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From visual comparison to Robust Satellite Techniques: 30 years of thermal infrared satellite data analyses for the study of earthquake preparation phases

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ABSTRACT This review paper reports the main contributions and results achieved after more than 30 years of studies on the possible relationships among space-time variation of Earth’s thermally emitted radiation, measured by satellite sensors operating in the Thermal InfraRed (TIR) spectral range (8-14 m), and earthquake occurrence. Focus will be given on the different existing methods/models to: 1) discriminate a possible pre-seismic TIR anomaly from all the other TIR signal fluctuations; 2) correlate such anomalies with space, time and magnitude of earthquakes; 3) physically justify such a correlation.

Key words: earthquake prediction, thermal radiation, satellite sensors.

1. State of the art

The Earth’s thermally emitted radiation, measured by sensors installed onboard satellite platforms in the Thermal InfraRed (8-14 μm) spectral range, will be hereafter referred to as TIR signal, expressed in Kelvin (K) degrees units of Brightness Temperature [BT][1].

Several studies have been performed in the past 25 years, based on TIR satellite imagery, which suggest the existence of a relationship between “anomalous” space-time TIR signal fluctuations (simply referred here onwards as “TIR anomalies”) and earthquake occurrence.

In literature, many authors cite the work of Gorny *et al*. (1988) as one of the first studies on possible relationships between an abnormal increase of TIR signal and earthquake occurrence in seismic active regions. The authors reported some short-term TIR enhancement occurred before the occurrence of some medium-to-large earthquakes in central Asia. However, some years

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[1] The Brightness Temperature BT [K] is obtained by inversion ($T=B_{\lambda}$-1) of the Planck function B_{λ} [T] substituting to the radiance B_{λ} [T] expected by a black body at the Temperature T [K] the measured radiance $I_{\lambda}=\varepsilon_{\lambda}\cdot B_{\lambda}$ [T] emitted by a target of unknown spectral emissivity ε_{λ} (i.e., $BT_{\lambda}=I_{\lambda}$-1 assuming the dependence of I_{λ} on BT identical to the one described by the Planck function in the case of B_{λ} and T. By definition for a blackbody ($\varepsilon_{\lambda}=1$) is $BT_{\lambda}=T$ and in general, at all wavelength, is $BT\leq T$.

before, by using AVHRR (Advanced Very High Resolution Radiometer located on board NOAA satellites), Wang and Zhu (1984) already reported TIR observations corresponding to soil surface temperature "anomalies", up to 2.5° C, in the zone of preparation of the 1976 Tanghsan earthquake (M_S>7.0).

Sometime after, Qiang *et al*. (1991, 1992, 1997) and Qiang and Dian (1992), using METEOSAT TIR satellite data, began to study several earthquakes occurred in China. In the case of the Datong earthquake (October 18, 1989: M~6.1) they considered the differences of TIR values observed in the epicentral area and in the north China Plain, reporting an "anomalous" increase of such differences (from 2 up to 6 K) 3 days before the earthquake. Qiang *et al*. (1991) report, in association with such TIR anomalies, significant increases in the concentration of CO_2 (from 3 to 4 times its normal value) and of other greenhouse gases (like H_2 and H_2O) in the atmosphere, with an abrupt reduction just one day before the event.

Qiang *et al*. (1992) report TIR anomalies few days before the Changsu event (February 9, 1990: M_S=5.1) in combination with an "anomalous" air temperature increase from the Earth surface up to an altitude of 5.5 km (with a maximum increase around 1.5 km).

Qiang and Dian (1992) report AVHRR TIR anomalies observed few days before the Gonghe earthquake (April 26, 1990: M_S=7.0) over an area of ~106 km^2. The same authors assert that eleven of fifteen earthquakes of magnitude greater than 5.1 occurring in China in 1989 had similar pre-event anomalies.

A similar method was applied by Huang and Luo (1992) to identify TIR anomalies in AVHRR images. In this case thermal anomalies were identified by comparing TIR images with a decadal temperature map obtained by interpolating ten-day averaged punctual temperature measurements. During the 1991 springtime, on the base of observed anomalies in crustal deformation, seismologists suspected that the Linfen area (China) was characterized by an increased seismic hazard. In order to analyze such a possibility, a specific project was approved by local authorities which was devoted to collect how many independent observations/information as possible. Among the others, a TIR satellite survey of AVHRR data was carried out by Huang and Luo (1992) for monitoring the changes in temperature. No thermal anomalies were detected and no strong earthquakes occurred in the area. Also, crustal deformation anomaly disappeared gradually since July 1991.

Using a different methodology, Tronin (1996, 2000) and Tronin *et al*. (2002, 2004), analyzing a sequence of AVHRR TIR data, identify the presence of positive pre-seismic TIR anomalies in correspondence of large linear structures and fault systems within the Earth's crust. The relationship between thermal anomalies and seismic activity was also suggested for central Asia (e.g., Gazli earthquake on March 19, 1984: M~7.3) and Japan (e.g., Kobe earthquake on January 16, 1995: M~6.9). In these analyses TIR anomalies were identified comparing TIR values of each image pixel with a reference value, calculated (as the spatial average value plus two times the standard deviation) over a "background" area selected (cloud-free, seismically unperturbed) on the same image. The authors report positive TIR anomalies (linked to active fault systems) up to distances of 200-1000 km from the epicentres. In China, TIR anomalies, up to 700 km in length and 50 km in wideness, were observed at the border between mountains and valleys. TIR anomalies were observed 6-24 days before earthquakes with M>4.7 and continued even one week after the main event. The maximum relative amplitudes of the observed anomalies amounted to 3 K. In Japan, TIR anomalies showed different characteristics: they were observed 7-10 days before the earthquakes, they had much smaller dimensions but higher relative amplitudes (up to 6 K).

A similar methodology [but in this case the criteria for selecting the “background” reference area are even less clear than in the case of the above quoted method of Tronin (1996, 2000) and Tronin *et al.* (2002, 2004)] was applied by Xu *et al.* (2000) using satellite data (almost 2000 images) provided by the Japanese Geostationary Meteorological Satellite (GMS), in order to study more than 60 earthquakes (M_S~6) occurred in east China from 1988. Reporting their results the authors show that about 66% of earthquakes occurred in the investigated area were preceded by evident infrared anomalies.

Lu *et al.* (2000), applying to NOAA/AVHRR data a methodology based on the images comparison, identify TIR anomalies (up to 8 K high) few days before the Zhangbei earthquake (M_S~6.2) occurred in China on January 10, 1998. Such method identifies TIR anomalies by:

- comparing manually the AVHRR image (radiometrically corrected for atmospheric effects) with a reference AVHRR image acquired in the preceding days chosen for representing “normal” thermal condition (low or no seismic activity, no meteorological disturbances, etc.) over the area;
- considering only TIR “anomalies” (but the amount of the TIR excess necessary to identify them is not indicated) occurring in correspondence of tectonic faults or regions.

Instead, Yang and Guo (2010) using geostationary satellite data provided by the Japanese MTSAT-1R (Multifunctional Transport Satellite) adopted a methodology of image comparison using a different approach. They first compared TIR images before the Zhangbei earthquake (January 10, 1998: M_S=6.2, 41.12° N, 114.51° E) with the images of the same period in the precedent years looking for possible TIR excesses (“anomalies”). Secondly, a subtraction method was used: for example, yesterday’s temperature is subtracted from today’s temperature (at the same hour of the day) and the temperature difference time series for subsequent days is plotted to find for which day the difference is maximum. Thirdly, in order to take into account occasional warming/cooling due to meteorological factors, the air temperature data of 700 weather stations from all over China was interpolated and a similar day-by-day subtraction method applied in order to identify small localized area of temperature increase (as meteorological fronts usually affect large areas).

TIR anomalies (identified in terms of local maximum temperature differences in the considered periods) are reported within 2 weeks before the main shock at distances from the epicentre less than 250 km by using satellite observations, less than 100 km by using meteorological stations.

Ouzounov and Freund (2004) use the Land (LST[2]) and Sea Surface Temperatures (SST) products, computed on the basis of radiances measured in the split-window bands (centred around 11 m and 12 m) of MODIS (MODerate resolution Imaging Spectroradiometer, onboard of Terra e Aqua satellites), in order to investigate the interaction between the ocean, the

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[2] Land Surface Temperature (LST) product can be used, instead of the simple TIR signal usually collected around 11m, for those sensors (like AVHRR and MODIS) having a second split-window TIR channels around 12 m. Differently from simple TIR radiances whose value depends on surface emissivity (highly variable with vegetation cover and soil moisture content as well as with atmospheric water vapour and aerosols content), LST is expected (with errors which however are higher than 3 K) to give an estimate of the land surface temperature corrected for the effects of atmospheric water vapour content and surface emissivity.

Earth surface and atmosphere before strong earthquakes. They report, six to five days before the Gujarat (India) earthquake (January 26, 2001: M~7.7), positive LST excursions (with a maximum of 4 K over an area of 100 km around the epicentre) in comparison with similar observations made in the same days the year after (in absence of similar seismic events in the area). No definition of thermal anomaly was given in this paper.

The attempt to identify thermal anomalies was done by using a different method in a subsequent paper of Ouzounov *et al.* (2006) where again, the Gujarat event and other strong earthquakes (e.g., Boumerdes, northern Algeria, May 21, 2003: M=6.8; Colima, Mexico January 21, 2003: Mw=7.8), were considered as test cases. The authors, on the base of the MODIS data, compute the difference $\Delta LST(t_i)$ between the daily LST root mean square, $LST_{RMS}(t_i)$ (i.e., the square root of the mean value of the quantity $LST^2(x,y,t_i)$ computed in an area of 100×100 km^2 centred on the epicentre) and its temporal average LST_{RMS} computed on the precedent 60 or 90 days. In order to identify possible pre-seismic anomalies, the quantity $\Delta LST(t_i)=LST_{RMS}(t_i)$ - LST_{RMS} is compared day by day with the same quantity computed for the same days (t_i, i=1,…,60) in the preceding year(s). Results partly confirm the ones already achieved for Gujarat event with $\Delta LST(t_i)$ values up to 4 K since 5-6 days before the event. Similar results are reported for the other considered events.

Saraf and Choudhury (2004, 2005a, 2005b, 2005c), Choudhury *et al.* (2006), Saraf *et al.* (2008, 2009, 2012) and Rawat *et al.* (2011), using TIR data from NOAA/AVHRR, studied various strong earthquakes (e.g., Gujarat in India on January 26, 2001; Boumerdes in Algeria on May 2003; Bam in Iran on December 26, 2003: M=6.6) analyzing TIR images 2 weeks before and after each seismic event. The authors just using a visual inspection of the TIR images are able to recognize meaningful anomalies of the TIR signal (about 5-7 K) close to the epicentral zone from 1 to 10 days before and within few days after the considered seismic events.

Saraf and Choudhury (2005c) using the data from SSMI [Special Sensor Microwave Imager onboard the satellite platform DMSP (Defense Meteorological Satellite Program)], a passive microwave sensor which, unlike TIR sensors, is able to collect Earth's emitted radiation also in the presence of clouds, were able to observe pre-seismic thermal anomalies (2-10 K of excesses in the measured BTs) in the same week of the Izmit (August 17, 1999: M_S=7.8) and of Hindukush (March 25, 2002: M_W=6.1) earthquakes and the week before the Kalat event occurred in Pakistan (March 4, 1990: M_W=6.1). In this case, weekly averages of the measured $\mathrm{M_W}$ signal were computed and the presence of anomalies evaluated by a simple visual comparison with the mean climatological temperature values computed for the same week in the previous 14 years.

In order to identify thermal anomalies, Yoshioka *et al.* (2005) compare LST products (obtained from AVHRR data) with a reference value "…*derived by averaging the temperature (LST values, editor's note) of four observation points taken from places, which are believed to have little or no relation with the case study earthquake*…". In the case of several strong earthquakes occurred in Japan (e.g., the Niigataken Chuetsu earthquake of October 23, 2004: M_W=6.6), they report a relative rise (2-10 K) of LST values in the epicentral areas just 2-3 days before the events.

Lixin *et al.* (2006) and Liu *et al.* (2007), just on the basis of visual interpretation of pre seismic TIR images from NOAA/AVHRR, reported some isolated and spoon-shaped high temperature areas near tectonic lineaments and the epicentre of the Dongsha (Taiwan) earthquake occurred on September 14, 1992 with: M_S=5.9.

Panda *et al.* (2007), using daytime LST images provided by MODIS sensor, reported some pre-seismic anomalies affecting a quite large area (about 111,000 km^2) a week before the Kashmir earthquake (October 8, 2005: M_W~7.6). In this case, at first, reference LST images for the considered dates were computed by averaging the LST images collected in the same days in the previous 5 years. Then LST difference images were generated by subtracting from the LST images collected during the days preceding the earthquake the corresponding reference LST images. Thermal anomalies were identified by simple visual inspection of the LST difference images of the days preceding the earthquake.

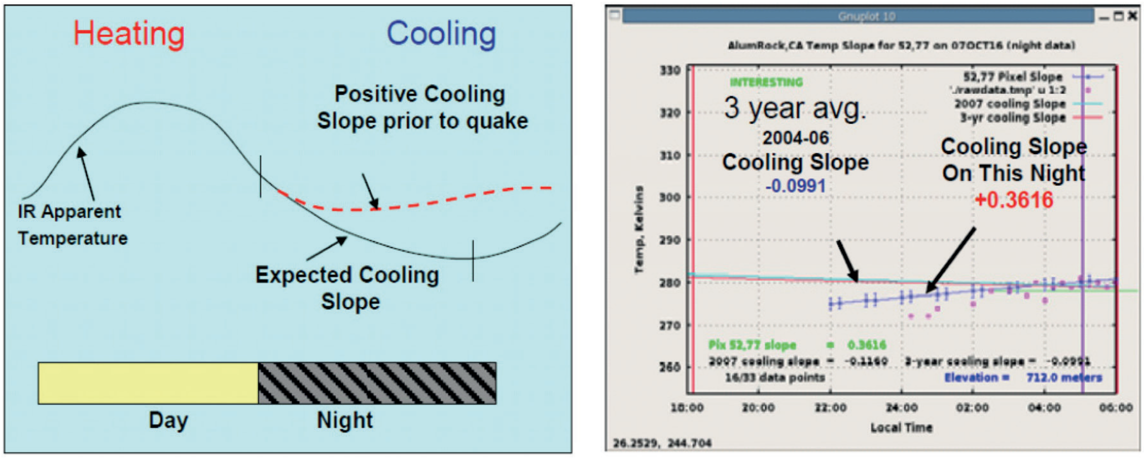
Qu *et al.* (2006), using NOAA/AVHRR data studied two seismic events occurred in Dayao, Yunnan Province (China) on July 21, 2003: M~6.2 and on October 16, 2003:, M~6.1, respectively. The authors, in order to avoid the disturbance due to persistent cloud coverage during the considered periods and observing that the temperature was higher than the background, focalized their analysis just on the fault area common to both events. The analysis was conducted dividing the area along the faults into three strips across its extending direction. Then the spatial average of TIR values were computed for each 130×10 km^2 region using only nighttime cloud free AVHRR images. Based on this approach, the annual variations of the BT around the fault for the year 2003 was compared with 1999 and 2004 years when no earthquakes with a magnitude greater than 6.0 occurred in the selected area. A persistent hot belt along the fault was noted by the authors with different time variations in the different segments. The authors report a higher average BT of the hot belt in the years with earthquakes than that in the years without earthquakes. No particular variations are reported in close correspondence of the considered earthquakes.

Huang *et al.* (2008) using thermal infrared data provided by MODIS sensor compare the TIR signal temperature measured in a (not defined) area around the epicentre of the Sichuan (China) earthquake (occurred on May 12, 2008: M_S~8.0) with the surrounding temperature of the scene reporting positive anomalies up to 5 K just one day before the seismic event.

Chen *et al.* (2006), Ma *et al.* (2010), Zhang *et al.* (2010, 2011), and Saradjian and Akhoondzadeh (2011) have performed a wavelet analysis on time series of TIR and/or LST image provided by satellite sensors, like NOAA/AVHRR, MODIS and the Chinese geostationary satellite FY-2C. Wavelet analysis was applied to the satellite imagery time series in order to isolate possible pre-seismic anomalies in Earth thermal emission field, from those (normal) variations due to the annual and daily solar cycle, to meteorological factors (including rain clouds, cold-heat air currents). Following this purpose, Chen *et al.* (2006) applied the wavelet method in order to separate the TIR signal acquired by NOAA/AVHRR in 3 frequency bands:

- high frequency band with period less than 1 year, which is related with weather;
- medium frequency band with predominant period of 1 year, related to the Sun, plant and seasons;
- low frequency band with period more than 1 year, related to the crustal activity and long-period variations of atmosphere temperature.

As a result they report that thermal anomaly of the low frequency band of LST is most likely related to fault activity and could offer a certain indicator of the tectonic activity of earthquakes. No firm conclusions but evidence of some correlation existing between tectonic activity and long-term variation of MODIS-LST residuals are reported by Ma *et al.* (2010), who also report



For Each Pixel

(10.7 μm) – (12 μm)
(long wave infrared window)
4 km pixel size

Fig. 1 - Nocturnal cooling model and typical cooling slope at Alum Rock site in normal condition and before the earthquake [adapted from Bleier *et al.* (2009), see text].

that major earthquakes can produce both LST rises and drops in the same area depending on the earthquake origin. By using a similar approach and TIR data coming from the Chinese GMS FY-2C, Zhang *et al.* (2010) report pre-seismic thermal anomalies extending for more than 10,000 km^2 up to 35 days before 3 great earthquakes occurred in China in 2008 (Wenchuan, May 12: M_S=8.0; Yutian-Xinjiang, March 21: M_S=7.3 12 and Pamirs, October 5: M_S=6.8). In the following paper, Zhang *et al.* (2011) report thermal anomalies up to six months before a M_S=7.2 earthquake occurred in north-eastern Myanmar on March 24, 2011.

The paper of Xie *et al.* (2013) presents a wavelet transform method to identify pre-seismic BT anomalies possibly associated with the Yushu (M_S=7.1) earthquake that occurred in one Qinghai province of China on April 14, 2010. By applying wavelet transform to daily infrared data collected by the Chinese 6MS FY-2E over the region 28.1°-38.1° N and 91.7°-101.7° E in the period from January 1, 2010 to December 31, 2011, they identify anomalies in the Relative Wavelet Power Spectrum (RWPS) both in the time and frequency domain: over the two analyzed years, RWPS showed anomalous variations in nine cases: two of these were followed by earthquakes.

The methods exploiting the high temporal repetition of geostationary TIR sensors to investigate possible "nocturnal heating" before strong earthquakes are based on the idea of N. Bryant [personal communication, 2007, see also: Ouzounov *et al.* (2006) and Bleier *et al.* (2009)]. In Bleier *et al.* (2009), 3 years of GOES-W IR (Geostationary Operational Enviromental Satellite-West) data are preliminarily used in order to characterize the behaviour of the nocturnal cooling expected in normal condition (Fig. 1). This is done by computing the average slope of the linear regression achieved for the function $BT(t)$ from t=6 p.m. to t=6 a.m., being $BT(t)$ the TIR BT measured by GOES-W in the 24 considered half-hour time slots in the previous 3 years. Daily mapping of the slope associated to each GOES-W pixel allow the authors to identify anomalous nocturnal heating effects (i.e., positive slopes of the nocturnal $BT(t)$ linear function) since 13 days before the M=5.4 Alum Rock (CA) earthquake occurred on October 31, 2007. In Ouzounov *et al*. (2006), the same approach is used to identify thermal anomalies just the night before Gujarat earthquake (January 26, 2001: M_W=7.7).

Looking for the same effect, Piroddi and Ranieri (2012) and then Piroddi *et al*. (2014) using MSG-SEVIRI (Meteosat Second Generation - Spinning Enhanced Visible and Infrared Imager) LST products, associate thermal anomalies to those pixels showing positive slope for the nocturnal $BT(t)$ linear function obtained by linear regression on the 41 LST measurements (one for each 15-minute slot between 6 p.m. and 4 a.m.) representing the average, on the previous 9 days, of the LST values measured at the same time (slot) of the day. In the case of Abruzzo (Italy) earthquake (April 6, 2009: M_W=6.3) they found thermal anomalies quite concentrated (distance < 100 km) around the epicentre during all the 8 days preceding the main shock.

Zoran (2012) analyzing an historical data set (2000–2011) of MODIS LST data, found thermal anomalies around the epicentral area of Tohoku/Sendai (Japan) earthquake (March 11, 2011: M_W=9.0) since two weeks before the main event as well as after the main shock. The LST anomalies were identified looking at the higher values of the quantity (LST-<LST>)/LST, being LST the spatial average of LST on the considered area and <LST> its multi-year mean value. In the case of March 11, 2011 Tohoku earthquake (M=9.0) they report LST-<LST> values up to 10 K by using MODIS observations and up to 5 K using AVHRR, since 2 weeks before the main shock.

In 2001, Tramutoli *et al*. (2001, 2005) start their work moving from a critical review of the previously quoted methods whose limits were so evident to justify the caution of the scientific community in accepting their results.

Even after several years, it is still possible to refer, (in different measure) to all the previously quoted methods, what Tramutoli *et al*. (2001) wrote introducing their first paper on this topic: the "*…relations of TIR anomalies with seismic activity have been considered, up to now, with some prudence by the scientific community mainly for the insufficiency of the validation data sets and the scarce importance attached to other causes (e.g., meteorological) that could be responsible, rather than seismic activity, of the observed TIR anomalies. Actually, a clear definition of TIR anomaly as well as a clear description of the satellite data processing phases which could permit to isolate TIR anomalies connected with seismic activities from any other cause, is very hard to find. Really this is a not trivial problem as satellite TIR radiances strongly depends on a number of natural (e.g., atmospheric transmittance, surface emissivity and topography) and observational (time/season, but also solar and satellite zenithal angles) conditions whose variable contributions to the investigated signal can be so high to completely mask (or simulate) the space-time anomaly possibly associated to the seismic event under study…*". Words further reinforced in Tramutoli *et al*. (2005): "*…Space-time fluctuations of TIR signal cannot, therefore, be assumed as pre-seismic TIR "anomaly" without referring them to a "normal" TIR signal behavior and without investigating whether or not similar space-time fluctuations can also be observed in the absence of seismic activity. Not only this fundamental "confutation" process but also a suitable definition of TIR "anomaly" (for "validation" purposes), are very hard to find in the above quoted studies…*".

Table 1 - Main studies and algorithms for pre-seismic TIR anomalies identification.

Methods	Authors	Satellite TIR sensors	Thermal Anomaly Definitions/ Indices	Reported Anomaly Intensities	Relation with EQ epicentre and time of occurrence		EQ Mag	Validation\ Confutation
					Affected area (km^2)	Time-lag		
M1	Qiang *et al.*, 1991, 1992, 1997; Qiang and Dian, 1992	MFG/MVIRI	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(t,H)$	2-10 K	100-50,000	3 days before	M 5.1 –7.0	V
M2	Huang and Luo, 1992	NOAA/ AVHRR	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(t,A)$	- - - -	- - - -	- - - -	- - - -	C
M3	Tronin, 1996, 2000; Tronin *et al.*, 2002, 2004	NOAA/ AVHRR	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(t,H)$	$\Delta T(x,y,t)> 2\cdot\sigma_T(t,H)$	35,000	6-24 days before 7 days after	M 4.7 – 7.3	V
M4	Xu *et al.*, 2000	GMS	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(t,H)$	>2 K	600,000	10 day before	M_S 7.6	V
M5	Lu *et al.*, 2000	NOAA/ AVHRR	$\Delta T(x,y,t) = T(x,y,t) - T(x,y,t')$ with $t'<t$	8 K	40,000	1-2 days before	M_S 6.2	V
M6	Tramutoli *et al.*, 2001; Di Bello *et al.*, 2004;	NOAA/ AVHRR	$\otimes_{\Delta V}(x,y,m)= \mu_{\otimes}(x,y)$ $V(x,y,t)= T(x,y,t)$	$\otimes_{\Delta V}(x,y,m)> 0,6$	100,000	3 days	$M_S = 6.9$	V&C
			$V(x,y,t)= LST(x,y,t)$	$\otimes_{\Delta V}(x,y,m)> 1$				
	Filizzola *et al.*, 2004; Corrado *et al.*, 2005; Tramutoli *et al.*, 2005; Aliano *et al.*, 2007, 2008a, 2008b; Genzano *et al.*, 2007, 2009a, 2009b, 2015; Lisi *et al.*, 2010, 2014; Pergola *et al.*, 2010; Eleftheriou *et al.*, 2015	NOAA/ AVHRR MFG/MVIRI GOES/ IMAGER MSG/SEVIRI EOS/ MODISGMS/ VISSR	$\otimes_{\Delta V}(x,y,t)=[\Delta V(x,y,t)-\mu_{DV}(x,y)]/\sigma_{DV}(x,y)$ with $\Delta V(x,y,t)=V(x,y,t)-\mu_V(t)$ $V(x,y,t)=T(x,y,t)$ or $V(x,y,t)=LST(x,y,t)$	$\otimes(x,y,t)> 1,5\div4$ (space/time persistence required)	100 -500,000	1-25 days before 1-5 days after	M_S 4.0 – 7.9	
M7	Ouzounov and Freund, 2004	EOS/MODIS	$\Delta LST(t)=LST_{2002}(d)- LST_{2001}(d)$	4 K	30,000	1-10 days days before	M_S 7.9	V
	Ouzounov *et al.*, 2006	EOS/MODIS	$DLST(t_i)=LST_{RMS}(t_i)- LST_{RMS}$				M_S 6.8 – 7.9	
M8	Saraf and Choudhury, 2004, 2005a, 2005b, 2005c; Choudhury *et al.*, 2006; Rawat *et al.*, 2011; Saraf *et al.*, 2008, 2009, 2012	NOAA/ AVHRR	Visual inspection	5-7 K	50,000-250,000	1-10 days before and 2-3 days after	M_W 5.8 – 7.7	V&C
M9	Yoshioka *et al.*, 2005	NOAA/ AVHRR	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(t,D)$	4-8 K	50,000	2/3 days before	M_W 6.8	V&C
M10	Lixin *et al.*, 2006; Liu *et al.*, 2007	NOAA/ AVHRR	Visual interpretation	4-5 K	80,000-920,000	1-25 days before and 2-3 days after	M_S 5.9	V
M11	Panda *et al.*, 2007	EOS/MODIS	$\Delta T(x,y,t)=T(x,y,t)-\mu_T(x,y,t)$	5-10 K	111,000	7 days before	M_W 7.6	V
M12	Halle *et al.*, 2008	NOAA/ AVHRR	As M6 with $V(x,y,t)=LST(x,y,t)$	$\otimes(x,y,t)>$ 2-3	2,600-5,000	2-10 days before and 4-7 days after	M =6.4-7.8	V&C
M13	Eneva *et al.*, 2008	EOS/MODIS	As M6 with $V(x,y,t)=LST(x,y,t)$ and with $\mu_{DV}(x,y)$ and $\sigma_{DV}(x,y)$ computed on 31 days before t	$\otimes(x,y,t)> 2,5\div3,5$	- - - -	20 days before - 20 days after	M 4.5 – 6.6	V&C
M14	Huang *et al.*, 2008	EOS/MODIS	Visual inspection	3-5 K	- - - -	1 day before	M_S 8.0	V

Table 1 - continued.

Methods	**Authors**	**Satellite TIR sensors**	**Thermal Anomaly Definitions/ Indices**	**Reported Anomaly Intensities**	**Relation with EQ epicentre and time of occurrence**		**EQ Mag**	**Validation\ Confutation**
					Affected area (km²)	**Time-lag**		
M15	Ouzounov *et al.*, 2006; Bleier *et al.*, 2009	EOS/MODIS GOES/ IMAGER	$T(x,y,t_i)=T_0+at_i$ $(6pm<t_i<6am)$	$a > 0$	- - - -	1-13 days before	M_W 7,7 *M* 5.4	V
M16	Piroddi, 2011; Piroddi and Ranieri, 2012; Piroddi *et al.*, 2014	MSG/SEVIRI	$<T(x,y,t_i)>=T_0+at_i$ $(6pm<t_i<4am)$		10,000	7 days before	M_W 6.3	V&C
M17	Chen *et al.*, 2010; Ma *et al.*, 2010; Saradjian and Akhoondzadeh, 2011	NOAA/ AVHRR EOS/MODIS	Wavelet transform	4-5 K	- - - -	15 days after	*M* >7.0	V
M18	Yang and Guo, 2010	MTSAT	$\Delta T_{year}(x,y,d)=$ $[T_{year}(x,y,d)-T_{year-n}(x,y,d)]-$ $T_{year}(x,y,d-1)$	4-5 K	30.000	1-14 days before	M_S 6.2	V
M19	Zhang *et al.*, 2010, 2011; Xie *et al.*, 2013	FY-2C FY-2E	Wavelet transform	4-10 K	10,000-600,000	Several days to 2 months before	M_S 7.2-9.0	V
M20	Saradjian and Akhoondzadeh, 2011	EOS/MODIS	interquartile, wavelet transform and Kalman filter method	1-4 K	- - - -	1-20 days before	M_W 6.1-6.6	V
M21	Zoran, 2012	EOS/MODIS	$\Delta LST(x,y,t)=(LST(x,y,t)-<LST>(t))/$ $LST(x,y,t)$	10 K	30,000	15 days before	M_W 9.0	V
M22	Xiong *et al.*, 2013	AATSR	As M6 using $\otimes_{\Delta V}(x,y,t)=[\Delta V(x,y,t)-\mu_{DV}(x,y)]/$ $\sigma_{DV}(x,y)$	$\otimes(x,y,t)>4$	130,000	15 days before	M_W 6.3	V&C

$T(x,y,t)$ = TIR signal measured in correspondence of the geographical coordinates (x,y) at the time t
$LST(x,y,t)$ = LST products computed in correspondence of the geographical coordinates (x,y) at the time t
$mT(t,D)$ = spatial average over a seismically unperturbed zone (D) on the same image
$mT(t,A)$ = spatial average over the same area (A) of punctual air temperature data (from meteorological stations and other sources).
$mT(t,H)$ = spatial average over a selected restrict area (H) on the same image (*cloud-free, seismically unperturbed*)
$\otimes_{\Delta V}(x,y,m)=\mu_{\otimes}(x,y)$ = monthly average of daily RETIRA index $\otimes_{\Delta V}(x,y,t)$
$<T(x,y,t_i)>$= average of $T(x,y,t_i)$ on ten days before $LST_{RMS}(t_i)$ = the square root of the mean value of the quantity $LST^2(x,y,t_i)$ computed in an area of MxN km² (in the considered case 100x100 km²) centred on the epicentre

LSTRMS = temporal average computed on the precedent 60 or 90 days
$T(x,y,t) = T_0(x,y) + a(x,y).t$ is the linear regression function computed on the base of 41 MSG-SEVIRI TIR values (41, 15-min slots between 6 pm and 4 am) $T(x,y,t_i)$ corresponding to the averages on the previous 9 days where a(x,y) is the coefficient of the linear regression $<T(x,y,t)>$ is the average of $T(x,y,t_i)$ computed for each
$LST_y(d)$=spatial average of the LST(x,y,t) image collected night-time on the day d of the year y over an area of MxN km² (in the considered case 100x100 km²) centred on the epicentre
d= Julian day

MFG/MVIRI =Meteosat First Generation/Meteosat Visible and InfraRed Imager
NOAA/AVHRR = National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer
GMS = Geostationary Meteorological Satellite
GOES = Geostationary Operational Environmental Satellite/IMAGER

MSG/SEVIRI = Meteosat Second Generation/Spinning Enhanced Visible and Infrared Imager
EOS/MODIS= Earth Observing System/Moderate Resolution Imaging Spectroradiometer
MTSAT= Multifunctional Transport Satellites
FY-2C= Fengyan 2C

In particular, with reference to the methods reported in Table 1 (hereafter indicated with Mn), with the exception of M6 and its variations used in the critical studies M12, M13 and M22, no one attempt was done to attribute a statistical significance to the excesses of the thermal signal which were reported as pre-seismic anomalies. By this way, variations $\Delta T(x,y,t)$ of the measured TIR signal $T(x,y,t)$ of only few degrees were reported as anomalies only because they are higher than some reference value [e.g., the spatial average $\mu_T(t,D)$ of $T(x,y,t)$] computed on a "seismically unperturbed" portion D of the same scene (like in the methods M1, M2, M3, M4, M9, M10, M14) without comparing them with the "normal" (i.e., not related to seismic events) variability of the signal, as observed in the past in similar observational conditions.

This circumstance also reduces the significance of the few confutation attempts made for instance in Saraf and Choudhury (2004, 2005b, 2005c), Yoshioka *et al*. (2005), Ouzounov *et al*. (2006), Piroddi (2011), Piroddi and Ranieri (2012), and Piroddi *et al*. (2014). In the other cases, the absence of whatever confutation attempt (devoted to control if or not similar TIR anomalies occur even in absence of earthquakes), prevented the authors to be warned of (and to account for) the possible occurrence of TIR anomalies related to "normal" space-time variations of the Earth's thermal emission.

This is a crucial point and first of all we have to demonstrate (by observations possibly supported by explanatory physical models) that a thermal signal actually related (in the space/time domain) to the earthquake occurrence exists and can be measured; only afterwards we will demonstrate the possibility of using TIR satellite surveys for earthquake prediction (which involved most of the efforts of quoted authors). But, how we will see in the next paragraph, some significant progress in this direction has been already achieved which poses (at least) the research in this field on a firm scientific ground. This is mostly due to the application of the general RST [Robust Satellite Technique: Tramutoli (1998, 2005, 2007)] approach to this kind of studies. This is the reason why a specific chapter will be devoted to this method and to its evaluation, independently performed, in the framework of projects funded by the National Space Agencies of Italy (ASI), Germany (DLR) and United States (NASA).

2. RST approach and RETIRA index

The method proposed by Tramutoli *et al*. (2001, 2005) is mostly based on the general approach RAT [Robust AVHRR Technique: Tramutoli (1998)]. Being all RAT-based algorithms solely based on satellite data at hand (do not requiring whatever ancillary data) they can be completely automated for operational real-time monitoring purposes. For the same reason, they are intrinsically exportable on different satellite packages, reason why the original name RAT was changed in the more general RST (Tramutoli, 2005, 2007).

The RST approach was used by Tramutoli *et al.* (2001, 2005) to isolate possible pre-seismic TIR anomalies from those signal variations which are related to known (see Table 2) but also unknown, natural and/or observational factors (what they call "natural/observational noise") that can be responsible of "false alarm" proliferation.

The RST methodology identifies space-time anomalies always with respect to a preliminarily defined "normal" (i.e., in unperturbed condition) signal behaviour which is achievable by the analysis of long-term series of satellite records.

In the case of TIR anomalies possibly associated to seismic events, the RETIRA [Robust Estimator of TIR Anomalies: Filizzola *et al*. (2004) and Tramutoli *et al*. (2005)] index $\otimes(\mathbf{r},t')$, was introduced which can be computed as follows:

$$\otimes(\mathbf{r},\mathrm{t}') \equiv \frac{\left[\Delta T(\boldsymbol{r},t') - \mu_{\Delta T}(\mathbf{r})\right]}{\sigma_{\Delta T}(\mathbf{r})} \qquad (1)$$

where:

- $\mathbf{r} \equiv (x,y)$ represents location coordinates on satellite image;
- t' is the time of acquisition of the satellite image at hand, with $t' \in \tau$ where τ defines the homogeneous domain of satellite imagery collected in the same time-slot (hour) of the day and period (month) of the year;
- $\Delta T(\mathbf{r},t') = T(\mathbf{r},t') - T(t')$ is the difference between the current ($t=t'$) TIR signal $T(\mathbf{r},t')$ measured at location $\mathbf{r}$, and its spatial average $T(t')$, computed *in place* on the image at hand, discarding cloudy pixels and considering only *sea* pixels, if $\mathbf{r}$ is located on the sea, only *land* pixels, if $\mathbf{r}$ is located over the land[3];
- $\mu_{\Delta T}(\mathbf{r})$ and $\sigma_{\Delta T}(\mathbf{r})$ are the time average and standard deviation values of $\Delta T(\mathbf{r},t)$, at location $\mathbf{r}$, computed on cloud-free satellite records belonging to selected homogeneous data set ($t' \in \tau$).

The $\otimes(\mathbf{r},t')$ index gives the *llocal*[4] excess of the current $\Delta T(\mathbf{r},t')$ signal compared with its historical mean value and weighted by its historical variability at the considered location. Both $\mu_{\Delta T}(\mathbf{r})$ and $\sigma_{\Delta T}(\mathbf{r})$ are computed for each location $\mathbf{r}$, processing several years of historical satellite records acquired in similar observational conditions. The excess $\Delta T(\mathbf{r},t') - \mu_{\Delta T}(\mathbf{r})$ then represents the Signal (S) which is to be investigated for its possible relation with earthquake space-time occurrence. It is always evaluated by comparison with the corresponding natural/observational Noise (N), represented by $\sigma_{\Delta T}(\mathbf{r})$[5]. This way, the intensity of anomalous TIR transients can be evaluated in terms of S/N ratio by the RETIRA index $\otimes(\mathbf{r},t')$. The RETIRA index is expected not only to be independent from the known sources of natural/observational noise, but also to strongly reduce them, as it is based on the comparison among measurements which are homogeneous respect to the observational conditions (daily and annual solar cycle, surface coverage and emissivity, etc.) which are responsible of most of TIR signal variability (Tramutoli *et al.*, 2001, 2005).

The RST technique has been applied for the first time to the observation of seismically active areas in the case of Irpinia-Basilicata earthquake (November 23, 1980: M~6.9). Using a historical data set of 5 years of NOAA/AVHRR satellite passes, collected in November from 1994 to 1998 around 18:00 GMT over the southern Italian peninsula, Tramutoli *et al.* (2001) showed how the use of RETIRA index can reduce the dependence on site properties like, topography, emissivity (strongly depending on vegetation cover), etc. (Fig. 2).

Although at a low S/N ratio, TIR anomalies (almost absents in non-seismic periods) were observed few days before the occurrence of the earthquake in some spatial correlation with the major faults in the area of study. These results were reinforced by Di Bello *et al.* (2004) who demonstrated that a doubling of the S/N ratio can be achieved by using AVHRR based LST products (which take into account the atmospheric water vapor variability) instead of simple TIR radiances as in Tramutoli *et al.* (2001).

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[3] Note that the choice of such a differential variable $\Delta T(\mathbf{r},t')$ instead of $T(\mathbf{r},t')$ is expected to reduce possible contributions (e.g., occasional warming) due to day-to-day and/or year-to-year climatological changes and/or season time-drifts.

[4] the double *l* has been introduced by Tramutoli (1998) (and will be hereafter used) to highlight a dependence not only on a specific place r but also on a specific time t'.

[5] $\sigma_{\Delta T}(\mathbf{r})$ describes the overall (*llocal*) variability of the signal S including all (natural and observational, known and unknown) sources of its variability as historically observed at the same site in similar observational conditions.

Table 2 - Main natural and observational factors affecting TIR (8-14 μm) signal (adapted from Tramutoli *et al.*, 2005).

Main factors contributing to TIR signal variability	**Description**
a) Surface spectral emissivity	Quite constant (~0.98) over oceans. Over land it is highly variable taking values within 0.90 and 0.98 mainly depending on soil vegetation.
b) Atmospheric spectral transmittance	Depends mainly on atmospheric temperature and humidity vertical profiles
c) Surface temperature (temporal variations)	Related to the regular daily and yearly solar cycles but sensitive also to meteorological (and climatological) factors
d) Surface temperature (spatial variations)	Depend on local geographical (altitude above sea level, solar exposition, geographic latitude) factors
e) Observational conditions (spatial variations)	Variations across the same scene of satellite zenithal angles introduce spatial variations of the registered signal not related to real near-surface thermal fluctuations
f) Observational conditions (temporal variations of satellite view angle)[a]	The same location is observed, at each revisiting time, at a different satellite zenithal angle: this introduces a spurious temporal variation of the measured signal due simply to the change in observational conditions (e.g., air mass)
g) Observational conditions (temporal variations of ground resolution cells)[a]	The change of satellite view angle also determines a sensible change in the size of the ground resolution cell. Spurious temporal variations of the measured signal have to be expected then because of the change in size of the ground resolution cell
h) Observational conditions (variations of the time of the satellite pass)[a]	Satellite pass occurs each day at different times falling in a time-slot up to 3 hours around the nominal time of pass. Spurious variations of the measured signal have to be then expected as a consequence of such (time) variability of observation condition

[a] Only for instrumental packages onboard of polar satellite (not applicable to geostationary platforms)

Fig. 3 shows how the reduction of the "natural noise" due to the variability of atmospheric transmittance (achieved passing from TIR radiances to LST products) increases from 0.6 to 1.0 the relative intensity of (monthly averaged) TIR anomalies and strongly reduces "false positives" in the confutation year 1998. The study of Filizzola *et al.* (2004) demonstrated, in the case of the Athens earthquake (September 7, 1999: M_S~5.9), the possibility to reach S/N ratios up to 1.5 by using daily (instead than monthly) RETIRA indexes $\otimes_{\Delta LST}(\mathbf{r},t)$. In this case, the authors, using a sequence of daily AVHRR images, report the appearance of (space-time) persistent TIR anomalies in the epicentral area some days before the seismic event (with a peak of intensity 4 days before the earthquake).

Since then, space-time persistence of TIR anomalies has been introduced as a further critical requirement in order to discriminate significant anomalies from residual spurious effects due to simple outliers, to geo-location errors or nighttime warm cloud shadows (see also: Aliano *et al.*, 2008a). Moreover, in the same paper, for the first time it was demonstrated the advantages expected of using TIR sensors on-board geostationary, instead than polar, satellite platforms. In fact, by using TIR data (i.e., even without correction for atmospheric water vapour variation) acquired from MFG (Meteosat First Generation) geostationary satellite (instead than LST products from the polar NOAA/AVHRR) they quite doubled the S/N ratio ($\otimes_{\Delta T}(\mathbf{r},t)>3$) associated to TIR anomalies observed in correspondence of the same (Athens) event.

Such abrupt improvement is to be solely attributed to a significant reduction of the observational noise (the denominator $\sigma_{\Delta T}(\mathbf{r})$ in the definition of RETIRA index) due to the fact that the last 3 elements of variability of TIR signal in Table 2 do not apply to sensors on-board

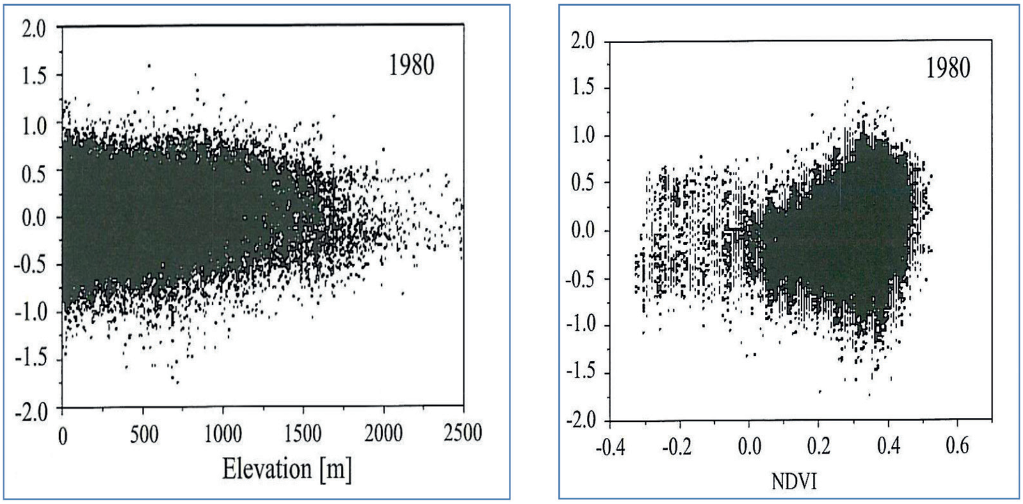

Fig. 2 - Dependence of RETIRA index (computed on AVHRR TIR images) on site properties (southern Italy, November 1980). Left, dependence on elevation; right: dependence on vegetation cover through the Normalized Difference Vegetation Index – NDVI (adapted from Tramutoli *et al.*, 2001).

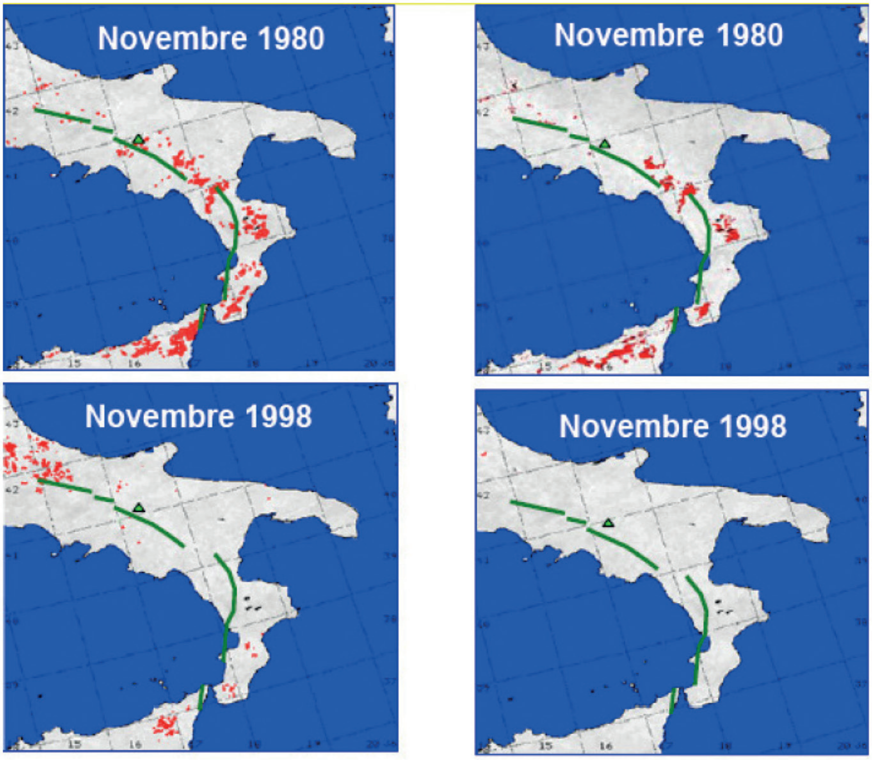

Fig. 3 - Monthly averages of RETIRA index based on AVHRR TIR radiances, $\otimes_{\Delta T}(r,m)$ (on the left) and on LST products, $\otimes_{\Delta L}ST(r,m)$ (on the right) calculated for the month (m=11) of (top) November 1980 (Irpinia earthquake) and (bottom) November 1998 (seismically unperturbed). In red TIR anomalies with $\otimes_{DT}(r,m)>0.6$ are depicted in the panels on the left (following Tramutoli *et al.*, 2001) and $\otimes_{\Delta LST}(r,m)>1$ in the panel on the right (following Di Bello *et al.*, 2004). The green triangle shows the position of the epicentre of the main shock of November 23, 1980 (adapted from Di Bello *et al.*, 2004)

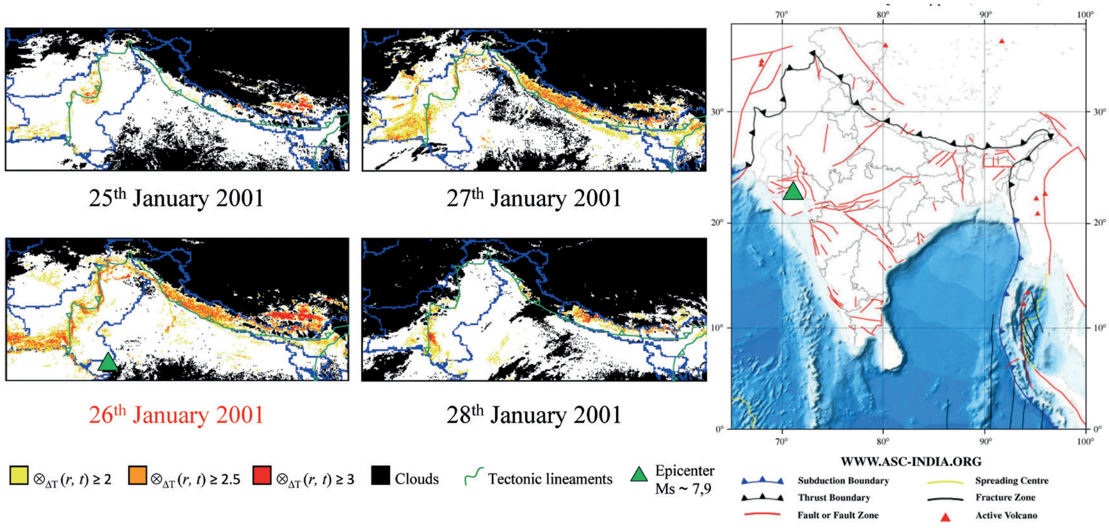

Fig. 4 - TIR anomalies detected by the RST approach since January 25 (1 day before Gujarat earthquake) up to January 28, 2001 (left) and the tectonic map of India subcontinent and the relative faults active since the Quaternary period (right). It is possible to note the correspondence between anomalous pixels and the tectonic boundary (adapted from Genzano *et al.*, 2007).

geostationary satellites. In fact, in this case, differently from what happens in the case of polar satellites, the same Earth's location is always "observed" with the same view angle, within the same ground resolution cell, exactly at the same time of the day.

In 2005, Tramutoli *et al.* (2005), related to the August 17, 1999: Kocaeli-Izmit (Turkey) earthquake (M_S=7,8), published in the top journal of remote sensing TIR anomalies $[\otimes_{\Delta T}(x,y,t)>3.5]$ observed until few days before and immediately after the main shock in apparent agreement with the "dilatancy model" of Scholz *et al.* (1973).

In the subsequent RST applications in the context of seismic active area monitoring, the space-time correlation between thermal anomalies and earthquakes was confirmed. In particular, in Genzano *et al.* (2007) the relationship between tectonic lineaments and thermal anomalies associated to the seismicity appears to be particularly evident[6] in the case study of Gujarat earthquake (January 26, 2001: M_S~7.9; see: Fig. 4).

Instead, Corrado *et al.* (2005) highlight the relation between TIR anomalies and earthquakes of medium-low intensity ($4.0<M_S<5.2$) occurred in Greece and Turkey from 1995 to 1996.

In Table 3, all seismic events which have been studied (and published) by applying the RST approach are reported, up to the L'Aquila earthquake (April 6, 2009: M_W=6.3) that was analyzed through independent RST analysis on 3 different satellite systems (namely MSG/SEVIRI, NOAA/AVHRR, and EOS/MODIS). In this case the authors (Genzano *et al.*, 2009b; Lisi *et al.*, 2010; Pergola *et al.*, 2010) found significant and simultaneous TIR anomalies in the epicentral area one week before the main shock and a few hours before its strongest foreshock (March 30, 2009 at 13:38 UTC: M_L~4.1).

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[6] See also Tramutoli (2013) and Blackett *et al.* (2011a, 2011b) to better appreciate how different can be the results achievable by using geostationary instead than polar satellites.

In all the previous quoted cases, confutation analysis was performed by considering the same period of time (month) in a different, seismically less affected, year. In the confutation phase rarely the presence of space-time persistent TIR anomalies of similar intensity was observed and quite always in connection with minor (but often with M>4.0) seismic events.

Table 3 - Seismic events which have been studied by applying the RST approach.

EVENT (date and magnitude)	**RST TECHNIQUES**	**REFERENCE DATA-SET (sensor, month, years, hour)**	**S/N ratio**
November 23, 1980, Irpinia-Basilicata-Italy M_s=6.9	$\otimes_{\Delta T}(x,y,m)$ monthly average (Tramutoli *et al.*, 2001)	NOAA-AVHRR - November (1994-1998) - 17:00 19:00	0.6
	$\otimes_{\Delta LST}(x,y,m)$ monthly average (Di Bello *et al.*, 2004)		1.0
September 7, 1999, Athens, Greece M_s=5.9	$\otimes_{\Delta LST}$ (x,y,t) daily analysis (Filizzola *et al.*, 2004)	NOAA-AVHRR - August and September (1995-1998) - 01:00 04:00	1.5
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Filizzola *et al.*, 2004)	METEOSAT - August and September (1995-1998) 24:00 GMT	3.0
August 17, 1999, Kocaeli-Izmit, Turkey M_s=7.8	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Tramutoli *et al.*, 2005)	METEOSAT August (1992-1998, 2000) - 24:00 GMT	3.5
	$\otimes_{T}$ (x,y,t) daily analysis (Aliano *et al.*, 2008a)	METEOSAT August (1995-2000) - 24:00 GMT	2.0
	$\otimes_{\Delta SST}$ (x,y,t) daily analysis (Halle *et al.*, 2008)	AVHRR 1997-2004 daytime	2-3
	$\otimes_{\Delta LST}$ (x,y,t) daily analysis (Halle *et al.*, 2008)	AVHRR 1998-2004 daytime- night-time	
May 28, 1995, Patras, Greece M_b=4.7	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Corrado *et al.*, 2005)	METEOSAT - May and June (1992-1999) - 24:00 GMT	3.0
May 29, 1995, Cyprus Greece-Turkey M_b=5.3			3.0
June 3, 1995, Crete, Greece Greece M_b=4.2			3.0
June 18, 1995, Crete, Greece Greece M_b=4,3			3.0
May 4, 1996, Erzurum,Turkey M_b=4.3			3.0
June 13, 1996, Ionian Sea (southern Greece) M_b=4.2			3.0
June 16, 1996, Patras, Greece M_b= 4.3			3.0
June 17, 1996, Crete, Greece M_b= 4.0			3.0
June 29, 1996, Isparta, Turkey M_b= 5.1			3.0
May 21, 2003 Boumerdes, Algeria M_s=6.9	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Aliano *et al.*, 2007, 2009)	METEOSAT - April and May (1992-1999) - 24:00 GMT	3.0

Table 3 - continued.

EVENT (date and magnitude)	**RST TECHNIQUES**	**REFERENCE DATA-SET (sensor, month, years, hour)**	**S/N ratio**
January 26, 2001, Gujarat, India M_S=7.9	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano *et al.*, 2007)	METEOSAT - January and February (1999-2004) - 24:00 GMT	3.0
September 26, 1997, Umbria-Marche, Italy M_S=5.9 to 6.4	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Aliano *et al.*, 2008b)	METEOSAT - September (1992-2000) –24:00GMT	2.0
October 16, 1999, Hector Mine, California M_S=7.4	$\otimes_{\Delta T}$ (x,y,t)) daily analysis (Aliano *et al.*, 2008a)	GOES (7-9-10)- October (1996-1999)- 24:00 LT	2.5
October 23, 1992, Mestia Tianeti, Georgia *M*=6.3	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano *et al.*, 2009a)	METEOSAT 7 October (1992-1999) - 24:00 GMT	3.0
Feb-2000 December 2006 83 Eq south-western US *M*=4.5÷6.6	$\otimes_{\Delta LST}$ (x,y,t) statistical correlation analysis (Eneva, 2008)	EOS-MODIS (Feb 2000–Dec 2006) 2442 daytime images EOS_MODIS (Jul 2002 – Dec 2006) 1625 nighttime images	|2.5|
April 6, 2009, Abruzzo, Italy M_w=6.3	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano *et al.*, 2009b)	MSG-SEVIRI March and April (2005-2009) - 24:00 GMT	4.0
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Pergola *et al.*, 2010)	EOS-MODIS March and April (2000-2009) - 24:00 GMT	3.5
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Lisi *et al.*, 2010)	NOAA-AVHRR March and April (1995-2009) - 24:00 GMT	3.5

3. Independent studies on the use of RST approach and RETIRA index for pre-seismic TIR-anomaly research

As already mentioned, the method proposed by Tramutoli *et al.* (2001, 2005) has been independently tested by several researchers around the world as well as in the framework of several projects funded by National Space Agencies, like the Italian ASI in 2002 [SEISMASS (Seismically Active Areas Monitoring by Advanced Satellite Techniques)] the U.S. NASA [Thermal Properties of Faults in Southern California From Remote Sensing Data, 2005-2007: Eneva *et al.* (2008)] and the German DLR [Early Warning of Earthquakes by Space-Borne InfraRed Sensors, 2005-2008: Halle *et al.* (2008)], as well as in the most recent EC-FP7 project named PRE-EARTHQUAKES (Processing Russian and European EARTH observations for earthQUAKE precursors Studies, 2011-12: http://www.pre-earthquakes.org). Several Ph.D. and Master Degree theses were also dedicated to the scope: some time only as a first (and last) attempt to come into the field [e.g., Blackett (2009), see also the comments by Tramutoli (2013) on the *occasional* paper of Blackett *et al.* (2011a), partly revised in Blackett *et al.* (2011b)], sometime as a starting point for an original research line (e.g., Piroddi, 2011; Okyay, 2012). We will refer in the following only to the studies that can be considered "independent[7]" and, under different profiles, relevant to this review.

Even if never published nor submitted to an ordinary peer review process, the study commissioned by NASA to Eneva *et al.* (2008) is surely one of the most statistically significant;

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[7] Not for instance to the results of SEISMASS and PRE-EARTHQUAKES projects both coordinated by V. Tramutoli.

it has been also the object of a discussion within the EMSEV[8] community (see for instance: Tramutoli, 2011) since 2010, and has been recently cited in support to the conclusions of the International Commission on Earthquake Forecasting [the so called Jordan's Commission: Jordan *et al.* (2011)] committed by the Italian Government to report on the state of knowledge on operational earthquake forecasting for Civil Protection.

In their report, after analyzing some of the other methods present in literature, Eneva *et al.* (2008) declare: "*We used as a starting point the state of the art RAT technique described by the Italian researchers (Tramutoli, 1998; Filizzola et al., 2004; Corrado et al., 2005)*" recognizing RST (previously named RAT) as the best available methodology to be used (and possibly improved) for their study[9].

They consider in the south-western part of the United States (Fig. 5) all the 83 occurred seismic events with M=4.5÷6.6, in the period between 2000 and 2006. A smaller portion of the same area was also considered being, however, both testing areas significantly smaller than the ones used in previous RETIRA index computation.

Different RETIRA and RETIRA-like indexes, based on EOS/MODIS LST products (MOD11A1), were computed for 2442 daytime and 1625 nighttime images. A non-parametric Kolmogorov-Smirnov (KS) significance test (at the 0.05 level of significance) was then applied to identify differences between the distributions of (the proportions of) anomalous (>2.5) RETIRA-values in four types of time intervals: b=t days before the quake; a=t days after the quake; c=within two or more events (clusters) distant less than t days each other; q=seismically quiet, i.e., outside previous periods.

The analysis was performed for different combinations of the implementation parameters the most important being:

- the time lag t=20, 15, or 10 days, used to define the b, c, a, and q periods;
- the used satellite data set, image/portion and observation time: Terra, early in the night, 82 months from February 2000 to December 2006, Terra-sub, the same over a restricted data set of 54 months from July 2002 to December 2006; Aqua, 3 hours later in the night, 54 months from July 2002 to December 2006;
- the implementation of additional improvements like: a) the implementation of a cloud edge filter (removing 2 or 4 pixels along cloud edges) devoted to guarantee a more conservative cloud-mask; b) the exclusion of images with cloud percentages over defined thresholds (50%, 60% and 70%).

Very remarkable results were achieved by using the standard RETIRA index in particular after the above mentioned improvements suggested by Eneva *et al.* (2008). In fact, Fig. 6a shows that, as soon as we consider t=15 and even better with t=20:

- all the significant comparisons of classes, bq, cq, aq (comparing seismic with quiet periods) appear only with positive sign (which means that TIR anomalies appears

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[8] EMSEV is an IUGG (IAGA-IASPEI-IAVCEI) Inter Association Working Group on Electromagnetic Studies of Earthquakes and Volcanoes who, since long time link together most of the international community of scientists working on earthquake precursors.

[9] The use of RAT/RST approach as a starting point for further improvement in TIR data analysis is not difficult to find even in minor scientific literature, for instance Li *et al.* (2007) after the application of different data analysis methods to the case of the Zhangbei earthquake (January 10, 1998: MS=6.2) conclude: "*…The comparison results indicate that Robust AVHRR Technology (RAT) is a better method for detecting pre-earthquake thermal anomaly…*"

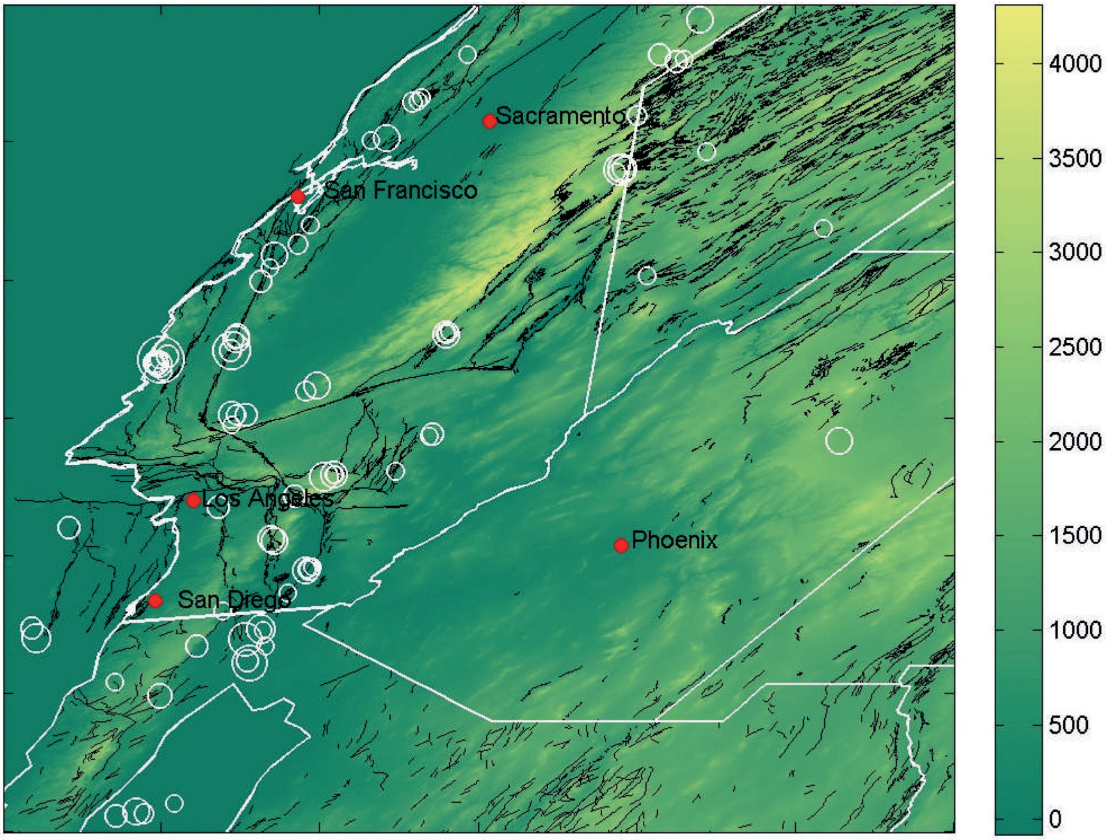


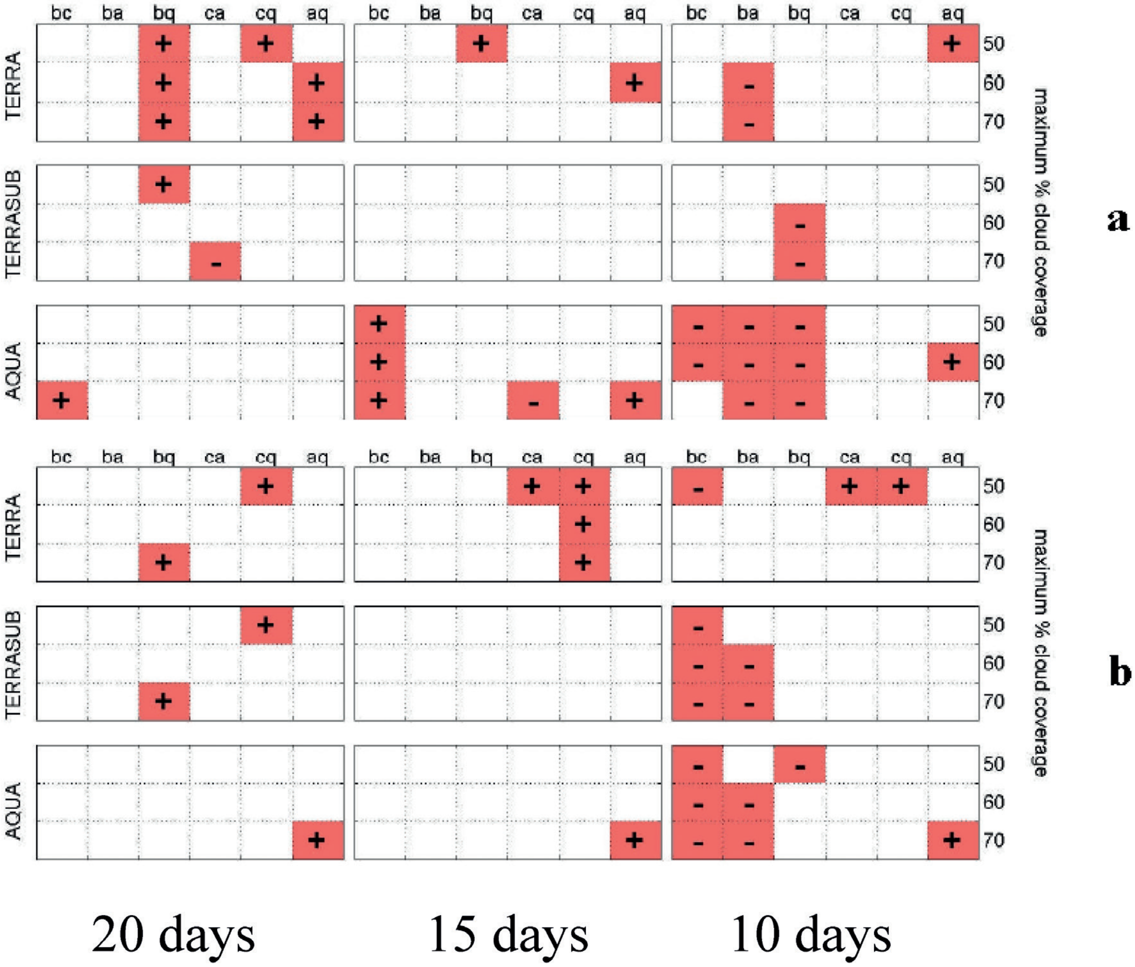
Fig. 5 - Test area used in the Eneva *et al.* (2008) study. MOD11A1 tile in sinusoidal projection. Active faults (black lines), borders, $M \geq 4.5$ earthquakes, major cities and elevation in metres are also shown (adapted from Eneva *et al.*, 2008).

significantly more frequently in relation with earthquake occurrence than in their absence);
- the above quoted comparison (*bq*, *cq*, *aq*) appears nowhere with negative signs.

Such conclusion is confirmed even after the introduction of a substantial modification of RETIRA index (computation of reference fields for means and standard deviations not more for each month on the base of corresponding records in the past years but on the base of monthly moving averages, i.e., 31-day windows) proposed by the authors of the NASA report. In Fig. 6b it is possible to note that, even if less stable, such a choice makes the results less dependent on the length of the used data set (Terra, Terra-sub, Aqua) as depending only on the satellite data of the year of the image at hands.

It should be noted that so important results were achieved applying the RST approach not in the condition most favorable (geostationary satellites, wide areas and long-term time series to increase the statistics, etc.) for reducing the observational noise. In fact, the investigated area (the same used for computing spatial averages) was relatively small, also relatively small was the overall data set (considering not only the reduced number of analyzed years but also the strict constraints imposed on the percentage of clouds per image as well as by the additional filter applied to the cloud masks).

Moreover, the analysis of Eneva *et al.* (2008) does not apply the fundamental “persistence



a

		20 days						15 days						10 days					
		bc	ba	bq	ca	cq	aq	bc	ba	bq	ca	cq	aq	bc	ba	bq	ca	cq	aq
TERRA	50			+		+				+									+
	60			+			+						+		-				
	70			+			+								-				
TERRASUB	50			+															
	60															-			
	70				-											-			
AQUA	50							+						-	-	-			
	60							+						-	-	-			+
	70	+						+			-		+		-	-			

b

		20 days						15 days						10 days					
		bc	ba	bq	ca	cq	aq	bc	ba	bq	ca	cq	aq	bc	ba	bq	ca	cq	aq
TERRA	50					+					+	+		-			+	+	
	60											+							
	70			+								+							
TERRASUB	50					+								-					
	60													-	-				
	70			+										-	-				
AQUA	50													-		-			
	60													-	-				
	70						+						+	-	-				+

Fig. 6 - KS-tests for positive LST anomalies with R>+2.5, using corrections for cloud edges within 4 pixels: a) with $R \equiv$ RETIRA index (i.e., with month-specific means and standard deviations); b) using moving averages with a 31-days moving window. Results are separately reported for different image data sets Terra (night, 82 months), Terra-sub (night, 54 months) and Aqua (night 3 hours later, in the same 54 months) and, from left to right, for t=20 days, 15 days and 10 days (adapted from Eneva *et al.*, 2008, see text).

criterion" [which is an integral part of the RST approach since Filizzola *et al.* (2004), Tramutoli *et al.* (2005), Genzano *et al.* (2007, 2009b), Aliano *et al.* (2008a, 2009), etc.] which discards, as not significant, all those TIR anomalies which are not persistent in space (e.g., single points) and in time (e.g., short-lasting). From this point of view, the Eneva *et al.* (2008) report [like the first paper of Tramutoli *et al.* (2001)] represents a very preliminary (blind) test whose results (quite surprising indeed) can be used to simply indicate if TIR anomalies computed following a RST based approach are, or not, in some way related to major earthquake occurrence in the considered area.

For these reasons, the results achieved by Eneva *et al.* (2008) are much more important than it could be expected:

- in terms of TIR anomaly relative intensity (≥2.5) which is the highest ever achieved before by using LST products from sensors onboard polar satellites [it was ≥1.0 in Di Bello *et al.* (2004), ≥1.5 in Filizzola *et al.* (2004)];

- in terms of possible correlation with seismic activity considering that all TIR anomalies have been included into the analysis without excluding the ones (usually the large majority) which do not meet the "persistence criterion".

Nonetheless, Eneva *et al.* (2008), probably hunting for the magic "silver bullet", were not happy of their results that they summarize using the following words: " … *While we did observe occasional temperature increases before M>4.5 earthquakes in California, such anomalies are common at other times as well, so we concluded that they cannot be used for earthquake prediction, including the case of the two largest events (M=6.0 and M=6.6) during the study period.…*". The fact that "other times" were only the periods immediately after the earthquake or in between two, close in time, earthquakes, is not mentioned at all. Yet, the occurrence of co-seismic and post-seismic TIR anomalies were widely documented not only in the fundamental (but not cited) papers of Tramutoli *et al.* (2005) and Genzano *et al.* (2007) but also in the few ones that Eneva *et al.* (2008) evidently cited without a carefully reading (e.g., Filizzola *et al.*, 2004). Moreover, physical models which foresee the occurrence of co-seismic and post-seismic TIR anomalies were already clearly proposed (at least) in Tramutoli *et al.* (2005) also in relation with more general and older models (e.g., Scholz *et al.*, 1973).

The lack of specific expertise (do not affecting the quality of the analysis done but "only" their interpretation), quite evident in the report of Eneva *et al.* (2008), appears to be an actual and not isolated problem; this report, never published nor peer reviewed, and their results (reported with the same identical words quoted before) were considered sufficient by the International Commission on Earthquake Forecasting for Civil Protection (Jordan *et al.*, 2011) to state: "… *In contrast, a systematic survey of satellite data collected over a seven-year interval in California found that the natural variability of TIR anomalies was too high to allow statistically significant correlations with seismic activity* …". That is not exactly what the cited report of Eneva *et al.* (2008) says but exactly the opposite of what it (with all the above mentioned limits) demonstrated[10].

In case the authors of Jordan *et al.* (2011) report will decide to more carefully read the Eneva *et al.* (2008) report, they will be surely more prudent to support its conclusive interpretation: in fact, following the same logic, it would be impossible to propose whatever prognostic use of foreshock sequence analysis for the simple reason that also aftershocks exist.

Other RETIRA-like indexes have been proposed and tested in the same report that will be not discussed here due to the poorness of results [like in the case of the use of two MODIS

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[10] For pity's sake let's skip the collection of:

- wrong statements ("… *Detection of TIR anomalies is limited by the spatial and temporal sampling of the earthquake regions afforded by the satellite based sensors*…", 1-4 km every 15-30 minutes for all the world since 30 years, what better ?);
- not scientifically demonstrated assumptions ("*Purported precursors show … irregular scaling with earthquake magnitude* …", why it should be regular ?);
- obvious prescriptions ("*The data processing is quite complex and must account for large variations in near-surface temperatures associated with solar cycles and atmospheric, hydrological, and other near-surface variations* … ") which, instead, have been clearly addressed since the first papers on the RST approach and RETIRA index application to the study of earthquake preparatory phases;
- examples of evident difficulties in navigating outside a, non-strictly seismological, scientific literature ("…*The background noise - TIR signal not associated with earthquake activity - has not been systematically characterized* …" well known studies exist since years starting exactly from this point);

that substantiates the Jordan *et al.* (2011) report (at least) in the part devoted to thermal anomalies (see also: Tramutoli, 2011).

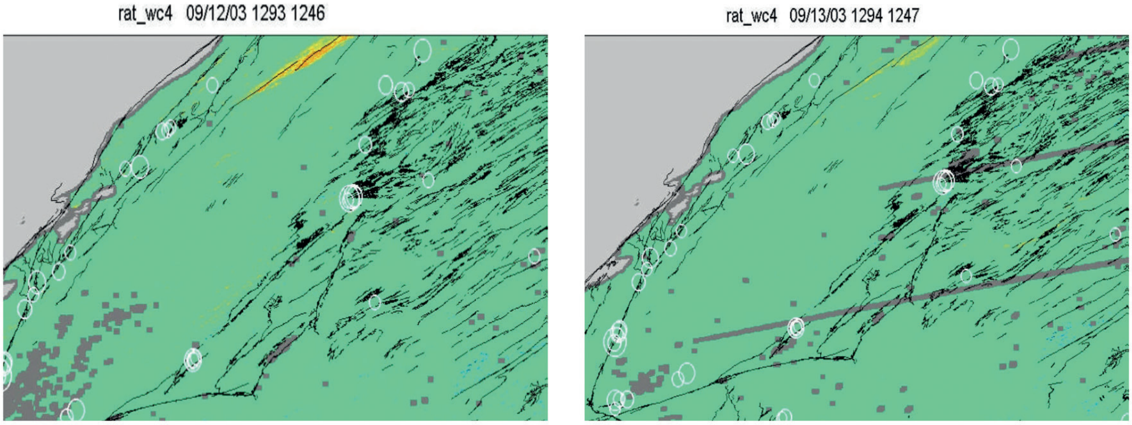

Fig. 7 - Anomalously high RETIRA values (in yellow) associated with Corning and Great Valley fault zones on the northern edge of the tile (from Eneva *et al.*, 2008), on two consecutive days (straight grey lines are data errors).

Terra and Aqua close nighttime passes to look for the same worming effect already exploited by Bleier *et al.* (2009), Piroddi (2011), Piroddi and Ranieri (2012) and Piroddi *et al.* (2014)] and/or to the absence of whatever physical justification (like for the search of negative TIR anomalies with RETIRA−2,5). One exception should be done for the reference that Eneva *et al.* (2008) give to some well localized and persistent TIR anomalies which " … *appear strongly associated with mapped fault zones without earthquake occurrence* ..." (Fig. 7) and surely merit to stimulate further studies.

Like Eneva *et al.* (2008), Halle *et al.* (2008) consider the RST approach and RETIRA index computation the best starting point for their TIR anomaly analyses contained in the final report of the 4-year project (2005-2008) "Early Warning of Earthquakes by Space-Borne InfraRed Sensors" funded by the German Space Agency (DLR). Differently from Eneva *et al.* (2008) and much more from Jordan *et al.* (2011), they demonstrate to have a deep knowledge of the scientific literature and a quite[11] good understanding of the potential of RST approach "…*to account as good as possible both for spatial and temporal background variability…*".

They compute standard RETIRA indexes on the base of SST and LST products obtained by NOAA/AVHRR data. They analyze space-time distribution of TIR anomalies in different original ways (i.e., looking at the temporal dynamics of the total number of anomalies within selected small areas). They report significant SST anomalies before the Izmit (Turkey) earthquake (August 17, 1999: M_S=7.8) and a Greek earthquake occurred on August 14, 2003 (M~6.4).

Their conclusions can be resumed in the following points:

- "*…SST based Robust Estimator of Thermal InfraRed Analysis (RETIRA) anomalies, which could be related to the earthquakes, were stronger than the nighttime LST RETIRA anomalies and better spatially localized, probably due to the physical mechanism of up-welling. This allows to recommend monitoring of SST based RETIRA anomalies in sea areas over plate boundaries or major faults, where water up-welling could be directly related to precursors of seismic activity"*;

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[11] However in their conclusion they complain the difficulty to exactly determine TIR emissivity (and correct LST values) over arid and semi-arid regions do not considering the fact that RETIRA index does not depend on the emissivity if the reference data set is correctly built using images collected all at the same observation time and period of the year.

- *"it is further recommended to look for time coincidences of adjacent SST RETIRA anomaly peaks. Nighttime LST based RETIRA anomalies are weaker and have a more "diffuse" character compared to such from SST maps. In this case, it is recommended to account the total area or the total intensity of nighttime LST RETIRA anomalies in the region for earthquake precursor monitoring";*
- "*further, SST anomalies can be separated and localized by two-dimensional multi-resolution wavelet approaches. However, for a reliable precursor detection, the wavelet approach should be applied in combination with multi-temporal techniques (for instance, RETIRA), techniques developed for the detection of ionospheric earthquake precursors and other recognition approaches developed for earthquake monitoring…*".

Also Akhoondzadeh (2013) applies the RST approach on LST products provided by EOS/MODIS satellite systems in the period July-August 2007 - 2012, in order to study the Varzeghan (Iran) earthquake (August 11, 2012: M_W=6.4). The author report LST anomalies (considering the simple value of LST instead that a differential variable at location *r*) with S/N>1.5 five days before the earthquake.

Xiong *et al*. (2013) apply the RST approach to TIR data collected by AATSR sensor (onboard ESA's Envisat spacecraft) to the L'Aquila earthquake (April 6, 2009: M_W=6.3). Reference fields were computed on the base of 7 years of AATSR data (collected from 2003 to 2009 in March and April) and space-time persistence was required in order to identify space-time TIR anomalies to be considered for their possible correlation with the occurrence of Abruzzo seismic sequence. The authors report several anomalies before (March 29, 2009) and after the Abruzzo earthquake. This is one of the few cases where also a confutation analysis is performed which allows authors to argue that anomalies observed from March 29, 2009 to April 5, 2009 (i.e., since 8 days before Abruzzo earthquake) could be associated with the Abruzzo earthquake.

On the basis of the previously reported studies on seismic prone areas, space/time persistent TIR anomalies observed by RST-based methods appear to share some common features which may be summarized as follow:

a) temporal domain: they have been observed from 4 weeks to few days before as well as immediately after (lasting up to 2 weeks more) earthquakes of M>4.0;
b) spatial domain: they often follow the distribution of main faults in the study areas but they have been also detected at distances of several hundreds of kilometres from the epicentre. In any case, spatial resolution does not seem to be the main constraint for satellite packages devoted to such studies;
c) intensity: it is generally low, in absolute terms, so that refined methods, like RST, are mandatory in order to discriminate them from those signal variations produced by changes of other natural/observational conditions;
d) no apparent relation has been observed until now (but no specific studies have been performed yet) between TIR anomaly extension/intensity and the magnitude/depth of the subsequent earthquake;
e) they have never been proposed for earthquake prediction [as is evident for instance in Tramutoli *et al*. (2001, 2005), where also satellite records collected after the year of the main event are used to build the reference data set] but their possible correlation with earthquake occurrence has been confirmed by several (also independent) studies.

4. Physical models

Several physical models have been proposed to justify a possible relation between anomalous variations of Earth's TIR emission and earthquake occurrence. The most quoted models refer to (see: Tramutoli *et al.*, 2013 and references therein):

1. increasing of green-house gases (like CO_2 and CH_4) emission rates [Qiang *et al.* (1991), Tronin (1996), Tramutoli *et al.* (2001, 2005, 2013), Singh *et al.* (2010), Zhang *et al.* (2010), Qin *et al.*, 2013 and references therein], together with deep-water rise and convective heat flow towards the surface (Tronin *et al.*, 2002; Surkov *et al.*, 2006) with increasing soil moisture and surface emissivity (e.g., Qin *et al.*, 2013);
2. activation of positive-hole pairs in rocks under stress (Wu *et al.*, 2000, 2002, 2006a, 2006b, 2012; Ouzounov and Freund, 2004; Freund *et al.*, 2006, 2007; Freund, 2007a, 2007b; Wu and Liu, 2009;).
3. anomalous ionization of near surface air due to intensive radon (Rn) emission over active tectonic faults and tectonic plates borders (Pulinets, 2004, 2006, 2009; Pulinets and Boyarchuk, 2004; Yasuoka *et al.*, 2006; Pulinets and Ouzounov, 2011).

It is possible to note that most of the processes mentioned above are in some way related to gas emission, mainly Rn and CO_2 or CH_4 (which are also carriers of Rn). However, it is worth stressing that each possibility does not preclude that further contributions to TIR signal increasing can be originated by other (concurrent) processes, differently related [like the one described in Freund (2007a, 2007b)] to the build-up of tectonic stresses before major seismic events.

Conductive heat transport from the focal zone up to the surface has been instead firmly excluded by Tronin (1996), whose computations indicate that the process would be too slow compared to the much more rapid development of observed anomalies.

In the following we will discuss the above mentioned processes in more details.

4.1. Increasing of greenhouse gases (like CO_2 and CH_4) emission rates

It is well known that Earth degassing activity (and particularly of optically active gases like CO_2 and CH_4) is generally more intense alongside seismogenic faults (e.g., Irwin and Barnes, 1980). Abrupt variations of such gases in near-surface atmospheric layers could result in a local greenhouse effect that increases near-surface temperature and, consequently TIR emission. The extensive process of micro-crack formation, as a consequence of the continuously increasing stress field, supports the increase of such degassing activity; it, together with deep-water rise and convective heat flow toward surface, could contribute to strongly increase TIR emission by increasing not only near surface temperature but also ground emissivity (See Fig. 8).

When the stress field becomes locally so high to close the cracks and earthquake occurrence is approaching, all the above processes (and then the measured TIR emission) are expected to reduce up to the time of earthquake occurrence. At this time, as a consequence of major cracks opening in the rupture zone, a new increase of degassing activity (and related phenomena) and TIR emission is expected before a gradual return to normality.

All these phases (manifestly coincident with the ones described in Scholz *et al.*, 1973) have been observed for instance by Tramutoli *et al.* (2005) by analyzing TIR anomalies observed before and after the Izmit earthquake (August 17, 1999: M_S=7.8). For the same event Barka

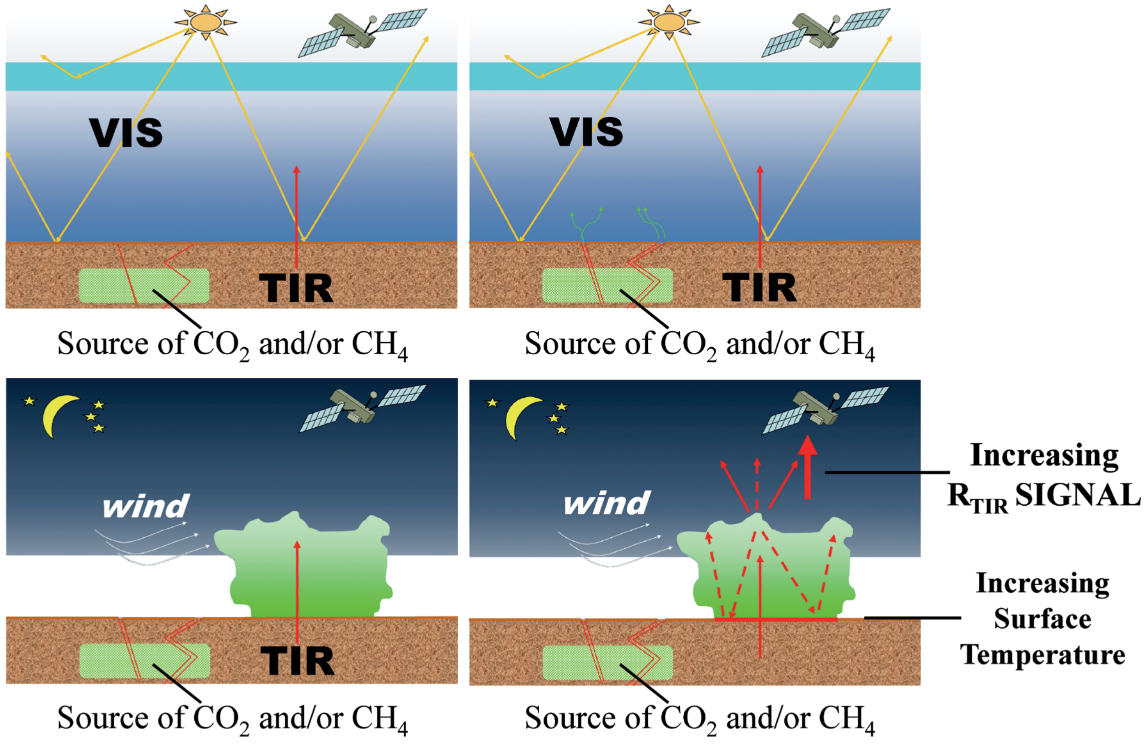

Fig. 8 - Physical model proposed by Tramutoli *et al.* (2001, 2005, 2013). In the preparatory phases of an earthquake, greenhouses gases, like CO_2 and CH_4, can reach the lower part of the atmosphere as consequence of their migrations through the fractures. These can locally operate like greenhouse gases, producing in this way an increase of TIR signal which is emitted by the Earth and measured by satellite sensors (adapted from Tramutoli *et al.*, 2013).

(1999) reported the appearance of an intense degassing activity, a few days before and up to several days after the main shock.

It should be noted that while earthquakes themselves (foreshocks, mainshocks, aftershocks) are generally expected [as in the model Scholz *et al.* (1973)] to increase fluids emissions, the role of deformation processes in modulating such emissions depends on local tectonic [see for instance: Doglioni *et al.*, (2014) and reference therein] and geochemical settings, which do not allow to make generalizations.

For instance, during the L'Aquila seismic sequence, local crustal deformations were monitored by laser strainmeters (Amoruso and Crescentini, 2010), by DInSAR satellite interferometry (e.g., Anzidei *et al.*, 2009; Luo *et al.*, 2014) and by GPS stations (e.g., Anzidei *et al.*, 2009). In all cases no significant pre-seismic deformations were detected[12] with the exception of the ones starting at the end of March 2009, reported but never published by Caporali (2009) on the base of GPS signals.

However, few days before the L'Aquila earthquake (April 6, 2009: M_W~6.3) Genzano *et al.* (2009b), Lisi *et al.* (2010), Pergola *et al.* (2010) and (independently) Piroddi and Ranieri

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[12] However, intrinsic limitations of observational techniques (see for instance: Bonfanti *et al.*, 2012) do not allow to exclude their occurrence.

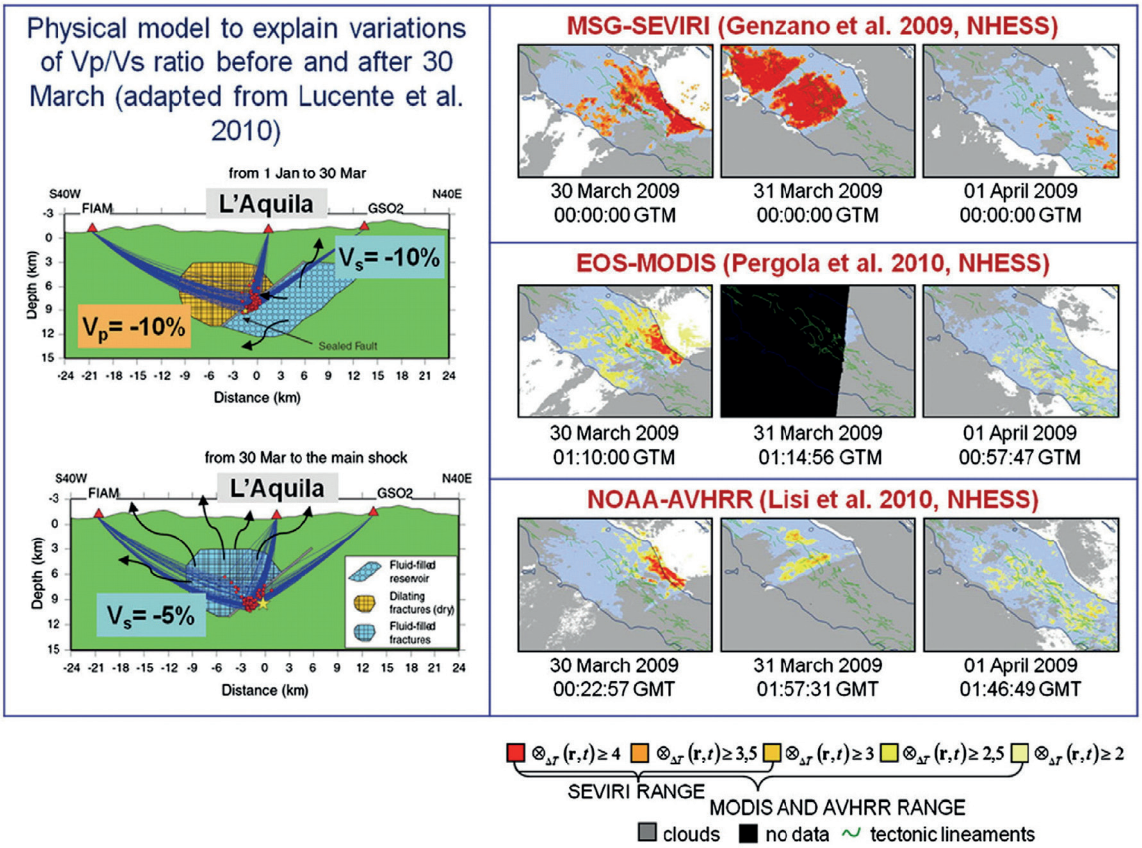

Fig. 9 - Left: the physical model used by Lucente *et al.* (2010) to explain geophysical observations (Vp/Vs) before the main shock of the L'Aquila earthquake (adapted from Lucente *et al.*, 2010); right: TIR anomalies detected by RST approach applied to different data sets (MSG/SEVIRI, EOS/MODIS and NOAA/AVHRR) of satellite images (adapted from Genzano *et al.*, 2009b; Lisi *et al.*, 2010; Pergola *et al.*, 2010). The explanatory model (progressive emptying of a wide gas reservoir triggered by the event of March 30) fits perfectly with the ones proposed (e.g., Tramutoli *et al.*, 2001, 2005, 2013) for correlating TIR anomalies with an abrupt increase of greenhouse gas emissions (adapted from Tramutoli *et al.*, 2013).

(2012) and Piroddi *et al.* (2014), by using 3 different satellite systems (namely MSG/SEVIRI, NOAA/AVHRR, and EOS/MODIS) and 2 different [RST: Tramutoli (2005) and Night Thermal Gradient (NTG): Piroddi and Ranieri (2012)] data analysis methods, found significant and simultaneous TIR anomalies in the epicentral area, starting just few hours before its strongest foreshock (March 30, 2009 at 13:38 UTC: M_L~4.1). For the same area, Lucente *et al.* (2010) report significant differences between the populations of V_P/V_S before and after March 30. The different V_P/V_S ratio measured by stations located in different places away from the fault suggested that, just before March 30, rocks in the hanging wall of the fault were dry and undergoing a progressive opening of cracks and fractures (low values of V_P/V_S), while rocks in the footwall side were fluid-filled (high values of V_P/V_S). After March 30, the increase in V_P/V_S in the rocks at the top of the fault and the drop of the same ratio in the rocks at the bottom of the fault suggested fluid migration from the footwall to the hanging wall. As far as the nature of the dominant degassing activity in the area is concerned, the presence of CO_2-

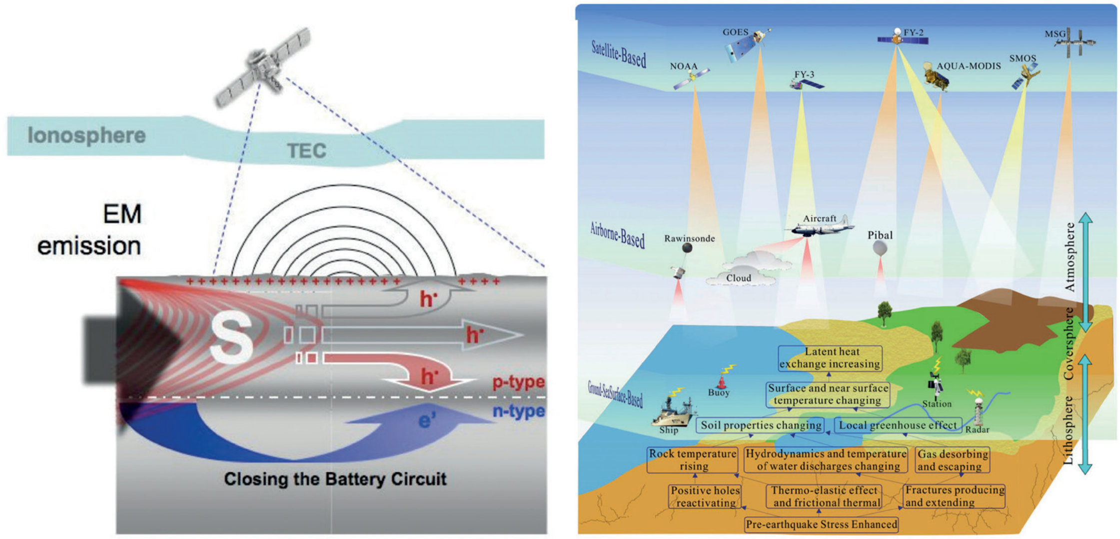

Fig. 10 - Left: Freund's PHP model with related ionospheric perturbations, low-frequency EM emissions and "thermal anomalies" (adapted from Freund, 2007b). Right: Lithosphere-Coversphere-Atmosphere (LCA) model by Wu and Liu (2009) (adapted from Wu *et al.*, 2012).

rich gas sources was suggested by Chiodini *et al.* (2011) and reported by Heinicke *et al.* (2011) and Bonfanti *et al.* (2012) about measurements performed 80 km distant from the L'Aquila epicentral area. The presence of methane, in huge quantities, is also well documented for the region (and this is the reason for its exploitation by oil companies) by Martinelli *et al.* (2012). Therefore (see: Fig. 9), during the preparatory phase of the L'Aquila earthquake, it is likely that [in agreement with the dilatancy model of Scholz *et al.* (1973)] an enhanced concentration of optically active gases (likely CO_2 and/or CH_4) reached the top of the Earth's surface and spread in the lower part of the atmosphere producing the local greenhouse effect responsible of TIR anomalies which were simultaneously and independently measured by Genzano *et al.* (2009b), Lisi *et al.* (2010), Pergola *et al.* (2010), Piroddi and Ranieri, (2012) and Piroddi *et al.* (2014).

4.2. Activation of positive-hole pairs in rocks under stress

P-holes are electronic charge carriers normally inactive in rocks in the form of positive-hole pairs (PHP). When PHPs become activated (e.g., during a rock deformation) they release p-holes, which propagate from the source volume into the surrounding rock. When p-holes arrive at the rock surface, they recombine and release energy, which in turn leads to an enhanced IR emission and other pre-seismic signals (Freund *et al.*, 2006; Freund 2007b; Dahlgren *et al.*, 2014).

The model seems confirmed (but also confuted) only by laboratory measurements (Freund, 2007a; Freund *et al.*, 2007; Dahlgren *et al.*, 2014) and has been incorporated (together with the previously mentioned "local greenhouse effect") in the more complex Lithosphere-Coversphere-Atmosphere (LCA) model proposed by Wu and Liu (2009) (Fig. 10).

4.3. Anomalous ionization of near surface air due to intensive Rn emission over active tectonic faults and tectonic plates borders

Air ionization generated by α-particles, during ^{222}Rn decay, starts several processes in all

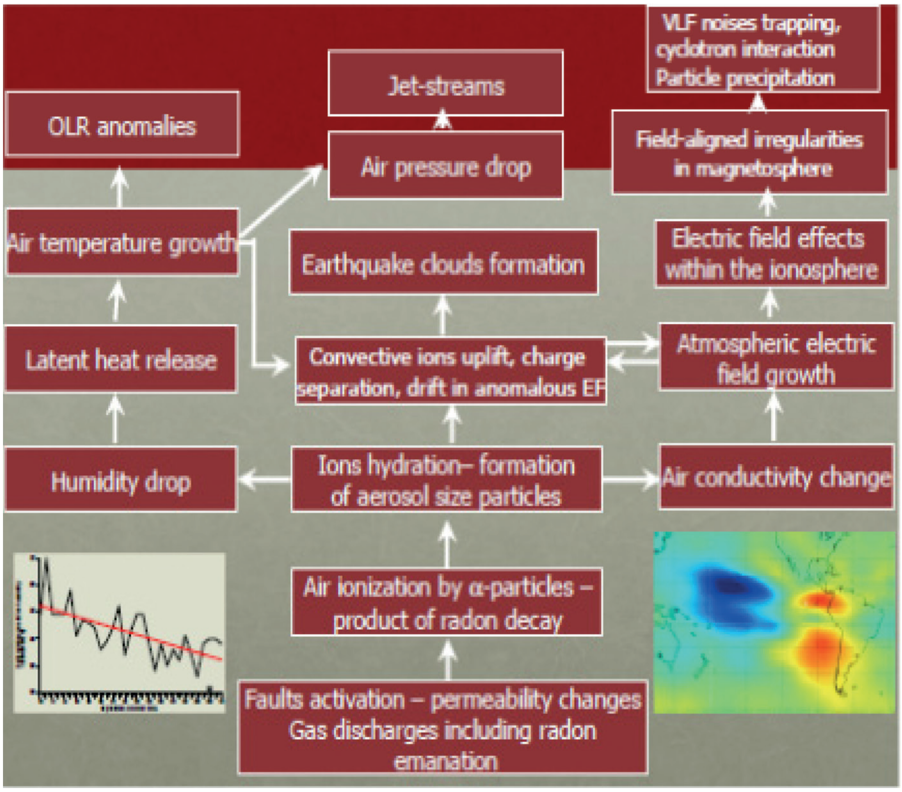

Fig. 11 - The physical model proposed by Pulinets (2009) named LAIC [Lithosphere-Atmosphere-Ionosphere Coupling; adapted from Pulinets (2009)].

the layers of the atmosphere and ionosphere and brings on a large amount of thermal energy exhalation due to latent heat release resulting from water condensation on ions formed after air ionization by Rn. So enhanced Rn emission acts like a key process triggering a cascade of exceptional effects involving all the Earth system from lithosphere up to ionosphere. It is the so called Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) model (Pulinets, 2009) which, like the LCA model of Wu and Liu (2009), seems able to explain the occurrence of TIR anomalies as well as most of the other chemical-physical phenomena [see for instance: Dey and Singh (2003) and references therein] already independently proposed as seismic precursors in the past years (Fig. 11).

The validation of the above mentioned models is still under way [for Model 1 see for instance Tramutoli *et al.* (2013) and references therein] exploiting computer simulation, laboratory measurements, statistical analysis of field observations. Research in this direction is advancing very slowly thanks only to individual initiatives as no specific funds are allocated to the scope all around the world.

5. Critical points and perspectives

The study of Earth's thermally emitted radiation surely represents one of the most promising line of research in the framework of a common effort to improve short-term forecast of strong

Fig. 12 - Participants to the EMSEV 2012 meeting in Gotemba (Japan). Most of them attended to the V. Tramutoli presentation on October 3, when the audience was invited into the "game of responsibility" to take a decision on the possible occurrence of an earthquake in Turkey (a double event actually occurred in the indicated area on October 16) for which an (internal) alert was sent the day before to the PRE-EARTHQUAKES partners. To this community of selected and perseverant scientists this paper is dedicated.

earthquakes. In the last 10 years huge progresses can be registered in data analysis and in the development of explanatory physical models. Observations and independent statistical studies (confirming the expectations of classical models), suggest the occurrence of TIR anomalies not only before an earthquake but also in the co-seismic and post-seismic phase. Conversely, TIR anomaly occurrence appears scarcely correlated with seismically quiet periods and, more in general, multi-parametric approaches are expected to further reduce the occurrence of false positives.

Real-time experiments performed for more than one year in different geographical regions confirmed the stability of such a product and its potential strategic role in the framework of a multi-parametric observational system devoted to t-DASH (Tramutoli *et al*. 2014a).

Looking at the future perspective (for research and, in case, for the use in an operational t-DASH context) further elements of strength of such techniques relies on:

- the availability (for free) of a unique database of TIR observations covering with continuity the whole globe since more than 30 years (spatial resolution 1-5 km, time repetition from 12 hours up to 15 minutes);
- the certainty of the continuation (with improvements) of such an observational capability for the future (presently the satellite missions for at least next 10 years are already funded) which encourage to develop applications based on such systems;
- the unique possibility (if, not huge, but adequate human and computational resources become available) to fully automate the processes validating the algorithms at the global scale even for events occurred in the past 30 years.

Finally, more in details, and with reference to the critical points announced in the abstract:

a. capability to discriminate a possible pre-seismic TIR anomaly from all the other TIR signal fluctuations. Important progresses can be registered in this direction and others can be obtained in the future exploiting last generation of geostationary satellite capable to offer LST and SST products at higher S/N (>4 and more) reducing the effects of atmospheric water vapor variability. The use of additional requirements (like space/time persistence) demonstrated to strongly reduce the probability of false positives. However, clouds strongly reduce continuity of the observations and the possibility to appreciate every time space/time persistence of anomalies. They affect monitoring continuity more than its reliability. The use of passive sensors operating in the MW spectral region (less affected by cloud presence) is expected to strongly reduce such a limitation. Their lower spatial resolution does not seem to be a vital requirement for such studies indeed. Moreover, major improvements are expected by satellite sensors combining all-weather capabilities offered by MW sensors with the reduced observational noise guaranteed by the geostationary attitude. Progresses in this direction are remarkable considering for instance the GeoSTAR sensor, developed at JPL-NASA (e.g., Lambrigtsen *et al*., 2006, 2007; Lim *et al*., 2012 and reference therein) which is already at the level of prototype. Its advanced design is expected to guarantee, even from geostationary platforms, spatial resolutions similar to the ones presently offered by MW sensors operating on polar satellites;

b. capability to correlate TIR anomalies with space, time and magnitude of earthquakes. Correlation analyses (after the independent reports supported by DLR and NASA) have been recently performed on quite long observation periods over Greece [10 years, by Eleftheriou *et al*. (2015)], Italy [9 years, by Genzano *et al*. (2013)], Taiwan [8 years, by Genzano *et al*. (2015)], and California (Tramutoli *et al*., 2014b) which seem to confirm the existence of a significant (from 55% up to 93% of cases), not casual, correlation (within prefixed space-time intervals) among TIR anomalies and earthquake (with M>4.0) occurrence. Such a correlation refers to TIR anomalies occurring not only before but also after, or in between more than one, earthquake. The above mentioned studies do not reveal particular dependence of TIR anomalies intensities on earthquake magnitudes [but see also the attempts to establish such a correlation made by Li *et al*. (2007)]. However, the possible relationships among spatial extension of the area affected by TIR anomalies and the magnitude of the impending earthquake have been suggested by some authors in the past (e.g., Pulinets *et al*., 2007 and reference therein). The primary role of RST based TIR surveys within a multi-parametric observational system for t-DASH was practically demonstrated during the real-time experiment PRIME (Pre-earthquakes Real-time Integration and Monitoring Experiment) as well as at the EMSEV 2012 conference (Fig. 12);

c. capability to physically justify observed correlation. Suitable models exist whose validation is still under way (but we do not expect quick progresses in this direction in absence of specific funds allocated to the scope).

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