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One year of RST based satellite thermal monitoring over two Italian seismic areas

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ABSTRACT In this study, Earth's emitted Thermal InfraRed (TIR) radiation measured from geostationary satellite sensors has been analyzed by using an original data analysis approach in order to evaluate possible space-time correlation with earthquakes ($M \geq 4.0$) occurrence. A clear definition of SSTA (Significant Sequence of Thermal Anomaly) concept is given and correlation rules are established in order to evaluate the potential of SSTAs among the parameters to be included in a pre-operational system for time-Dependent Assessment of Seismic Hazard (t-DASH). On the considered time period (July 2012 - June 2013) and testing areas (Italian southern Apennines and Po Plain) a false positive rate lesser than 33% has been obtained. Notwithstanding a missing rate up to 67% (mostly because of the presence of clouds preventing the continuity of observations), as confirmed by other independent studies performed on longer period of time and different geographic areas, seems to strongly support the inclusion of SSTAs [identified by the RST (Robust Satellite Technique) methodology] among the parameters whose continuous monitoring and integration with all the other relevant information available, could strongly improve our present capabilities to dynamically assess seismic hazard in a pre-operational context.

Key words: earthquake prediction, thermal infrared radiation, satellite recordings.

1. Introduction

Seismic hazard assessment and medium/long-term earthquake forecasting has been for years a research topic generously funded by worldwide national governments interested to give scientific bases to their building codes in earthquakes prone areas. The probabilistic seismic hazard assessment [(PSHA, e.g., Cornell (1968)] approach has been since long term used to extrapolate from the frequency of (even very small) earthquakes occurred in the past, the annual probability of occurrence of (even very large) earthquakes in the future. Recently such methods have been strongly criticized for "… *the significant consequences of their failures in terms of* *human and economic losses…*" (Wyss *et al.*, 2012). Particularly significant is the case of Japan where "*…since 1979, earthquakes that caused 10 or more fatalities … actually occurred in places assigned a relatively low probability*" (Geller, 2011). Exemplary became (e.g., Kagan and Jackson, 2013) the underestimation of Tohoku earthquake (March 11, 2011, M_W=9.0) intensity by the Japanese National Seismic Hazard Maps and their limits (mostly related to the use of PSHA) were at the end officially recognized (e.g., Fujiwara *et al.*, 2013). Together with the 2011 Tohoku event, Stein *et al.* (2012) report other highly destructive earthquakes (e.g., 2008 Wenchuan, 2010 Haiti, etc.) occurred in areas predicted to be relatively safe. Kossobokov and Nekrasova (2012) found the GSHAP (Global Seismic Hazard Project) maps (based on PSHA) significantly underestimating ground accelerations of most of strong earthquakes occurred in 2000-2010. Quite frequently probabilistic maps of seismic hazard require a revision after the occurrence of a major earthquake, with a general increase of seismic hazard in the affected area (e.g., Bommer and Abrahamson, 2006).

This was also the case of the Italian seismic code, which needed to be updated after the Palermo (September 6, 2002) and San Giuliano-Molise (October 31, 2002) earthquakes (e.g., Zuccolo *et al.*, 2011). The last one (October 31, 2002, M_L=5.4), that killed 27 kids in a school, occurred in an area that was previously considered of minor concern (Zuccolo *et al.*, 2011). Intrinsic limits of PSHA in areas that have not been struck by earthquakes in historical times are very well described by Chiarabba *et al.* (2005) who in relation with that event wrote: "… *Seismic hazard for the region had not been previously retained high and the earthquake was mostly unexpected by seismologists. The reason was that neither historical or instrumental events had been previously reported in seismic catalogues for that area*". Actual risks and possible consequences of such underestimations have been moreover described in Artioli *et al.* (2013) and Peresan *et al.* (2013).

In this context additional observations and data analysis methods should be considered in order to improve quality of seismic hazard forecast particularly in the short-medium term. A multi-parametric system capable to exploit and continuously update all the available observations and accumulated knowledge is presently the most promising research line toward an effective time-Dependent Assessment of Seismic Hazard [t-DASH, Tramutoli *et al.* (2014)].

However, a very preliminary step of whatever multi-parametric approach is to identify those parameters (chemical, physical, biological, etc.) whose variations can be, to some extent, associated to the process of preparation of an earthquake. A preliminary study in this direction was started in 2012 in the framework of the S3 Project (2012-2013) supported by the Italian National Department of Civil Protection (DPC) and the National Institute of Geophysics and Volcanology (INGV). The project was particularly devoted to analyze long-term measurement of different observables in two selected Italian test areas: the Po Plain and southern Apennines.

Among the others observables, Earth's thermally emitted radiation measured by satellite sensors operating in the Thermal InfraRed (8-14 μm) spectral range (TIR) was considered. In fact, since the 1980s, the occurrence of TIR anomalies in some relation with earthquake occurrence has been reported by several authors [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), Choudhury *et al.* (2006), Ma *et al.* (2010), Tramutoli *et al.* (2015), and reference herein]. Moving from the main elements of criticism (rightly highlighted by scientific community) to the previously quoted papers, Tramutoli *et al.* (e.g., 2001, 2005) proposed a data analysis approach [Robust Satellite Technique (RST)] suitable for defining on a scientific basis the concept of TIR anomaly and to identify (if any) those anomalous space-time TIR transients possibly associated to seismic activity (Filizzola *et al*., 2004; Corrado *et al*., 2005; Tramutoli *et al*., 2005, 2009; Aliano *et al*., 2007, 2008a, 2008b; Genzano *et al*., 2007, 2009a, 2009b; Lisi *et al*., 2010; Pergola *et al*., 2010).

This paper describes the results of the first phase of evaluation of the space-time correlation existing among TIR anomalies [defined following the scheme described in Tramutoli *et al*. (2005)] and earthquakes (with M>4.0) occurred in the project S3 testing period (July 2012 - June 2013) and areas (the Po Plain and southern Apennines).

To this aim ten years (2004-2013) of SEVIRI [Spinning Enhanced Visible and Infrared Imager on board the geostationary Meteosat Second Generation satellite (MSG)] night-time TIR images over Italian region were collected and analyzed.

2. The Robust Satellite Techniques and the robust estimator of TIR anomalies (RETIRA index)

The Earth's thermal radiation measured by satellite sensors at the top of the atmosphere is influenced by different factors. As reported in Tramutoli *et al*. (2005), they can be natural (like atmospheric transmittance, surface emissivity and topography) and/or observational (e.g., time/season, but also solar and satellite zenithal angles). Individual changing of only one of the mentioned factors could be responsible of a variation of the observed TIR signal, as large as (in some cases larger than) the fluctuations reported in literature as thermal anomaly and related to impending earthquakes.

It is evident, instead, that only those signal variations not related to the "normal" (i.e., independent from any, natural and observational, variation of the investigated signal) space-time variability of the signal itself, could be assumed as anomalous and further investigated for their possible relation with earthquake occurrence. A preliminary definition of the "normal" behavior of the TIR signal at specific time and place of the observation is then particularly important (e.g., Tramutoli, 1998, 2005).

Within this context, the proposed RST approach, unlike preceding methods, allows a statistically based definition of TIR anomalies and a way for their identification even in presence of highly variable natural and observational conditions. Initially proposed for monitoring the major environmental risks using AVHRR-NOAA [Advanced Very High Resolution Radiometer onboard NOAA (National Oceanographic and Atmospheric Administration)] data, and therefore named «RAT» [Robust AVHRR Techniques: Tramutoli (1998)], its full exportability on different satellite systems suggested a more generic name «RST» [Robust Satellite Technique: Tramutoli (2005)].

Since its first application to seismic area monitoring (Tramutoli *et al*., 2001), the RST methodology identifies space-time anomalies always respect to a preliminarily defined "normal" (i.e., in unperturbed condition) signal behavior which is achievable by the analysis of long-term series of satellite records collected under similar observational conditions for each image pixel and period of the year.

For earthquake prone areas monitoring, anomalous TIR patterns are identified by using a specific index, RETIRA [Robust Estimator of TIR Anomalies: Filizzola *et al.* (2004), Tramutoli *et al.* (2005)] which can be computed on the image at hand as in the equation below:

$$\otimes_{\Delta T}(\boldsymbol{r},t) = \frac{\Delta T(\boldsymbol{r},t) - \mu_{\Delta T}(\boldsymbol{r})}{\sigma_{\Delta T}(\boldsymbol{r})} \tag{1}$$

where:

- $\Delta T(\boldsymbol{r},t)=T(\boldsymbol{r},t)-T(t)$ is the difference between the TIR radiance $T(\boldsymbol{r},t)$, i. e. the punctual value of the brightness temperature measured at the location $\boldsymbol{r}\equiv(x,y)$ and acquisition time t, measured at the location $\boldsymbol{r}$ and time t and its spatial average $T(t)$, that is the spatial average of $T(\boldsymbol{r},t)$ computed in place on the image at hand considering cloud-free pixels only, all belonging to the same, land or sea, class in the investigated area [i.e., $T(t)$ is computed considering only sea pixels if $\boldsymbol{r}$ is located on the sea and only land pixels if $\boldsymbol{r}$ is located on the land]. Note that the choice of such a differential variable $\Delta T(\boldsymbol{r},t)$ instead of $T(\boldsymbol{r},t)$ 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;
- $\mu_{\Delta T}(\boldsymbol{r})$ and $\sigma_{\Delta T}(\boldsymbol{r})$ are the time average and standard deviation of $\Delta T(\boldsymbol{r},t)$ obtained for each location $\boldsymbol{r}\equiv(x,y)$ using cloud free records belonging to a homogeneous data set of observations collected in different years in similar (same month, same time of the day, etc.) observational conditions.

The RETIRA index $\otimes_{\Delta T}(\boldsymbol{r},t)$ gives the local excess of the current $\Delta T(\boldsymbol{r},t)$ signal compared with its historical mean value and weighted by its historical variability at the considered location. The excess $\Delta T(\boldsymbol{r},t)$ - $\mu_{\Delta T}(\boldsymbol{r})$ represents then 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 $\sigma_{\Delta T}(\boldsymbol{r})$. This way, the intensity of anomalous TIR transients can be evaluated in terms of S/N ratio by the RETIRA index $\otimes_{\Delta T}(\boldsymbol{r},t)$. 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 homogeneous measurements (Tramutoli *et al.*, 2001).

Space-time persistence of TIR anomalies is a further critical requirement to be considered in order to discriminate significant anomalies from residual, well known spurious effects due, not only to simple outliers, but also to geo-location errors, nighttime warm cloud shadows and other effects related to cloud abundance and distribution over the scene which have been all described in previous papers [see for instance: Filizzola *et al.* (2004), Aliano *et al.* (2008b) and Genzano *et al.* (2009b)].

3. Results

Nine years of MSG/SEVIRI images (collected from June 2004 up to December 2012, at 24:00 GMT) have been processed in order to compute, for each month of the year and each location $\boldsymbol{r}$, the reference fields $\mu_{\Delta T}(\boldsymbol{r},t)$ and $\sigma_{\Delta T}(\boldsymbol{r},t)$ representing the signal behavior expected in unperturbed conditions.

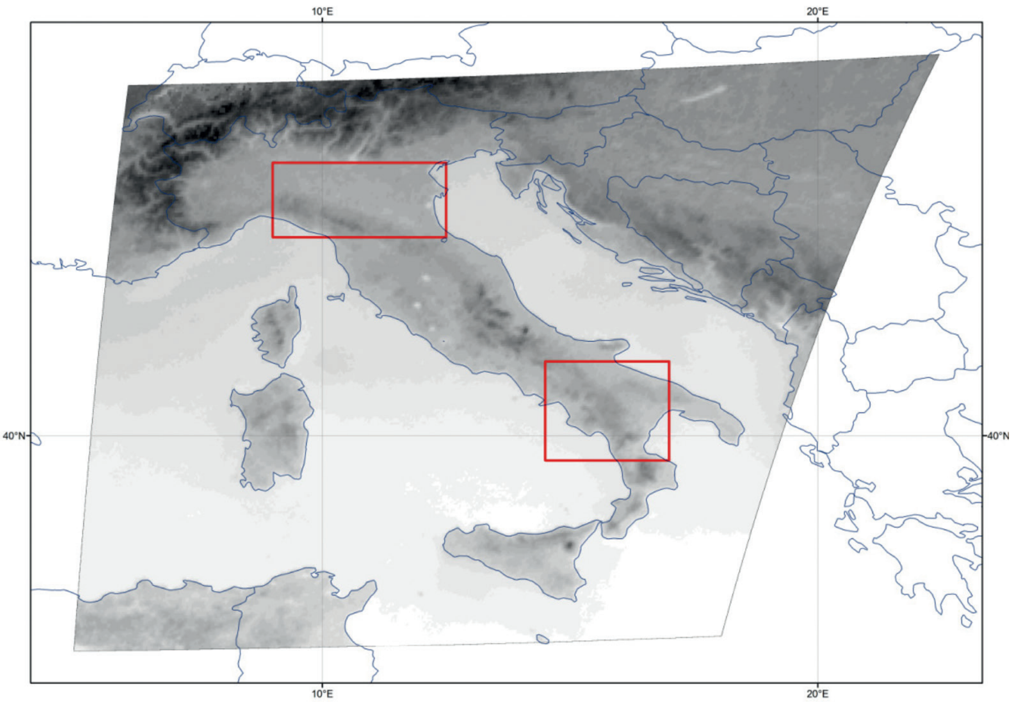


Fig. 1 - Portion of the SEVIRI scene used to calculate the spatial average T(t) appearing in the expression of the considered signal $\Delta T(r,t) \otimes T(r,t) - T(t)$. The red contoured boxes in figure represent the two investigated areas: the Po Plain (top: 9.0°÷12.5° E; 44.0°÷45.5° N) and (bottom) southern Apennines area (14.5°÷17.0° E; 39.5°÷41.5° N).

RETIRA index [see: Eq. (1)] values have been then computed for all the SEVIRI/MSG images belonging to the testing period (July 2012 - June 2013) within the two selected testing areas represented in Fig. 1 (Po Plain and southern Apennines).

All RETIRA maps $\otimes_{\Delta T}(\boldsymbol{r},t)$, obtained as a result of RST methodology implementation, have been then subjected to a preliminary analysis devoted to identify Significant (i.e., space-time persistent, not related to known spurious effects) Sequences of Thermal Anomalies (SSTAs) to be further investigated for their possible relation with earthquake occurrence.

To this aim each single location $\boldsymbol{r} \equiv (x,y)$ has been considered (at the time of observation t) to be part of an SSTA, if satisfying the following requirements:

a) **relative intensity:** $\otimes_{\Delta T}(\boldsymbol{r},t) \geq K$, (with K=3 in our case). Hereafter, for sake of simplicity we will refer to such pixels simply as "anomalous pixels" or as individual TIR Anomalies (TA);

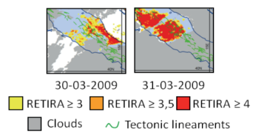
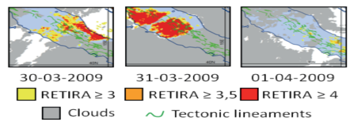
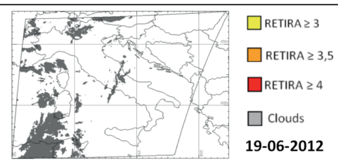
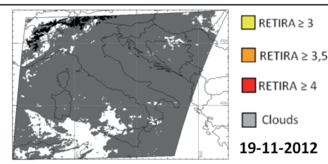
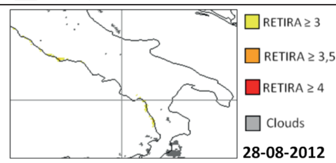
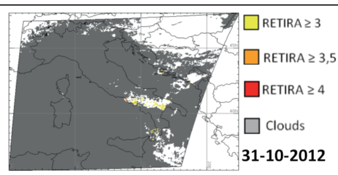
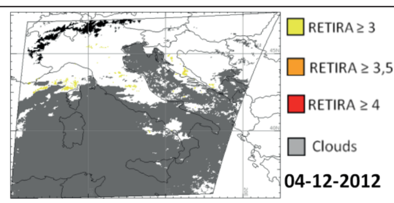
b) **control on spurious effects:** it is not related to a known sources of spurious thermal anomalies as the ones described in Filizzola *et al.* (2004), Aliano *et al.* (2008b), Genzano *et al.* (2009b) or is occurring in a scene affected for more than 80% by clouds;

c) **spatial persistence:** it is not spatially isolated being part of a group of TAs covering at least 150 km^2 within an area of 1×1°;

d) **temporal persistence:** previous conditions (i.e., the existence of a group of TAs covering at least 150 km^2 within an area of 1×1° around $\boldsymbol{r}$) are satisfied at least one more time in the 7 days preceding/following t.

Thanks to such a precise definition of SSTAs, and considering all the known possible causes of spurious TAs, a TIR Anomaly Code (TAC) has been introduced in order to classify, depending on the presence and characteristics of TAs, each scene (Table 1). It should be noted that the codes (STA, SSTA and vSSTA) describing the significance of observed TAs are attributed considering a real-time monitoring process which prevents to attribute more than a code STA (SSTA) at the first (second) appearance of spatially extended TAs.

Table 1 - TAC used to describe the significance of TIR anomalies identified by RST methodology.

Description (and corresponding TIR Anomaly Code)	Details	Example
Single Thermal Anomaly (STA)	Single image showing spatially extended TIR anomalies with RETIRA≥*K* (becomes a yellow SSTA if persistent)	
Significant Sequence of Thermal Anomalies (SSTA)	Second image showing spatially extended and time persistent TIR anomalies with RETIRA≥*K* (becomes a red vSSTA if continuing)	
very Sinificant Sequence of Thermal Anomalies (vSSTA)	Images after the second one showing spatially extended and time persistent TIR anomalies with RETIRA≥K	
NO Thermal Anomalies (NTA)	Valid data processing without spatially extended (for less than 150 km^2 within an area of 1×1°) TIR anomalies detected	
No Data (ND)	Clouds presence over more than 80% of the testing area prevent data analysis	
Spurious Anomalies for Navigation errors (SAN)	Presence of only spurious TIR anomalies (typically along coastlines) due to image navigation errors (Filizzola *et al.*, 2004, Aliano *et al.*, 2008b)	
Spurious Anomalies for Cold spatial average effect (SAC)	Presence of only spurious TIR anomalies due to the cold spatial average effects (Genzano *et al.*, 2009b)	
Spurious anomaly for Cloud Passage (SCP)	Spurious TIR anomalies due to a nocturnal clouds passages (Filizzola *et al.*, 2004; Aliano *et al.*, 2008b)	

However it should be clear that, by definition, the occurrence of each new persistence changes also the significance of previous ones. In fact, looking at the example given in the first 3 lines of Table 1 (which refers to L'Aquila earthquake of April 6, 2009) it is possible to note that the yellow code SSTA is attributed not only to the image corresponding to March 31, 2009 but also to the previous one (March 30, 2009) to which, at its first appearance, was attributed the blue code STA. The same happens for the third persistence (April 1, 2009) of such TAs whose vSSTA code is retroactively extended to both previous scenes.

Following TAC code all the SEVIRI scenes belonging to the considered testing period have been separately classified with reference to the two selected testing areas.

The results of such analysis are resumed in Fig. 2 both for the Po Plain (top) and southern Apennines (bottom). Earthquakes with $M\geq4.0$ occurred in the same period/areas are also reported.

The dates of the days of occurrence of SSTAs and/or vSSTAs are reported in Table 2. In general, they were very rare: in one year we registered only 4 sequences, for a total of 10 days, in the case of the southern Apennines area, only 1 sequence (2 days) in the case of the Po Plain.

In order to evaluate possible correlations among the appearance of SSTAs and time, location and magnitude of earthquakes, empirical correlation rules were applied which were mostly based on general (e.g., Scholz *et al.*, 1973) or specific (e.g., Tramutoli *et al.*, 2013) physical models as well as on more than 14 years of similar analyses (Tramutoli *et al.*, 2001, 2005, 2009, 2012, 2013; Di Bello *et al.*, 2004; Filizzola *et al.*, 2004; Corrado *et al.*, 2005; Aliano *et al.*, 2007, 2008a, 2008b, 2009; Genzano *et al.*, 2007, 2009a, 2009b; Pulinets *et al.*, 2007; Lisi *et al.*, 2010; Pergola *et al.*, 2010; Bonfanti *et al.*, 2012) performed by authors in 4 different continents, different tectonic settings, for tens of earthquakes with magnitudes ranging from 4.0 to 7.9.

On this basis, each single SSTA (or vSSTA) observed at the time t has been considered in a possible correlation with seismic activity if an earthquake of $M\geq4.0$ occurs 30 days after its appearance or within the 15 days before[1] (temporal window) within a distance D (from whatever TAs belonging to it) so that 150 km$\leq D\leq R_D$ being $R_D=10^{0.43M}$ the Dobrovolsky *et al.* (1979) distance (spatial window).

The possible correlation among previously identified SSTAs (Table 2) and earthquake occurrence was investigated considering only earthquakes with magnitude $M\geq4.0$ occurred from July 1, 2012 to June 30, 2013 within the investigated area as reported by ISIDe Working Group (2010) INGV seismic catalogue.

With reference to the 5 observed sequences (4 in the case of the southern Apennines area, 1 in the case of the Po Plain) the correlation analysis gave the following results:

1. southern Apennines vSSTAs September 29, 2012 - October 2, 2012 (Fig. 3). It is a four days lasting vSSTA associable (i.e., falling within the prescribed space-time correlation window) to 3 different earthquakes;
2. from September 29 until September 30, extended TAs are present quite close to the epicentre of Benevento earthquake (September 27, 2012: M_W=4.2) occurred few days before (POst-EarthQuake TAs, hereafter POEQ-TAs). Apparently less extended (but cloud coverage, limiting the observable area, could determine an underestimation of their

[1] on the models which foreseen the occurrence of similar anomalies also immediately after the quake see for instance, Scholz *et al.* (1973) and, with reference to TIR anomalies, Tramutoli *et al.* (2005, 2013).

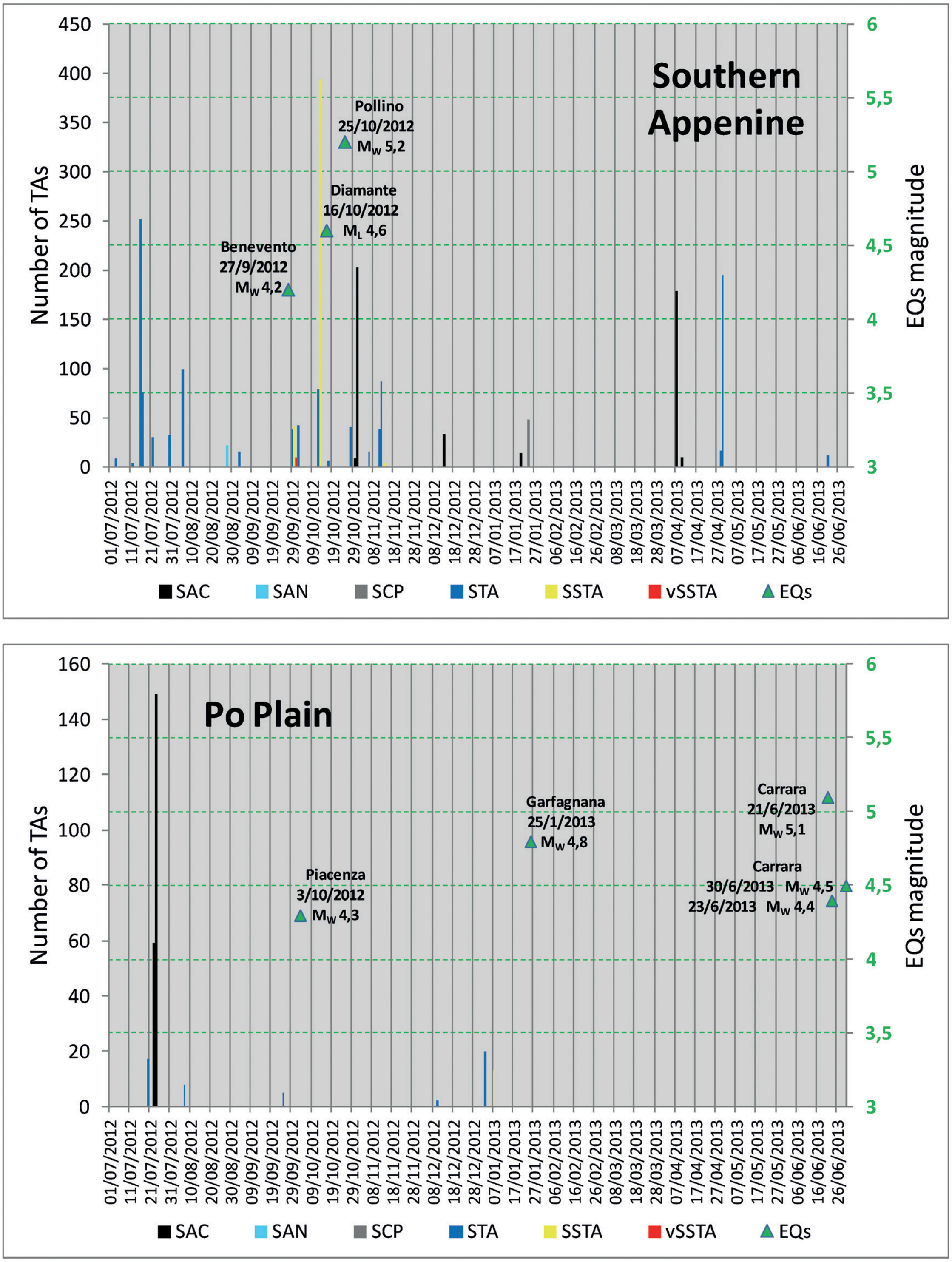


Fig. 2 - Number of TAs (pixels whit $\otimes\Delta T(\mathbf{r},t)\geq 3$) in the Po Plain portion (upper part) and for southern Apennines (bottom part) are reported for every day/scene of the testing period (July 2012 - June 2013) with the exclusion of days classified as NTA or ND (see text). Colours are the same used in the TAC (Table 1). Earthquakes with $M\geq 4.0$ occurred in the testing period in the corresponding areas are indicated by green triangles.

amount) TAs are present also in correspondence of the earthquakes of Diamante (October 16, 2012: M_L=4.6) and Pollino (October 25, 2012: M_W=5.2) occurred few weeks later (PRe-EarthQuake TAs, hereafter PREQ-TAs);

3. on October 1, extended TAs are still observable close to the epicentre of Benevento earthquake and, on October 2, they seem to move in the southern direction toward the epicentres of Diamante and Pollino earthquakes. In both days extended cloud coverage made not observable the area directly affected by those 2 events. Taking into account the previously established correlation rules, the four vSSTAs affecting this sequence were classified both as POEQ-TAs (with respect of Benevento earthquake occurred few days before) and PREQ-TAs (with respect to the Diamante and Pollino earthquakes occurred 2 and 3 weeks later). This is a not rare class of TAs appearing in between subsequent earthquakes to which they seem anyhow correlated;
4. southern Apennines SSTAs October 12-13, 2012 (Fig. 4). It is a two days lasting SSTA associable (i.e., falling within the prescribed space-time correlation window) to the Diamante and Pollino earthquakes occurred respectively 3-4 and 12-13 days after. For spatial extension and relative intensity of TAs (many of them with $\otimes_{\Delta T}(\boldsymbol{r},t)\geq 4$) they represent the most important SSTAs observed during the whole study period. Taking into account of the previously established correlation rules, they can be classified both as PREQ-TAs;
5. southern Apennines SSTAs November 11-12, 2012 (Fig. 4). It is a two days lasting SSTA not strictly associable (falling two days outside the prescribed time window for post-earthquake TAs) to seismic activity. It has to be, then, considered as a FALSE positive even if, the spatial behavior of TAs (particularly the ones on November 11 which seem to follow the same fault systems joining Benevento and Diamante-Pollino earthquakes epicentres) and the short time delay (only 2 days more) respect to the 15 days post-earthquake limit assumed as tolerable by the (empirically) established correlation rules, can justify some doubt on this assignation suggesting a more likely POEQ-TAs choice;
6. southern Apennines SSTAs April 29-30, 2013. It is a two days lasting SSTA occurring in a seismically quite period (only one 3.5 magnitude event in a wide area around the testing one) that according with the pre-established validation rules has to be considered as a FALSE positive;
7. Po Plain SSTAs January 3 and 7, 2013 (Fig. 5). It is a two days lasting SSTA and the only one observable on this testing area during the whole testing period. Even if most of TAs seem concentrate in the eastern part of the testing area and only few of them very close to the Garfagnana earthquake (January 25, 2013: M_W=4.8) epicentre, according with the pre-established correlation rules, both days have to be classified as affected by PREQ-TAs associated to that earthquake occurred just 22 and 18 days after TAs observed, respectively, on January 3 and 7, 2013.

Looking at Table 2, it is possible (with all the prudence coming from the limited extent of the considered data set) to receive some indication on the reliability (here measured by the fraction of SSTAs occurred in the investigated area/period preceded or followed by an earthquake with M>4.0 in the prescribed space-time correlation window) of SSTAs as potential indicator of running or impending seismic activity. In fact, according with the pre-established correlation rules:

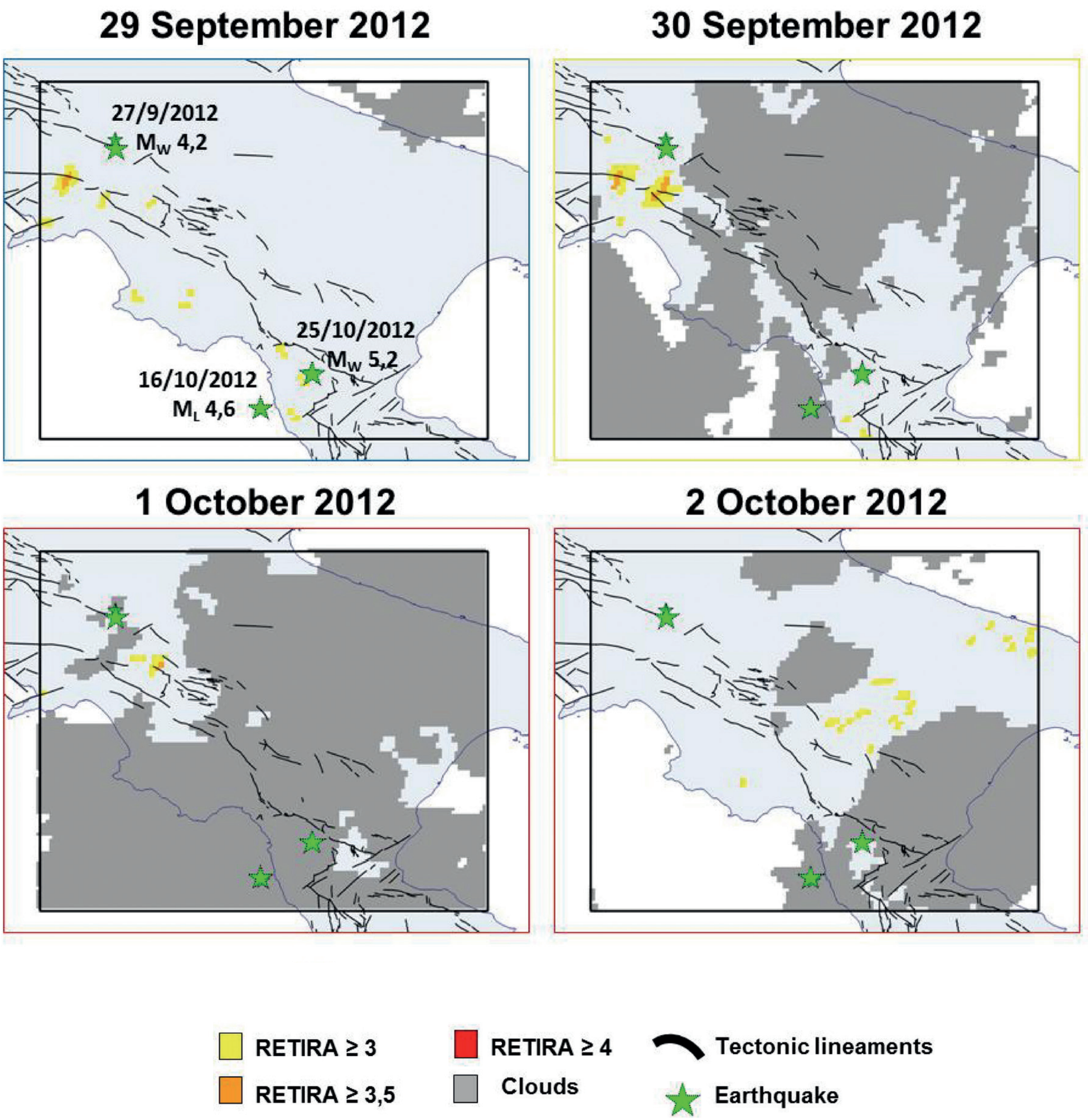


Fig. 3 - vSSTA observed immediately after the Benevento earthquake (September 27, 2012: M_W=4.2) and few weeks before Diamante (October 16, 2012: M_L=4.6) and Pollino (October 25, 2012: M_W=5.2) earthquakes.

- 67% of all observed SSTA occurred in apparent relation with earthquake with $M \geq 4.0$ (all of them appeared from few days to few weeks before the events);
- 33% of all observed SSTA (but likely less than 20%) occurred not in relation with earthquake with $M \geq 4.0$;
- 42% of all the observed SSTAs were observed (also) after the quakes.

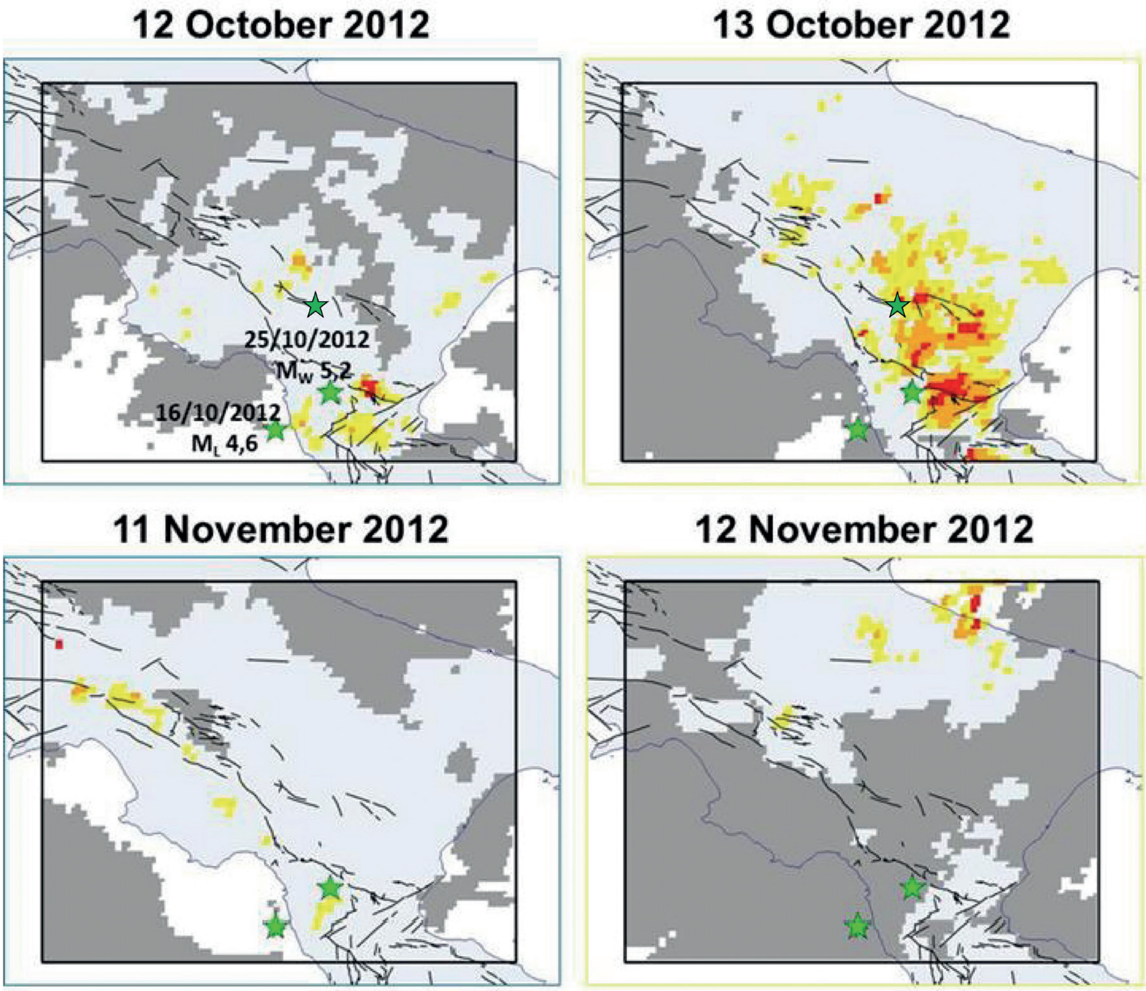


Fig. 4 - SSTAs observed: (top) few days before Diamante (October 16, 2012: M_L=4.6) and Pollino (October 25, 2012: M_W=5.2) earthquakes; (bottom) 16 and 17 days after Pollino earthquake.

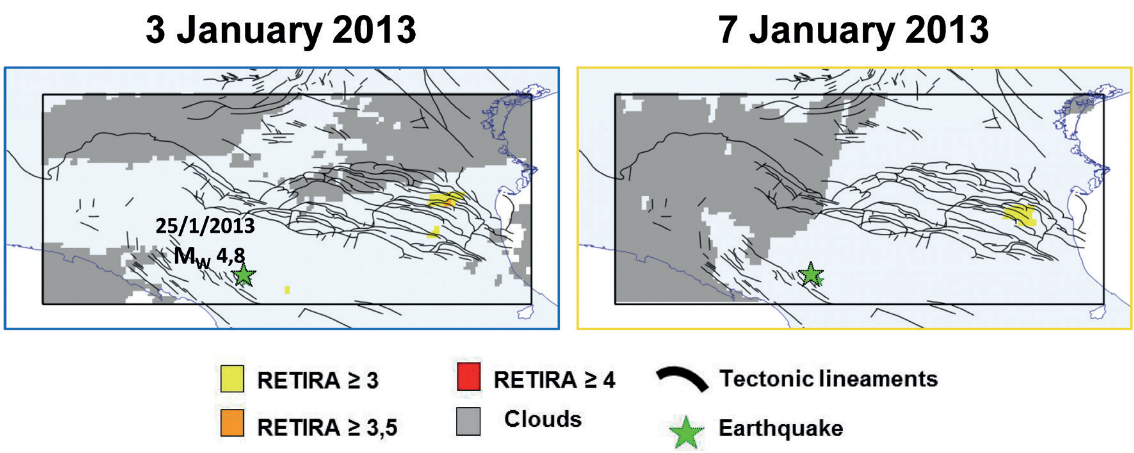


Fig. 5 - SSTAs observed 22 and 18 days before the Garfagnana earthquake (M_W=4.8) occurred on January 25, 2013.

Table 2 - Results of the reliability analysis performed over all the SSTAs identified in the considered testing period (July 2012 - June 2013) in the two selected testing areas (see text) of: southern Apennines (top) and Po Plain (bottom).

Southern Apennines		
Date (yyyy-mm-dd)	**TIR Anomaly Code (TAC)**	**Reliability analysis results**
2012-09-27	**EQ1 M_W 4.2 (Benevento)**	
2012-09-29	STA→**SSTA→ vSSTA**	Post EQ1, Pre EQ2 and EQ3
2012-09-30	**SSTA→ vSSTA**	Post EQ1, Pre EQ2 and EQ3
2012-10-01	**vSSTA**	Post EQ1, Pre EQ2 and EQ3
2012-10-02	**vSSTA**	Post EQ1, Pre EQ2 and EQ3
2012-10-12	STA→**SSTA**	Post EQ1, Pre EQ2 and EQ3
2012-10-13	**SSTA**	Pre EQ2 and EQ3
2012-10-16	**EQ2 M_L 4.6 (Diamante)**	
2012-10-25	**EQ3 M_W 5.2 (Pollino)**	
2012-11-11	STA→**SSTA**	False[2] (16 days after EQ3)
2012-11-12	**SSTA**	False[2] (17 days after EQ3)
2013-04-29	STA→**SSTA**	False
2012-04-30	**SSTA**	False
TOTALS	10 (**SSTAs**=6; **vSSTAs**=4)	EQ-Related = 6 (5 PRE and POST) NON-EQ-Related (FALSE) = 4[3]
Po Plain		
Date (yyyy-mm-dd)	**TIR Anomaly Code (TAC)**	**Reliability Analysis results**
2012-10-03	**EQ4 M_W 4.3 (Piacenza)**	
2013-01-03	STA→**SSTA**	Pre EQ5
2013-01-07	**SSTA**	Pre EQ5
2013-01-25	**EQ5 M_L 4.8 (Garfagnana)**	
2013-06-21	**EQ6 M_W 5.1 (Carrara)**	
TOTALS	**2** (**SSTAs**=2; **vSSTAs**=0)	EQ-Related = 2 (PRE) NON-EQ-Related (FALSE) = 0
SCORES		
Number of SSTAs	**EQ-Related**	**NON EQ-Related (False)**
12	**8**	**4**[3]
	67%	**33%**

It should be moreover noted that meteorological clouds prevent Earth's emitted TIR signal to reach the satellite sensor, so that, corresponding portions of the scene represent an information gap (data missing) both in the space and time dimension. This circumstance has several important effects:

- it makes impossible to give continuity to the observations and to fully appreciate possible space-time persistence of TIR anomalies;
- it reduces the amount of usable satellite records within the historical data set weakening (particularly in specific zones) the significance of the computed reference fields.

Notwithstanding the evident limiting factors due to the intrinsic absence of continuity of TIR observations (and the absence of theoretical or experimental elements that could justifies the occurrence of TIR anomalies in correspondence of whatever earthquakes in whatever places) an analysis of sensitivity (here measured by the fraction of earthquakes

[2] likely to be Post EQ3 TAs (see text).

[3] of them likely to be Post EQ3 TAs (see text).

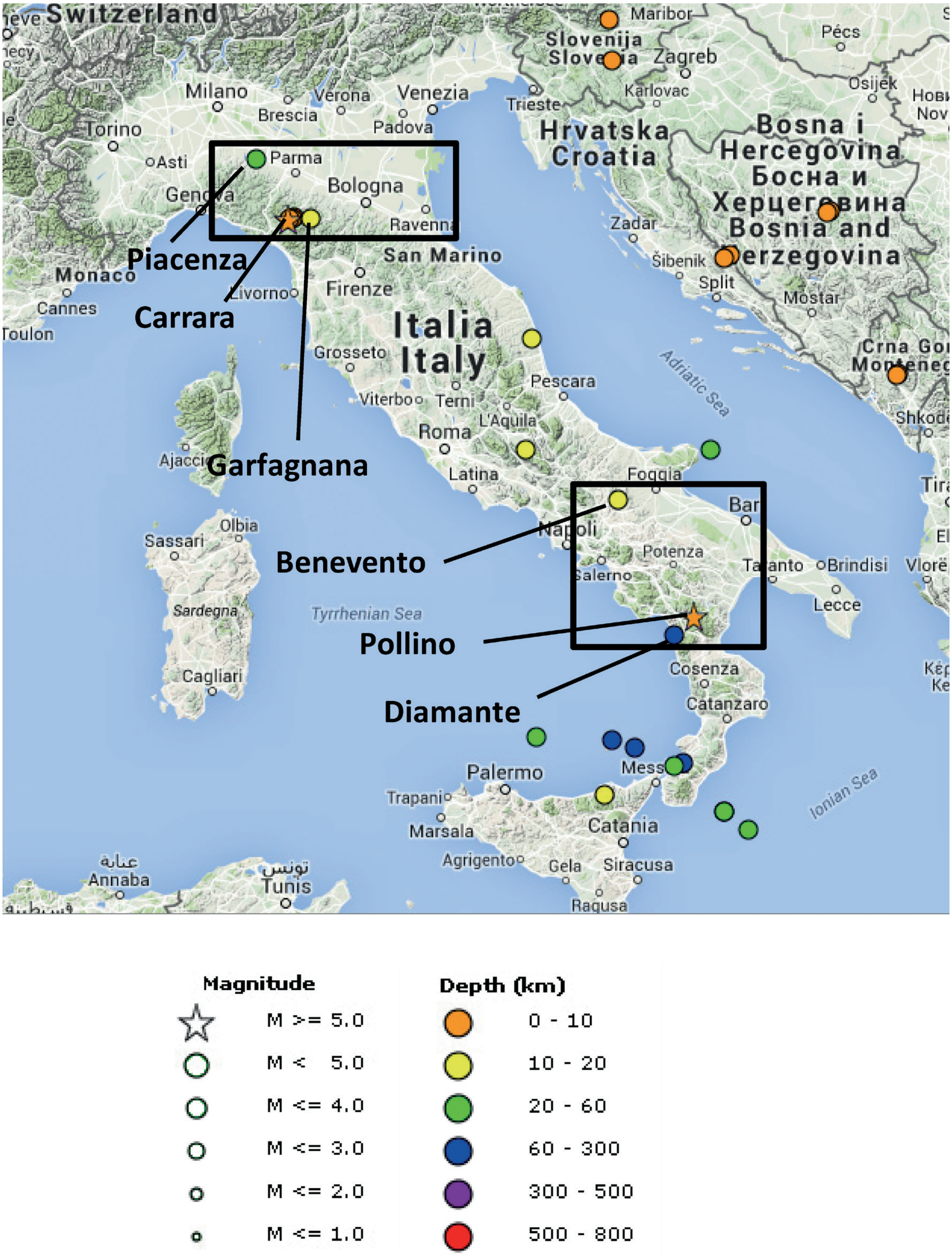


Fig. 6 - Seismic events (M≥4.0) occurred in Italy in between July 1, 2012 and June 30, 2013 as reported by ISIDe Working Group (2010). Black boxes indicate the two considered testing areas.

occurred in the investigated period/areas preceded or followed by SSTAs in the prescribed space-time correlation window) was performed considering all earthquakes with $M \geq 4.0$ occurred within the investigated areas in the considered period (Fig. 6) in order to verify in how many case, the appearance of SSTAs was preceding (or at least accompanying) their occurrence (Table 3).

Table 3 - Results of the sensitivity analysis performed considering all earthquakes (with $M \geq 4.0$) occurred between July 1, 2012 and June 30, 2013 in the two selected testing areas (see text) of: southern Apennines (top) and Po Plain (bottom).

Southern Apennines		
Date (yyyy-mm-dd)	**EQ magnitude (location)**	**Sensitivity analysis results**
2012-09-27	**M_W 4.2 (Benevento)**	5 POEQ-SSTAs
2012-10-16	**M_L 4.6 (Diamante)**	6 PREQ-SSTAs
2012-10-25	**M_W 5.2 (Pollino)**	6 PREQ-SSTAs
TOTALS	**3 EQs with $M \geq 4.0$**	EQs preceded by SSTAs 2 EQs followed by STTAs 1 EQs not preceded by SSTAs 1 (missed)
Po Plain		
Date (yyyy-mm-dd)	**EQ magnitude (location)**	**Sensitivity analysis results**
2012-10-03	M_W **4.3 (Piacenza)**	NO SSTAs associated
2013-01-25	M_L **4.8 (Garfagnana)**	2 PREQ-SSTAs
2013-06-21	M_W **5.1 (Carrara)**	NO SSTAs associated
2013-06-23	M_W **4.4 (Carrara)**	NO SSTAs associated
2013-06-30	M_W **4.5 (Carrara)**	NO SSTAs associated
TOTALS	**3 EQs with $M \geq 4.0$**	EQs preceded by SSTAs 1 EQs followed by STTAs 0 EQs not preceded by SSTAs 4 (missed)
Scores		
Number of EQs with $M \geq 4.0$	**With TAs associate (only PREQ-TAs)**	**Without TAs associate (without PREQ-TAs or missed)**
8	**4 (3)**	**4 (5)**
	50% (37%)	**50% (63%)**

From Table 3 it is possible to see that SSTAs were present for 50% of all considered earthquakes. The appearance of SSTAs few days/weeks before the earthquake was observed in 37% of cases so that, in the perspective of an operational use of SSTA observations for seismic hazard forecast, we have to consider a missing rate of about 67%.

It should be again emphasized that, as far as the possible occurrence of pre-seismic TAs is concerned, such a missing rate has to be considered only as an upper limit due to the used observational technology[4] which is not able to guarantee the continuity needful to identify all possible occurrence of STAs. For instance (see Fig. 7) we cannot exclude that, in the cases

[4] The same limitation is not expected to similarly affect passive satellite sensors operating in the microwaves (MWs) spectral range (e.g., Aliano *et al.*, 2008a) instead than in the TIR.

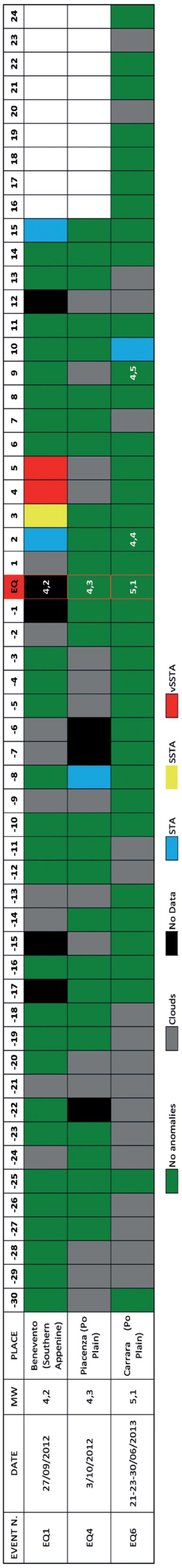


Fig. 7 - TAC analysis for the 6 earthquakes (with $M \geq 4.0$) without observed PREQ-TAs in the considered investigation period (July 2012 - June 2013) and testing areas. All scenes in the useful correlation temporal window (30 days before and 15 days after the earthquake) are represented by one cell. The column 0 corresponds to the date of occurrence of the (first, in the case of Carrara sequence) earthquake indicated in the 4 column on the left. Green cells represent days (mostly) not affected by clouds over the area of interest. The other used colors respect the code established in Table 1. Note that for EQ6 the considered time window has been extended on the right side in order to include possible POEQ-TAs occurring within 15 days after the last (June 30) event.

of Piacenza and Carrara earthquakes (and also before, Benevento earthquake) the SSTAs were not observed because of data gaps and/or the presence of clouds which actually were affecting the interested areas for more than 40% of the considered time windows (around the day of occurrence of each earthquake). For instance (Fig. 8), the STA observed on September 25, 2012 (8 days before the Piacenza earthquake) appears just in between 6 continuous days of absence of available observations. So it remained at the level of spatially extended TA (STA) without possibility to have a confirmation of its temporal persistence in the preceding/following days.

In the same way we cannot exclude (even if less probable than in the previous case) that the STA observed after the Carrara event of June 30, 2013 (M_W=4.5) had before or after some persistence in the 3 days (over six around that date) discarded because affected by clouds.

4. Conclusions

With reference to the previously given definition of SSTA and to the established correlation rules among SSTAs and earthquakes with $M \geq 4.0$, the results obtained within the S3 DPC-INGV project after (just) one year of continuous thermal monitoring (by using RST approach) of the two selected testing areas of southern Apennines and Po Plain, can be resumed as follows:

- a reliability better[5] than 67% (>60% in the southern Apennines, 100% in the Po Plain) was achieved which means less[5] than 33% of false positive (<40% in the Southern Apennines, 0% in the Po Plain);

[5] 2 possible POEQ-TAs occurred only 1 and 2 days outside the prescribed correlation temporal window (see text).

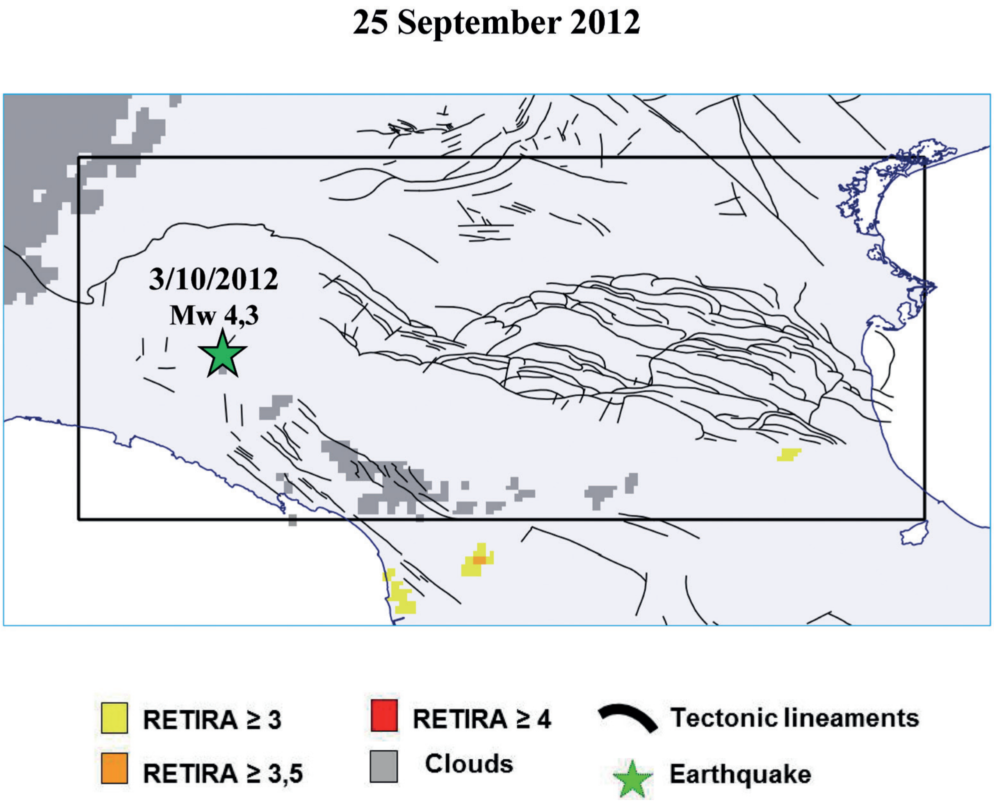


Fig. 8 - STAs observed 8 days before the Piacenza earthquake (M_W=4.3) occurred on October 3, 2012.

- a sensitivity of 50% (100% in the southern Apennines, 33% in the Po Plain) with a percentage of missed (i.e., fraction of earthquakes not preceded by SSTAs in the prescribed space-time correlation window) events of 37% (33% in the southern Apennines, 75% in the Po Plain).

Even if based on a very short period of time and a limited selection of testing areas, the results achieved seem to confirm (and strongly extend) the results already achieved by independent, 3-year long, studies funded by the German Space Agency [DLR: Halle *et al.* (2008)] and by NASA [together with USGS and University of South California: Eneva *et al.* (2008)] which successfully applied the same method (RST approach and RETIRA index) on longer data sets, different satellite sensors, different geographic areas and tectonic setting in Europe and in Asia. Results seems, moreover, confirm the ones achieved during the 2-year long EU-FP7 project PRE-EARTHQUAKES (Tramutoli *et al.*, 2012; www.pre-earthquakes.org), where the considered techniques played a major role (trough the integration with several independent observations) for demonstrating, in different geographic area of the world, the potential of an improved system of t-DASH (Tramutoli *et al.*, 2014).

The study of TIR anomalies has been never considered/proposed by the authors for providing whatever kind of earthquake prediction. It has, instead, since long time performed to understand if, or not, the integration of such observations with all the other relevant information available, can allow, in some measure, to improve our present capabilities to dynamically assess seismic hazard in a pre-operational context ready to profit of all the knowledge and information available day-by-day hour-by-hour.

The results of this study, confirming the ones achieved by similar (Genzano *et al.*, 2015) and other (above quoted) independent studies, seem to strongly support the inclusion of SSTAs (identified by the RST methodology) among the parameters whose continuous monitoring (and integration with all the other relevant information available) could strongly improve our present capabilities to dynamically assess seismic hazard in a pre-operational context.

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