal IR satellite sensor data application for earthquake research, in China. Inter. J. Remote Sensing, 21, 3169–3177.

Tronin, A. A., Hayakawa, M., Molchanov, O. A., 2002. Thermal IR data application for earthquake research in Japan and China, in Journal Of Geodynamics, vol. 33 (4-5), 519-534.

Wan, Z., Dozier, J., 1996. A generalized split-window algorithm for retrieving land-surface temperature from space, in IEEE Trans. Geosci. Remote Sens., vol. 34, 892-905.

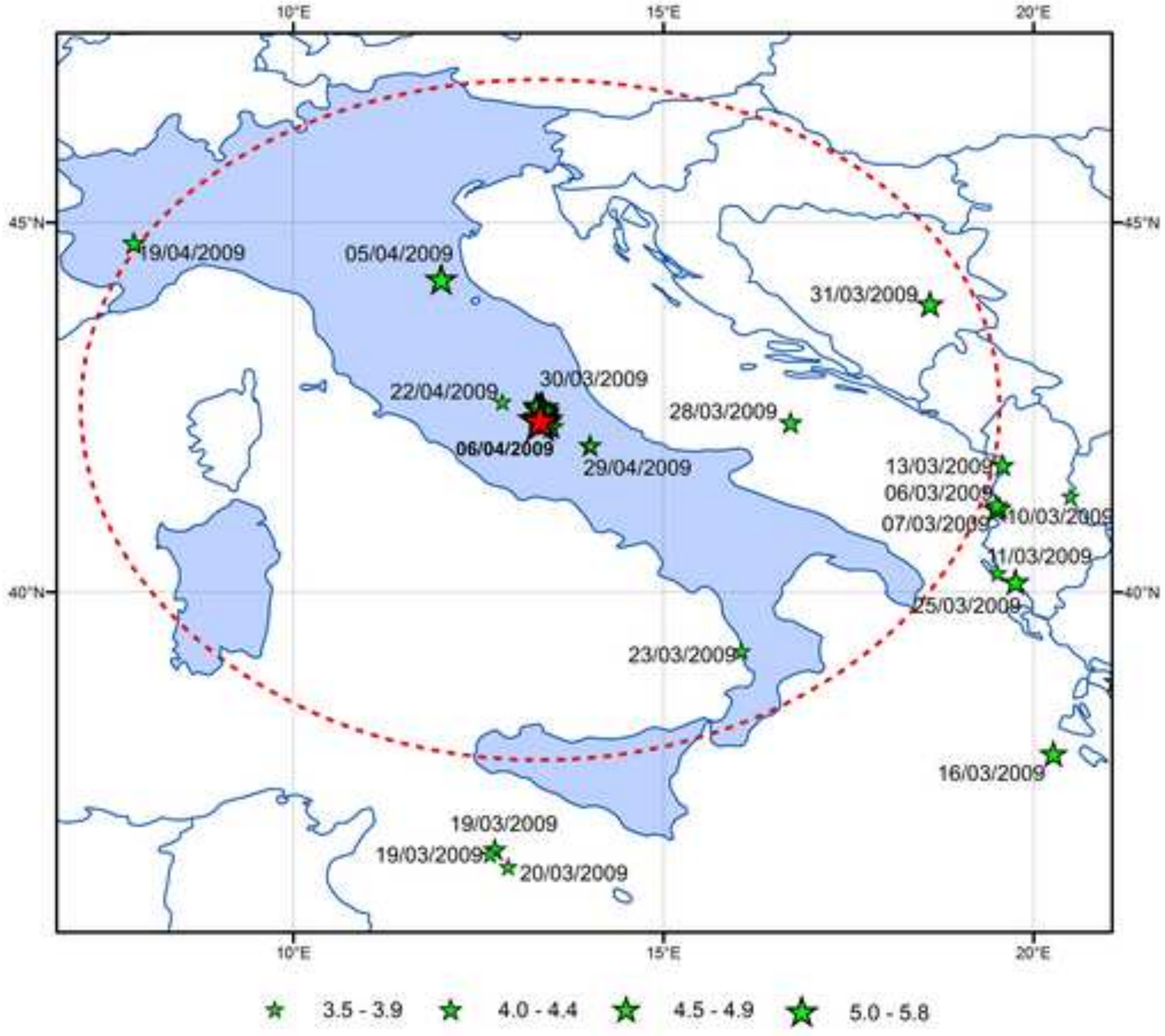
Figure 1. Seismic events with $M_L > 3.5$ occurred during March and April 2009. Red star indicates the main shock of Abruzzo earthquake (INGV, 2010). The red circle represents the earthquake preparation zone according to the Dobrovolsky equation (see text).

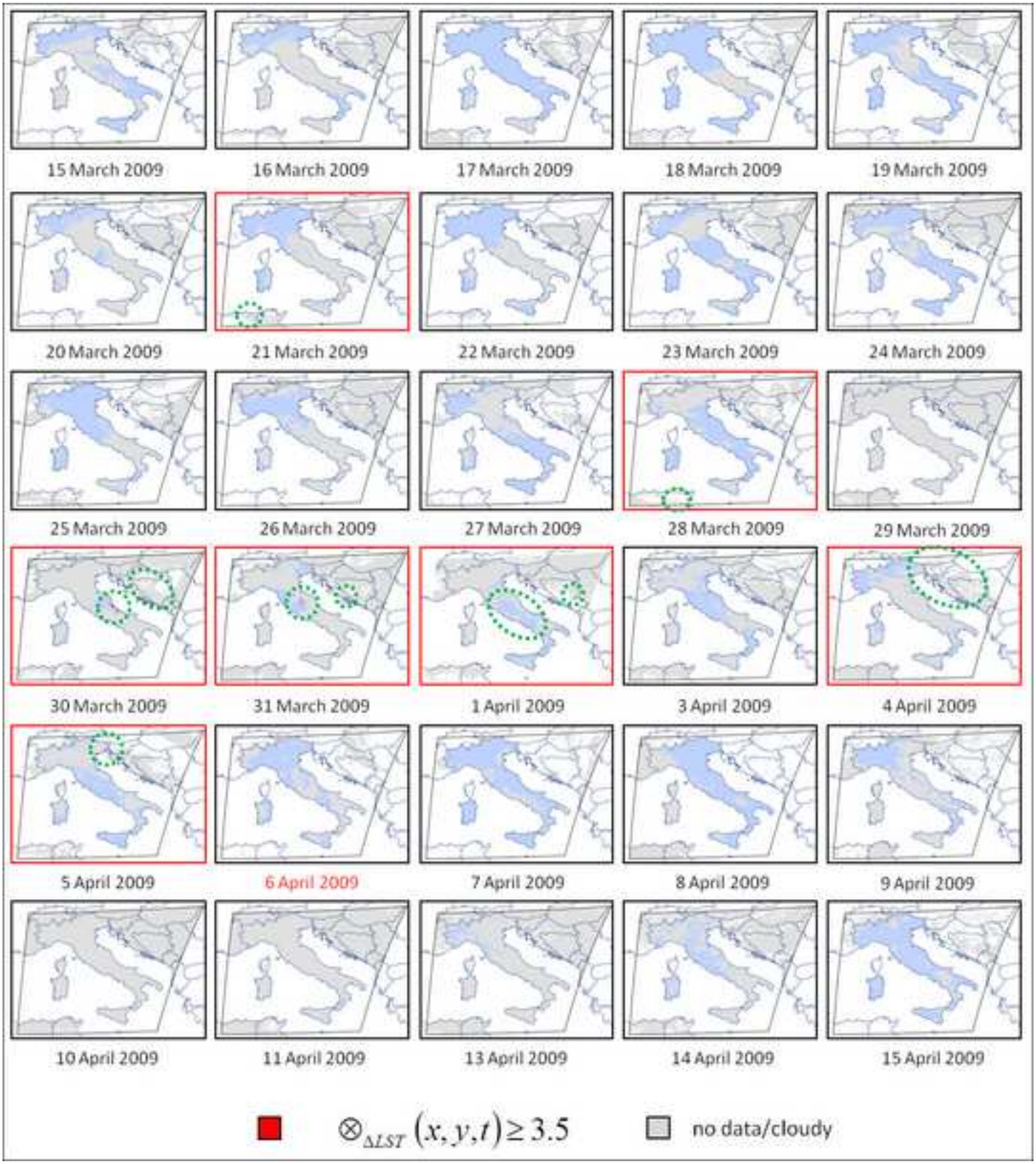
Figure 2. LST validation phase: results of the RETIRA index computation on the investigated area at the time of Aquila earthquake (6 April 2009, M_W=6.3). LST anomalies (i.e. pixels with $\otimes_{\Delta LST}(x,y,t) > 3.5$) are depicted in red. Cloudy locations and missed data are depicted in gray. Red boxes contour images containing LST anomalies. Green dashed circles indicate the areas of occurrence of LST anomalies (see text).

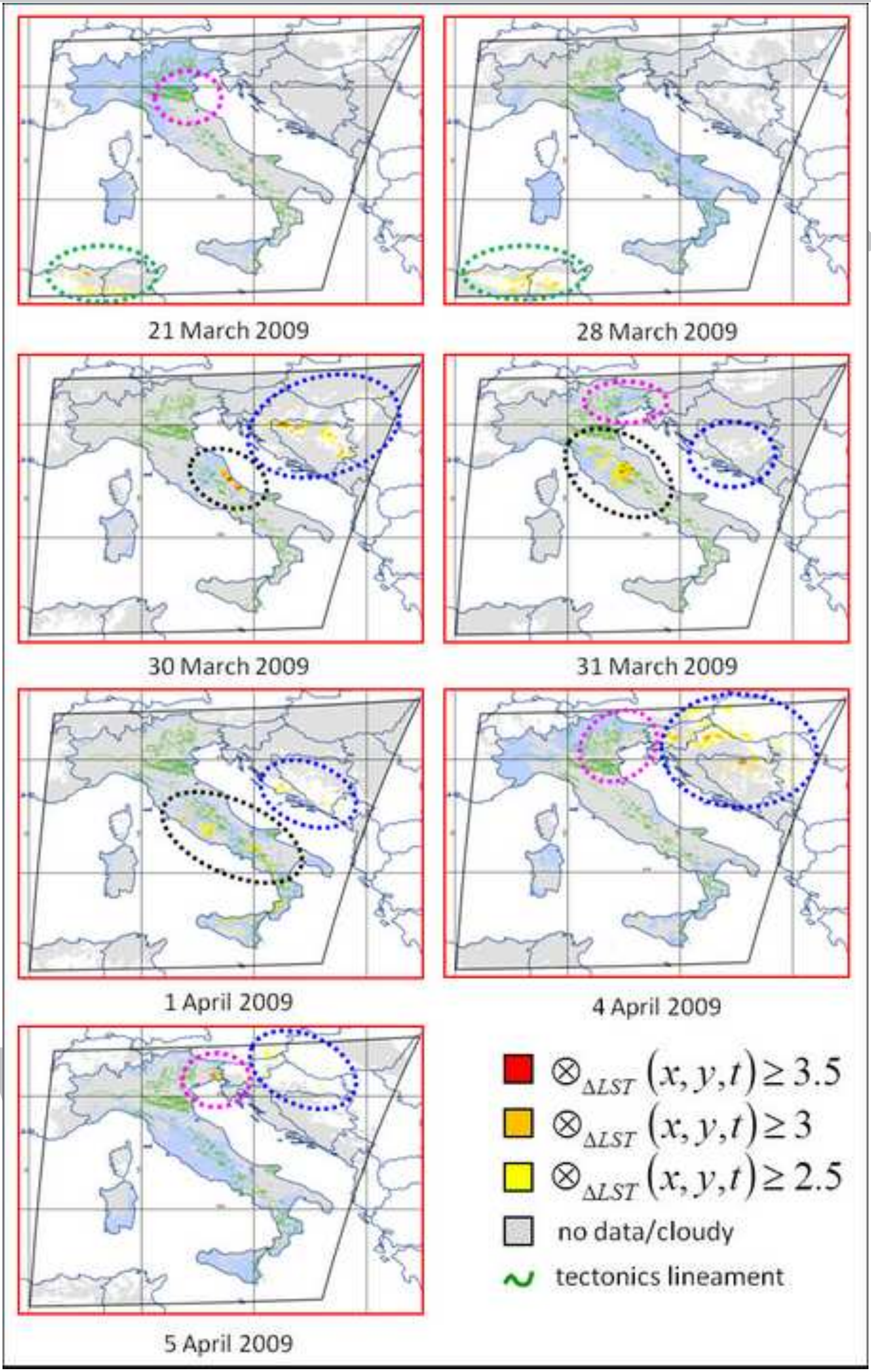
Figure 3. LST validation phase: results of the RETIRA index computation on the investigated area at time of Aquila earthquake (6 April 2009, M_W=6.3) considering also lower intensity LST anomalies (i.e. pixels with $\otimes_{\Delta LST}(x,y,t) > 3$ and $\otimes_{\Delta LST}(x,y,t) > 2.5$). Generally, low intensity anomalies follow the ones of higher intensity noticeably enlarging the anomaly area and filling gaps both in the space (among isolated anomalous pixels) and time domains. The coloured circles represent sequence of LST anomalies(see text). The green circles (on 21 and 28 March 2009) show LST anomalies probably related to the residual local warming effect due to the night time passage of a cloudy system.

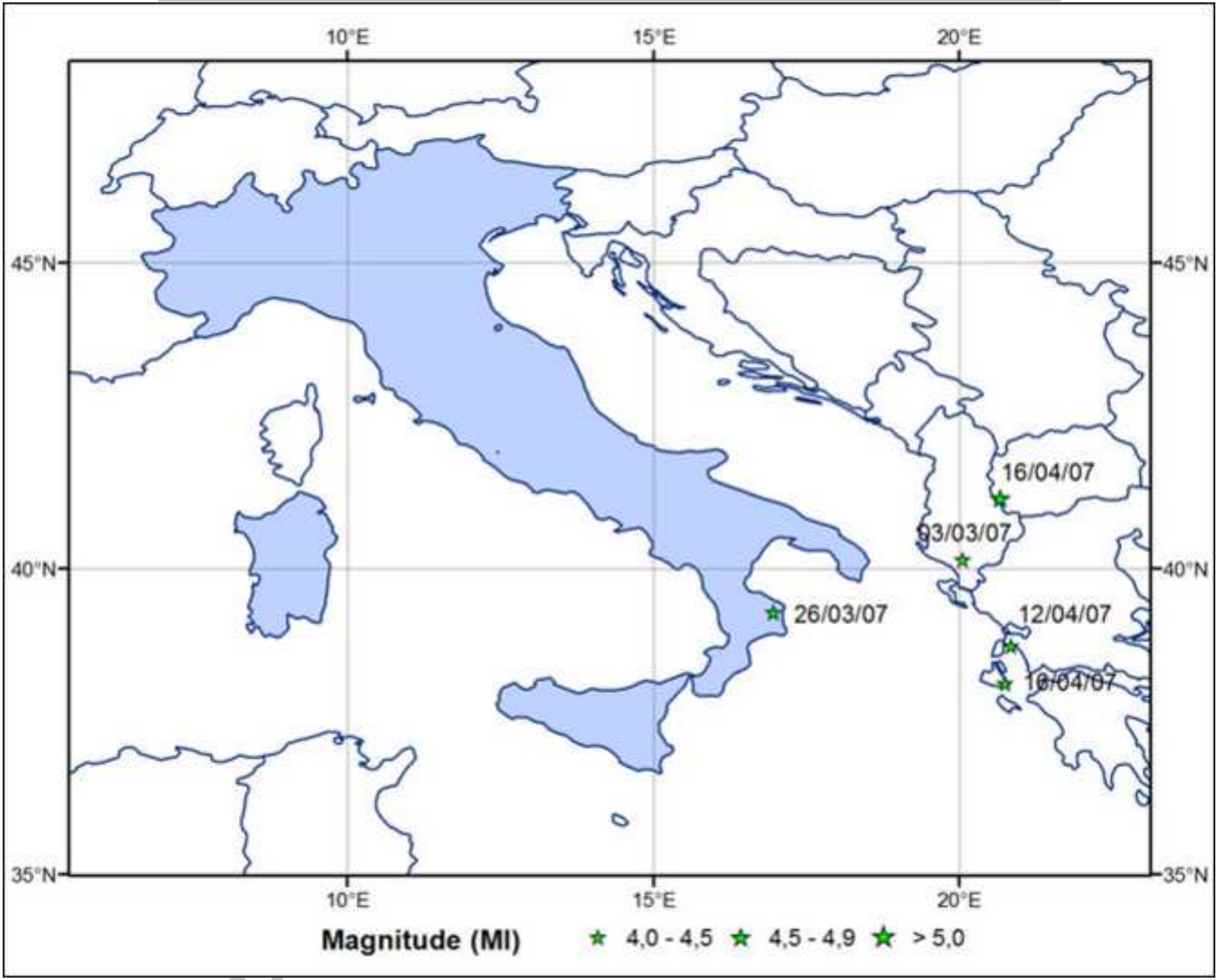
Figure 4. Seismic events (M_L>4.1) occurred during March–April 2007 (INGV, 2010).

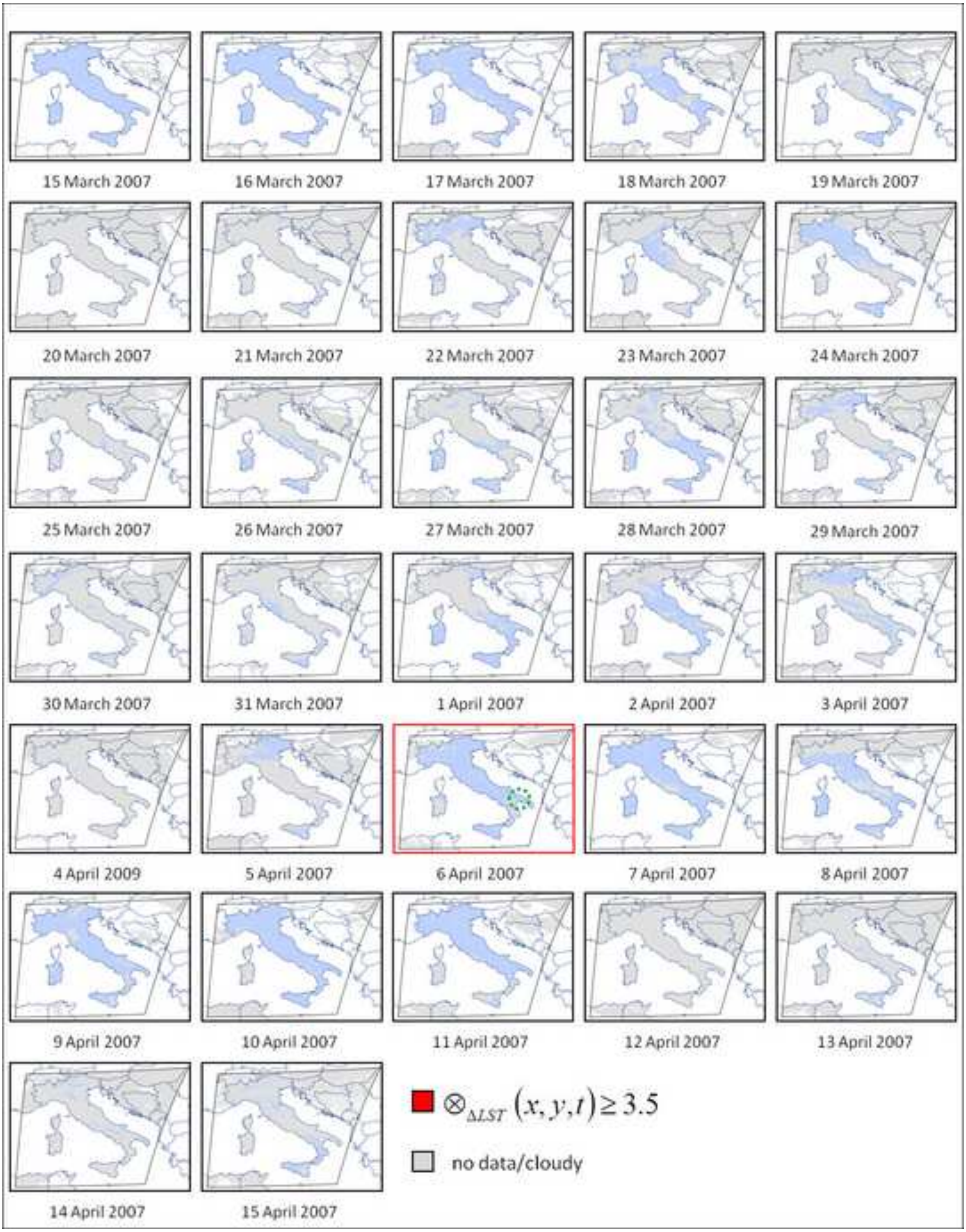
Figure 5. Confutation phase: results of the RETIRA index computation over the investigated area for the relatively unperturbed year 2007. Red boxes contour images containing LST anomalies with $\otimes_{\Delta LST}(x,y,t) > 3.5$. Green circles indicate the areas of occurrence of LST anomalies.


10°E
15°E
20°E
45°N
40°N
19/04/2009
05/04/2009
31/03/2009
30/03/2009
22/04/2009
28/03/2009
06/04/2009
29/04/2009
13/03/2009
06/03/2009
07/03/2009
10/03/2009
11/03/2009
25/03/2009
23/03/2009
16/03/2009
19/03/2009
19/03/2009
20/03/2009
3.5 - 3.9
4.0 - 4.4
4.5 - 4.9
5.0 - 5.8


15 March 2009
16 March 2009
17 March 2009
18 March 2009
19 March 2009
20 March 2009
21 March 2009
22 March 2009
23 March 2009
24 March 2009
25 March 2009
26 March 2009
27 March 2009
28 March 2009
29 March 2009
30 March 2009
31 March 2009
1 April 2009
3 April 2009
4 April 2009
5 April 2009
6 April 2009
7 April 2009
8 April 2009
9 April 2009
10 April 2009
11 April 2009
13 April 2009
14 April 2009
15 April 2009
🟥 $\otimes_{\Delta LST}(x,y,t) \geq 3.5$
☐ no data/cloudy


21 March 2009
28 March 2009
30 March 2009
31 March 2009
1 April 2009
4 April 2009
5 April 2009
🟥 $\otimes_{\Delta LST}(x,y,t) \geq 3.5$
🟧 $\otimes_{\Delta LST}(x,y,t) \geq 3$
🟨 $\otimes_{\Delta LST}(x,y,t) \geq 2.5$
⬜ no data/cloudy
tectonics lineament


10°E
15°E
20°E
45°N
40°N
35°N
16/04/07
03/03/07
26/03/07
12/04/07
16/04/07
Magnitude (Ml)
4,0 - 4,5
4,5 - 4,9
> 5,0


15 March 2007
16 March 2007
17 March 2007
18 March 2007
19 March 2007
20 March 2007
21 March 2007
22 March 2007
23 March 2007
24 March 2007
25 March 2007
26 March 2007
27 March 2007
28 March 2007
29 March 2007
30 March 2007
31 March 2007
1 April 2007
2 April 2007
3 April 2007
4 April 2009
5 April 2007
6 April 2007
7 April 2007
8 April 2007
9 April 2007
10 April 2007
11 April 2007
12 April 2007
13 April 2007
14 April 2007
15 April 2007
🟥 $\otimes_{\Delta LST}(x,y,t)\geq 3.5$
☐ no data/cloudy

Highlights

1) Robust Satellite Technique has been used in order to study the Aquila earthquake;
2) In this work we use LST data products instead than just TIR radiances at the sensor
3) The results obtained confirms and improve the ones obtained by using TIR radiances