Earthquake anomalies recognition through satellite and in-situ monitoring data

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Abstract
Cumulative stress energy in seismic active regions under operating tectonic force manifests various earthquake precursors. For seismic hazard analysis in Vrancea area placed in the Eastern Carpathians, Romania have been selected the earthquake presignals detectable from space: land (LST) and air (AT) surface temperature anomalies, outgoing longwave radiation (OLR) provided by time-series satellite NOAA AVHRR and MODIS (Terra/Aqua) data. This study analyzed the presignal anomalies of geophysical parameters for some strong and medium recorded earthquake events in Vrancea geotectonic active area: 1977, March 4th, $M_w = 7.4$; May 30th, 1990, $M_w = 7$; 1986 August, $M_w = 7.1$; 2004, October 27th, $M_w = 5.9$.

Keywords: Seismic precursors, land surface temperature, air surface temperature, outgoing longwave radiation, AVHRR (NOAA) and MODIS, Vrancea.

Introduction
Earthquake prediction is one of the major imperative tasks of modern geophysics, with two potentially compatible, but distinctly different objectives: (a) phenomena that provide information about the future earthquake hazard and (b) phenomena causally related to the physical processes governing failure on a fault that will improve our understanding of those processes. According to the classical earthquake theory, small earthquakes should continue to grow into large earthquakes until they spread all along the fault line. The mechanical processes of earthquake preparation are always accompanied by deformations, afterwards complex short- or long term precursory phenomena can appear. Cumulative stress energy in seismic active regions under operating tectonic force manifests various earthquake precursors (defined as changes in the Earth physical-chemical properties that take place prior to an earthquake). The most important earthquake precursors are changes of electric and magnetic fields, gas emissions (radon, methan, etc.), water level and quality (wells), land and air surface temperature days or weeks prior to strong, even moderate earthquakes [Freund, 2011; Varotsos et al., 2011; Erdal et al., 2016]. Also have been recorded ground surface deformations (elevations) increase in earthquake-prone areas. It seems that Vrancea region in Romania is fitting such a model [Zoran, 2012; Zoran et al., 2014].
With the development of space-based technologies to measure surface geophysical parameters and deformation at the boundaries of tectonic plates and large faults, earthquake science has entered a new era. Different criteria can be used to select the remote sensed earthquake precursors for which appear a clear evidence of the geophysical observable anomalies. Observations from Earth orbiting satellites are complementary to local and regional airborne observations, and to traditional in field measurements and ground-based sensor networks. Remote sensing plays a critical role in operational seismotectonics monitoring due to the remote locations of active fault systems and the large spatial extent of potential seismic presignals. In order to select the main geophysical parameters to be surveyed by geospatial and in-situ measurements in an integrated monitoring system, this paper focused on the analysis of major earthquake activities of moment magnitude $M_w > 5$ recorded in the Vrancea tectonic active area in Romania for which specific precursors can be reliably detected using satellite sensors, and establishes an important critical energy threshold for lithosphere and atmosphere coupling.

One of the earthquake short-term presignals that have gained a lot of attention and support from the scientific community across the world is thermal anomaly, defined by sudden rise in land and air surface temperature a few days or weeks before the earthquake occurrence. Due to possibly changes in physical properties that reflect the dilated or undilated state of the region, the occurrence of a large or moderate earthquake may well change in response to tectonic stress in a region. Thus, observed changes of some geophysical and geochemical parameters in that area are attributed to changes in the crustal elasticity of the region [Dey, et al., 2003]. The micro-crack formation strongly suggests unusual stress accumulation in the fracture zone of an active fault. This energy transformation may result in enhanced transient thermal infrared (TIR) emission, which can be detected through satellites equipped with thermal sensors like MODIS Terra/Aqua (Moderate Resolution Imaging Spectroradiometer), NOAA AVHRR (Advanced Very High Resolution Radiometer) TRMM TMI (Tropical Rainfall Measuring Mission Microwave Imager), AMSR-E (Advanced Microwave Scanning Radiometer). Regarding pre-earthquake “thermal infrared” (TIR) anomalies, have been considered CO$_2$ emanation leading to a local greenhouse effect or latent heat due to condensation of water on air ions formed as the result of radon emanation [Tronin, 1996; Tronin et al., 2004; Cervone et al., 2006; Pulinets et al., 2006; Freund, 2011]. Earthquake forecasting depends, in general, on the ability to detect precursory phenomena and understand its relation to the nature of on-going physical processes in active tectonic areas. As seismic events are some of the most catastrophic natural disasters to affect mankind, the threat of earthquakes will probably increase because of global urbanization, and thus millions of people are exposed to earthquakes. Remote sensing techniques, both spaceborne and airborne, can bring an effective contribution for earthquake prediction.

In this paper, changes before and after the Vrancea earthquakes in the atmosphere-land parameters have been investigated on the basis of time-series geospatial and field data analysis. The detected changes show a complementary behavior in terms of the various land, and atmospheric parameters, further showing strong evidence of coupling between lithosphere-land surface-atmosphere associated with the Vrancea’s earthquakes. Continuous monitoring and surveillance of these potential presignals helps us in differentiating earthquake related variations from seasonal changes and atmospheric effects. Strong and even moderate earthquakes are exceptional events reflecting very long-term deformation.
processes in a subduction zone [Takeshi et al., 2011; Chmyrev et al., 2013]. To develop a comprehensive understanding of seismic events beside short-term precursors we must also consider geodetic, geological and geomorphological information about crustal deformation. A better understanding of the physics of earthquakes and an increase in the knowledge about the space-time variation of the crustal process (i.e., seismicity and strain accumulation) would allow geoscientists to make useful statements on long-term behavior of the crust, so called “intermediate and long-term earthquake prognosis”, which are very important tools for long-term seismic hazard reduction measures such as development of realistic building codes, retrofitting existing structures, and land-use planning.

**Vrancea study test site**

Vrancea zone in Romania bounded by latitudes 45.6 °N and 46.0 °N and longitudes 26.5 °E and 27.5 °E (Fig.1) is one of the most active intracontinental tectonic areas in Europe, with high potential of seismic hazard associated to a few strong intermediate depth earthquakes (10 November 1940, $M_w = 7.7$, $H = 150$ km; 4 March 1977, $M_w = 7.4$, $H = 94$ km; 30 August 1986, $M_w = 7.1$, $H = 131$ km; 30 May 1990, $M_w = 6.9$, $H = 91$ km; 31 May 1990, $M_w = 6.4$, $H = 87$ km; 27 October 2004, $M_w = 5.9$, $H = 96$ km) [Ardeleanu et al., 2005; Oth et al., 2007].

![Figure 1 - Location of the Vrancea seismic zone in Romania.](image)

The seismic activity of Vrancea is concentrated at the contact between the main tectonic units being represented by the intermediate depth earthquakes concentrated in a narrow area of some 3000 km$^2$, near-vertical volume in the depth range of 85-220 km placed at the Eastern Carpathian Arc Bend. Because earthquake hypocenters are concentrated within a small volume, the Vrancea Zone is often described as unique. The existence of two kinds of major tectonic units- the orogenic units (the Carpathian Orogen and the North Dobrudjan Orogen) and platform units (the Moldavian Platform, as the South-Western margin of the East-European Platform, and the Moesian Platform) leads to the hypothesis of a mobile and seismic active contact between these units. Based on the hypothesis that the lithosphere blocks are separated by comparatively thin, weak, less consolidated fault zones such as
lineaments and tectonic faults, and that major deformation and most earthquakes occur in such fault zones, Vrancea seismically active region is considered as a system of absolutely rigid blocks divided by infinitely thin plane faults which interact between themselves and with the underlying medium. The interaction of the blocks along the fault planes is elastic-viscous (normal state) while the ratio of the stress to the pressure is below a certain strength level. When the critical level is exceeded in some part of a fault plane, a stress-drop (a failure) occurs (in accordance with the dry friction model), and it can cause a failure in other parts of the fault planes. These failures produce earthquakes. Immediately after the earthquake and for some time, the corresponding parts of the fault planes are in the creep state. This state differs from the normal state because of the fast growth of the inelastic displacements and lasts until the stress falls below some other threshold. According to such model, the strains are accumulated in fault zones, which reflect strain accumulation due to deformations of plate boundaries [Martin et al., 2005]. According to a 3D magneto-telluric tomographic images model, the trigger action of the intermediate depth earthquakes in the Vrancea zone may be interpreted as the rock response to active torsion processes induced by the complex interplay among the structure of the litho-sphere and the surrounding asthenosphere, in this sector of the Eastern Carpathians [Stanica et al., 2010]. This may explain the increase shear stress and drive faulting system and re-shearing within the rigid slab in the Carpathian Arc Bend and Vrancea zone. Located at Eastern Carpathians bend, intermediate-depth seismogenic Vrancea zone is a complex tectonic environment, the heat flux budget in the area playing a decisive role in defining the lithospheric rheological properties. Sedimentation, palaeoclimate, under compaction and heat refraction effects, on one hand, and the heat generated in the upper crust, on the other, combine to explain the observed subsurface temperature field, and in particular the pronounced curvature of the vertical temperature profiles. Due to the interplay of thermal effects of high sedimentation rate episodes (13-12.5 Ma) and subsequent thermal relaxation and new sedimentation episodes, the overall effect of the Neogene-Quaternary sedimentation is rather uniform along the study zone. In the investigated area, both the thermal effects of rapid sedimentation and palaeoclimatic effects contribute to the temperature field in the upper part of the sedimentary section. The sedimentation process induces a significant time-dependency of the temperature field of the underlying lithosphere with repercussions on its thermal thickness, metamorphic state and rheological behavior. Temperature variations as large as 70-100°C occurred in the crystalline crust immediately under the sedimentary pile. Progressively smaller variations were present up to 40-50 km depth. The temperature increases in the upper crust caused by sedimentation. Thermally defined lithosphere thickness is considered to be of about 160 km. The lithosphere has not reached yet the thermal steady - state, the present temperatures being about 80-90% of the equilibrium temperatures, depending on depth and on location along geologic profiles [Demetrescu et al., 2007]. This study investigated the selected intermediate-depth seismic events presented in Table 1. The strength of an earthquake is usually measured on different magnitude scales, but the moment magnitude \( M_w \) is regarded as the most representative value of the seismic source. Earthquake data for four earthquakes with moment magnitude \( M_w \) between 5.9 and 7.4 and focal depth between 91km and 131 km are provided by the National Institute of Earth Physics Catalog and USGS Catalog.
Table 1 - Selected intermediate-depth Vrancea earthquakes.

| Earthquake number | Date yyyy/mm/dd | Time (UTC) | Latitude (°N) | Longitude (°E) | Focal Depth (km) | Earthquake Moment Magnitude (M_w) |
|-------------------|-----------------|------------|---------------|---------------|-----------------|----------------------------------|
| 1.                | 1977/03/04      | 19:21:54.1 | 45.77         | 26.76         | 94.0            | 7.4                              |
| 2.                | 1986/08/30      | 21:28:35.7 | 45.52         | 26.49         | 131.0           | 7.1                              |
| 3.                | 1990/05/30      | 10:40:06.4 | 45.83         | 26.89         | 91.0            | 6.9                              |
| 4.                | 2004/10/24      | 20:34:36   | 45.79         | 26.63         | 96.0            | 5.9                              |

Methodology and geospatial data used

Pre-earthquake physical and chemical interactions in the earth’s ground may cause anomalies of land surface temperature, outgoing longwave radiation, air temperature, etc. Earthquake preparing is a transient dynamic process. Any tectonic activity is accompanied by energy transfer and material movements, which can change the state of ground thermal radiation. Based on this assumption is possible to derive present-day tectonic activities from thermal infrared satellite data regarding thermal radiation state on the ground. As received satellite infrared information is influenced by many types of factors, the main problem to be solved is to extract useful information associated with tectonic activities and to eliminate the effects of non-tectonic factors.

Our methods to find the anomalies of geophysical parameters identified as seismic precursors have been used in the following steps: firstly, we analyzed thermal infrared information provided by satellite data, removing data which were not related to tectonic activity and selecting the data which were correlated with tectonic processes in the Vrancea zone; secondly, we studied the relationship between tectonic strain and thermal exchange through theoretical analysis; thirdly, we analyzed in-situ available data provided by the seismic network in Vrancea area as well as meteorological stations. Finally, we compared the ground surface and satellite data, and established the possible relationship between these two kinds of observations. Before a potential anomaly can be nominated as a reliable precursor, it should pass or be proved by the following tests or analyses: whether or not it is an artificial anomaly, whether or not it correlates with an investigated event, whether or not it is a random anomaly.

Prior to strong and moderate seismic events the earthquake precursors appear at different distances and heights over the active seismogenic areas. It seems that the earthquake preparation area on the ground can be estimated according to the relation:

\[ R = 10M_w^{0.43M} \]  \[ 1 \]

where \( R \) is the radius of the preparation zone and \( M_w \) is the earthquake moment magnitude [Dobrovolsky et al., 1979; Dobrovolsky et al., 1989]. Most of the precursory phenomena may exhibit different patterns in which systematic growth takes place during the pre-seismic period, corresponding to the local stress build-up. After that is followed by a relatively rapid return to near equilibrium conditions following the seismic event. As examples, for 4 March 1977 Vrancea strong earthquake with \( M_w =7.4 \), the corresponding calculated radius
of preparation zone would be \( R \approx 1520.5 \) km and \( \pm 13.7 \) degrees in the latitudinal and longitudinal direction from the epicenter, while for moderate earthquake from 27 October 2004 with \( M_w = 5.9 \), the corresponding calculated radius would be \( R \approx 344 \) km and \( \pm 3.1 \) degrees in the latitudinal and longitudinal direction from the epicenter.

Function of their occurrence elevation the seismic presignals can be grouped into three classes: on the surface (land surface temperature, radon gas, etc.); in the lower atmosphere (outgoing long wave radiation, surface latent heat flux, and air temperature; and in the higher atmosphere - ionosphere (total electron content - TEC, etc), [Dey et al., 2003; Tronin et al., 2004; Ozunov et al., 2004; Tramutoli et al., 2005]. Some of the seismic presignals have been observed by satellite remote sensing, while others by in-situ monitoring techniques. Different criteria can be used to select remotely sensed earthquake presignals for which there is evidence of anomalies in geophysical observables. Observations from Earth-orbiting satellites are complementary to local and regional airborne observations, and to traditional in-field measurements and ground-based sensor networks [Saraf et al., 2005; Zoran et al., 2012a; Zoran et al., 2012b].

During last decades the remote sensing data have been widely used for the assessment of prior and after strong earthquakes changes as well as for the detecting and mapping of post-earthquake damages based on the earth observation data like (ALOS, PALSAR, SPOT, Landsat TM/ETM, TerraSAR, RADARSAT-1/2, as well as some other remote sensing imagery) [Singh et al., 2001; Yusuf et al., 2001]. With the advent and continuous enlargement of space-based observations, researchers extended that use of geospatial data in different geosciences applications which enables new solutions to determining interrelations among various geophysical-geochemical phenomena like are earthquake precursory phenomena [Zoran et al., 2007]. The relevant parameters (Outgoing Longwave Radiation, Land Surface Temperature and the mean daily Air Temperature) related to investigated earthquakes in Table 1 have been provided by the NOAA Climate Prediction Center, National Environmental Satellite Data and Information Service (NESDIS), National Centers for Environmental Prediction (NCEP) and the NOAA/ESRL Physical Sciences Division, Boulder Colorado, USA from their web site at (http://www.ncep.noaa.gov/), (www.nesdis.noaa.gov), (http://www.esrl.noaa.gov/psd/).

For Vrancea earthquake recorded on 27 October 2004 have been used also the available time series of MODIS Terra/Aqua Land Surface Temperature/Emissivity ( LST ) 8-Day L3 Global 1km SIN Grid MOD11A2 LST_Day_1km and LST_Night_1km data and MODIS/Aqua Land Surface Temperature/Emissivity ( LST ) 8-Day L3 Global 1km SIN Grid MYD11A2 LST_Day_1km and LST_Night_1km data, over different periods of time provided by Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (http://daac.ornl.gov/MODIS/modis.html). The available MODIS Terra/Aqua satellite data starting from 2000/2002 years make it possible to resolve land surface thermal anomalies globally with better than 1°C resolution. Meteorological data around the Vrancea region in Romania: air temperature and anomaly on the base period of normals 1975-1995 and 1981-2010, have been provided by the Romanian Meteorological Administration (www.meteoromania.ro) and (www.wunderground.com). Also, in-situ meteorological data have been compared with satellite data.

Surrounding Vrancea, the several seismic stations belonging to the Romanian Seismic Network are recording seismic and other geophysical, geoelectromagnetic, geodynamic
and meteorological parameters. ENVI 5.0 and IDL 6.3 software for satellite data processing have been used.

**Results and discussion**

In order to set accurate, precise, and stand-alone criteria for the earthquake prediction, simultaneous integration of several precursor parameters which reduce the parameter uncertainty must be considered. Using time-series remote sensing observations, this paper examines spatio-temporal variations of land surface temperature, outgoing long-wave radiation, and mean air temperature several weeks to several days before the studied earthquakes. Earthquake is a dynamic phenomenon, usually accompanied by crust displacements attributed to an energy transfer due to a breakdown between source and environment. The changes prior to the earthquake or along with it may have different physical and chemical effects on the lithosphere, atmosphere and ionosphere, therefore making it detectable. These variations of lithosphere, atmosphere and ionosphere parameters before the main earthquakes are considered as earthquake precursors which are used as hints for impending earthquakes. As earthquakes are large-scale fracture phenomena, associated fracture-induced physical fields allow a real-time monitoring of electromagnetic (EM) emissions in a wide frequency spectrum ranging from kHz to MHz which are produced by opening cracks. Those emissions can be considered as the so-called precursors of general fracture.

These presignals suggest the existence of a strong coupling between the dynamics of lithospheric processes land- atmospheric anomalies associated with seismic processes [Pulinets et al., 2006]. Prior to a strong or moderate earthquake event in the areas close to the earthquake epicenter, due to high tectonic stresses can be released radon, and greenhouse gases (CO$_2$, CH$_4$, N$_2$, etc.) that escape to the lower atmosphere and create a localized greenhouse effect and thus augment the LST of the area. There is a great deal of interest in the emissions of various gases from the earth prior to earthquakes. Another possible mechanism responsible of the temperature rise preceding an earthquake is the presence of positive hole-type charge carriers in rocks which become activated when rocks are subject to high levels of stress prior to an earthquake, the appearance of these electronic charge carriers within a finite rock volume leads to enhanced infrared emission from the rock surface in the 8-12 mm region and hence an increase in LST [Dobrovolsky et al., 1989; Ouzounov et al., 2004]. Pre-earthquake spatio-temporal thermal anomalies are controlled by various factors like as earthquake moment magnitude and its focal depth, geological setting, topography and land covers. Have been reported several observations of such thermal anomalies preceding several major earthquakes in different parts of the world [Tronin, 1996; Tronin et al., 2004; Saraf and Choudhury, 2004; Saraf and Choudhury, 2005; Saraf et al., 2009].

**Outgoing Longwave Radiation**

Outgoing Longwave Radiation which is the emission to space of terrestrial radiation from the top of the Earth’s atmosphere is controlled by the temperature of the earth and the atmosphere above it, the water vapor content in the atmosphere, and the clouds. Long wave radiation of the Earth is a major driver of the Earth climate system. OLR is the thermal radiation flux emergent from the top of the atmosphere and connected with the earth-
atmosphere system in general, being dependent on cloud and land surface temperature. This energy has been measured at the top of the atmosphere by the National Oceanic and Atmospheric Administration satellites and includes all of the emission from the ground, atmosphere and clouds formation. The possible link of transient thermal fields on the ground with pre-earthquake processes establishes the rationale to explore the radiation budget prior to four major earthquakes in Vrancea area. OLR is a NOAA polar-orbiting satellite derived measurement of the radiative character of energy radiated from the warmer earth’s surface to a cooler space in the 10-12 μm infrared windows. The interpolated OLR data are continuous spatially as well as temporally. The estimates of interpolated OLR values (W/m²) originally observed by polar orbiting NOAA are based on dedicated developed algorithms. Maximum and minimum OLR value ranges including other parameters were defined in the analyzed earthquake cases. The high stress field prior to earthquakes is responsible for surface and subsurface deformation in the epicentral region, which, in turn, is responsible for changes in the thermal, electrical and magnetic fields [Zoran et al., 2012]. Daily OLR anomalies have been investigated in detail for selected Vrancea earthquakes because these can reflect the energy variation in the earth-atmosphere system and record the earthquake thermal anomalies in different time scales over the seismic monitoring field. Based on NOAA 1981-2010 climate data, for strong Vrancea earthquake 4 March 1977 $M_w = 7.4$, starting with the 16 February 1977 till 20 February 1977 has been developed a high positive daily OLR anomaly in the range of 10- 35 Watt/m², with a maximum positive value on 18 February 1977 (Fig. 2). After that, between 21 -24 February 1977 was recorded a strong negative OLR anomaly between -10 Watt/m² to -40 Watt/m². Other weak positive daily OLR anomalies have been registered on 27 -28 February and 1-3 March 1977, followed by another negative daily OLR anomaly on 28 February-1 March 1977 and 4 March 1977.

In case of 30th August 1986 earthquake with $M_w = 7.1$ in the Vrancea tectonic active zone, from NOAA derived data and based on 1981- 2010 climate have been recorded some positive daily OLR anomalies between 17-19 August and 22-24 August 1986 in the range of 10- 30 Watt/m², but a very high positive anomaly between 26- 30 August 1986 in the range of 15- 35 Watt/m² with an intense maximum one day before the main shock in value of 35 Watt/m² (Fig. 3). The same the temporal variation of daily mean OLR anomaly, NOAA derived data over the Vrancea area (Fig. 4) have been observed for 30th May 1990 $M_w = 6.9$ earthquake based on 1981- 2010 climate data. Prior almost 3- 4 weeks (1-10 May, 15-18 May, 21-24 May 1990) before the main shock appeared significant daily OLR positive anomalies of 20-30 Watt/m². Three days before earthquake (27-30 May 1990) a strong negative daily OLR anomaly (-20 to -50 Watt/m²) was evidenced over Vrancea area, which can be interpreted due to contraction the rocks. Similarly, for moderate 27th October 2004 earthquake ($M_w = 5.9$) recorded in Vrancea region, 3-4 days prior to the main event have been recorded daily OLR positive anomalies of 20-50 W/m² higher than the normal, which evidenced gradually increase of the outgoing long-wave radiation OLR emitted by land surface in the epicentral area before earthquake registered on 27 October 2004.
Figure 2 - Daily OLR anomaly variation over Vrancea area before and after 4 March 1977 earthquake.

Figure 3 - Daily OLR anomaly variation over Vrancea area before and after 30 August 1986 earthquake.
Figure 4 - Daily OLR anomaly variation over Vrancea area for 30 May 1990 earthquake.

Figure 5 - Daily OLR anomaly variation over Vrancea area for 27 October 2004 earthquake.

Figure 5 presents the temporal variation of daily mean OLR anomaly, NOAA derived data over Vrancea epicentral area during 20 October 2004- 3 November 2004 expressed
in W/m² with an accuracy of 3 W/m². The mean daily OLR increased starting from 24 October 2004, with a maximum value between 25-26 October and then decreased gradually till 27 October in the morning, after that increased again between 27 - 30 October. OLR anomalies covered an extended area described by latitudes 45N - 47N and longitudes 25E - 27E and were distributed along the fault zone system in the Vrancea region. OLR is dependent on local meteorological parameters, temperature and humidity and changes in these variables may be responsible also for anomalous OLR values associated with seismic events.

Land Surface Temperature

Land surface temperature, a measure that is widely used for thermal anomaly studies in the epicentral and surrounding areas of strong earthquakes, can be retrieved by a variety of satellite sensors depending on the spatial and temporal resolution needed. Data from satellite sensors such as NOAA AVHRR series satellites, MODIS Terra and Aqua Earth Observation System satellites, AATSR (Advanced Along-Track Scanning Radiometer) on board the ENVISAT satellite, provide LST products retrieved for a specific area with a spatial resolution of about 1 km, while SEVIRI (Spinning Enhanced Visible and Infrared Imager) sensor on board the METEOSAT Second Generation (MSG) series geostationary satellites, retrieves LST at a lower spatial resolution (about 3 km). Land surface temperature anomalies (A_LST) have been obtained by subtracting the multi-year mean LST from the area averaged values and divided by multi-year mean values, which can be expressed as:

$$A_{LST} = \frac{LST - LST_{mean}}{LST_{mean}}$$  \[2\]

From NOAA AVHRR data, generation of all the land surface temperature LST maps was based on the split window algorithm, which uses the differential absorption effect in NOAA AVHRR channels 4 and 5 for correcting the atmospheric attenuation mainly caused by water vapor absorption [NOAA KLM, 2006]. Data calibration and temperature calculation were based on the method provided in NOAA user’s guide [Gruber et al., 1984]. Selected digital data sets (scenes) were kept consistent in terms of the time of acquisition. This is followed by the time-series layouts of these LSTs that are finally studied to analyze the temperature variation of the ground surface. Cloud-covers were delineated and avoided from any type of calculation. As TIR radiation cannot penetrate clouds, the temperature of cloudy areas will be only the temperature of cloud tops and not the actual LST of the area.

A succession of temporal LST images show the gradual development of TIR anomaly in epicentral area Vrancea and surroundings. As in case of daily OLR anomalies, mean daily LST anomalies investigated for selected Vrancea earthquakes recorded the thermal anomalies in different time scales over the seismic monitoring field. Based on NOAA 1981-2010 climate data, for strong Vrancea earthquake 4th March 1977 Mw =7.4, starting with 16 February 1977 till 27 February 1977 has been developed a high positive mean daily land surface temperature in the range of 5-11°C and maximum values of almost 11-13°C between 20-26 February 1977. In case of daily OLR, the positive anomaly recorded almost
4 days before 4\textsuperscript{th} March 1977 earthquake was followed by a negative mean daily LST anomaly with values of -1°C to -5°C for 28 February-3 March 1977 period (Fig. 6).

**Figure 6** - Mean Daily LST anomaly over Vrancea area for 4 March 1977 earthquake.

**Figure 7** - Mean Daily LST anomaly over Vrancea area for 30 August 1986 earthquake.
Clear mean daily LST positive anomalies were developed for 30th August 1986 earthquake with $M_w = 7.1$ in Vrancea zone, between 16-20 August in the range of 1.6- 3.2°C with a maximum value on 19th August 1986 of 4.8 and 26-30 August 1986, in the range of 1-3.2°C (Fig. 7) from NOAA derived data and based on 1981-2010 climate data. The same behavior of temporal variation of mean daily LST anomaly has been observed for 30th May 1990 $M_w = 6.9$ earthquake based on 1981-2010 climate and NOAA derived data over Vrancea area. The pregnant appearance of mean daily LST positive anomaly was recorded during 23-27 May 1990 period in the range of 2-8°C with 1°C resolution (Fig. 8). Three days before the main shock was recorded a negative mean daily LST anomaly up to - 4°C.

![Figure 8 - Mean Daily LST anomaly over Vrancea area for 30 May 1990 earthquake.](image)

Based on NOAA derived data over Vrancea and 1981-2010 climate data, for 27th October 2004 $M_w = 5.9$ earthquake appeared a high mean daily LST positive anomaly almost one week prior the main event with 5-10°C with 0.8°C resolution (Fig. 9) and a maximum value of 12.8°C almost one week after the earthquake. As from 2002 are available time-series products MODIS/Terra Land Surface Temperature/Emissivity (LST) 8-Day L3 Global 1km SIN Grid, OD11A2/LST_Day_1km data, was possible to represent land surface temperature variation during 2004 year over the Vrancea region (Fig.10) centered on earthquake of 27 October 2004 epicenter (45.787 N, 26.622 E), 101 km x 101 km surface area. For Land Surface Temperature (LST) anomaly analysis over the Vrancea area during October 2004 month have been considered LST mean values of MODIS/Terra time-series data during 2000-2012 period and MODIS/Aqua time-series and different area size polygons centered on Vrancioaia (VRI) seismic station (Latitude 45.8657 and Longitude 26.7276).
Time series satellite data analysis revealed a clear increase of land surface temperatures LST around the epicentral area ranging 5-10°C in good accordance with NOAA AVHRR satellite data. MODIS classification considered Pixel Aggregation Method (PAM) and found that 3559 of 10201 pixels [34.89%] were belonging to the same class as the center pixel “(5) Mixed Forests”. In all test cases considered earthquakes in this paper, the increase in land surface temperature LST and OLR near Vrancea epicentral area can be attributed to enhance
greenhouse gas emission from the squeezed rock pore spaces and/or to the activation of p-holes in stressed rock volume and their further recombination at rock-air interface. Due to high tectonic stresses, prior to a strong earthquake event in the areas close to the earthquake epicenter from the earth’s surface can be released radon gas, and greenhouse gases (CO$_2$, CH$_4$, N$_2$, etc.) that escape into the lower atmosphere and create a localized greenhouse effect and thus augment the LST anomaly of the area [Zoran et al., 2012b].

**Air Temperature**
In order to study the relationship between the air temperature and Vrancea earthquakes have been analyzed time-series mean daily air temperature anomalies, on the base period of normals 1981-2010 around the Vrancea zone in Romania provided by NOAA satellites. For 4$^{th}$ March 1977 strong earthquake was analyzed 10 February -15 March 1977 period. The positive air temperature anomaly started developing to North West and South East of the epicentral area, air temperature showing a rise of around 6$^\circ$C - 10$^\circ$C during 11-28 February 1977 (Fig. 11), in good correlation with in-situ measurements.

![Air Temperature anomaly over Vrancea area - Romania, earthquake 4 March 1977](Figure 11 - Air Temperature anomaly over Vrancea 4 March 1977 earthquake.)
Figure 12 - Air Temperature anomaly over Europe before 4 March 1977 Vrancea earthquake.

NOAA/ESRL/Physical Sciences Division results for 10 February-28 February 1977 over Europe (Fig. 12) revealed a pronounced increase of mean air temperature anomaly over Romania and neighbor countries of more than 3.5°C, which can be explained through long distance calculated radius of preparation zone of $R \approx 1520.5$ km from the epicenter according Equation [1] for earthquake 4 March 1977 with $M_w = 7.4$. During 28 February-4 March 1977 period, was recorded a clear evidence of negative air temperature anomaly in range of $-2^\circ \text{C}$ to $-6^\circ \text{C}$, also in accordance to in-situ measurements and other findings for strong earthquakes in the world [Zoran, 2012]. The recorded negative air temperature anomaly over the Vrancea zone and Romania five-six days before strong earthquake 4 March 1977 can be explained by an increased field compression in the epicentral and the surrounding area. For next ten days period during 5-15 March 1977, again was recorded a small positive air temperature anomaly in alternating with small negative temperature anomaly over the Vrancea area and Romania. This observation fits well with the concept that the thermal anomaly can appear some days to weeks before strong earthquakes and dissipated after the quake. Time-series analysis of mean daily air temperature anomalies for test case 30 August 1986 Vrancea earthquake revealed two strong positive air temperature anomalies recorded about ten days (17-20 August 1986) and another with three days (27-30 August 1986) before the main shock in the range of 1.8-3.6°C with 0.6°C resolution (Fig. 13).
Similarly, mean daily air temperature anomalies have been registered before 30\textsuperscript{th} May 1990 earthquake, when air temperature higher than the normal were observed one week prior to the main event between 23- 26 May 1990 in the range of 1.6-6.4°C with 0.8°C resolution. Figure 14 presents a succession of positive air temperature anomalies and negative anomaly which appeared between 27- 31 May 1990 over Vrancea area. It seems that the negative air temperature anomaly developed 3 days before the main shock of $M_w = 6.9$ on 30\textsuperscript{th} May, followed by a second seismic event of $M_w = 6.4$ on 31\textsuperscript{st} May 1990 can be attributed to a cold air masses front developed over Romania in that period of time.

In case of the 27\textsuperscript{th} October 2004 earthquake, have been analyzed time-series of mean daily air temperature and anomaly data for the period of 15 October -15 November 2004, on the base period of normals 1981-2010 around the Vrancea region provided by NOAA satellites. The positive air temperature anomaly started developing to North West and South East of the epicentral area, air temperature showing an increase of around 4.8°C- 8°C during 24-27 October 2004 (Fig. 15), in good correlation with in-situ measurements, which revealed a pronounced increase of air temperature over the Vrancea region.
Figure 14 - Air Temperature anomaly over Vrancea region for 30 May 1990 earthquake.

Figure 15 - Air Temperature anomaly over Vrancea region for 27 October 2004 earthquake.
After the main shock of 27th October, during 27 October -3 November 2004, air temperature recorded a gradual increase with a maximum of 5°C degrees.

**Conclusion**

This study attempts to acquire information on seismic precursors in the Vrancea geotectonic active area in Romania from in situ and satellite data (NOAA AVHRR and MODIS Terra/Aqua time series). This study presents observations made using meteorological satellite NOAA-AVHRR time-series data-derived outgoing long-wave radiation (OLR), land surface temperature (LST) and air temperature (AT) in case of three strong Vrancea earthquakes (4th March 1977, 30th August 1986, 30th May 1990) using anomalous TIR signals as reflected in LST and AT rise and high OLR values which follow similar spatio-temporal growth pattern. In addition, in order to investigate thermal anomaly pre-signal for a moderate earthquake (27th October 2004) beside NOAA AVHRR time-series data have been used MODIS Terra/Aqua time-series satellite data. In all cases, the spatio-temporal statistical analysis revealed thermal anomalies enhancements of OLR, LST and AT parameters developed some days to weeks before main seismic events and disappeared after the main shock, having a good spatial correspondence with the epicenters and the active fault’s location as well as with moment magnitude and preparation areas. This is in good accordance with the seismogenic coupling processes between lithosphere-surfacessphere-atmosphere and for recognizing earthquake anomalies with multiple parameters from integrated Earth observation system. The analysis of all available geospatial data shows evidence of a thermal build up near the epicentral area related to the investigated earthquakes in the Vrancea zone in Romania.

NOAA AVHRR time-series data analysis evidenced a transient thermal infrared rise in land surface temperature ranging 5°C-10°C and outgoing longwave radiation increase ranging 20-50 W/m² around Vrancea epicentral area, function of latitude and longitude around epicenters. Air temperature data recorded by meteorological in-situ observatories and NOAA AVHRR time-series satellite data also support the development of short-term thermal anomaly prior to earthquakes.

The results of pre-earthquake thermal anomalies recorded prior strong and moderate earthquake analyzed in this paper are promising tools towards the future short-term forecasting of the impending earthquakes in tectonically active region Vrancea as well as in other seismogenic areas in the world.

As Earth science is multidisciplinary, it is very important as surveillance and research of tectonic active areas to integrate all available satellite and observational information with different temporal and spatial scales and review all the seismic, geodetic, geomorphological, geological, geospatial data. Other precursory phenomena such as foreshocks and nonseismological anomalies (electromagnetic, atmospheric, ground-water gas emissions, etc.) must be well considered.

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