ANOMALOUS LAND SURFACE TEMPERATURE DETECTED FROM TIME-SERIES SATELLITE DATA AS PRECURSOR OF STRONG EARTHQUAKE

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ABSTRACT

The earthquake energy may result in enhanced transient thermal infrared (TIR) emission, which can be detected through satellites equipped with thermal sensors like AVHRR (NOAA), MODIS (Terra/Aqua). The received satellite infrared information is, however, likely influenced by many kinds of factors. The first problem to be solved is to extract information associated with tectonic activities and eliminate non-tectonic factors. This paper presents observations made using time series MODIS Terra/Aqua and NOAA AVHRR satellite data to derive land surface temperature (LST) parameter for some strong and moderate seismic events recorded in Vrancea tectonic active region situated beneath the Southern Carpathian Arc in Romania, which is one of the most active intracontinental seismic areas in Europe. The region is characterized by a high rate of occurrence of large earthquakes in a narrow focal volume. This study investigated Two significant earthquakes: the March, 4th, with moment magnitude Mw = 7.4, *H* = 94 km; and October 27th 2004, with moment magnitude Mw =5.9 and epicenter depth of *H* =96 km. Our joint analysis of LST together air temperature (AT) shows that starting with almost one week prior to a moderate or strong earthquake a transient thermal infrared rise in LST and AT of several Celsius degrees (°C) values higher than the normal have been recorded around epicentral areas, function of the magnitude and focal depth, which disappeared after the main shock.

INTRODUCTION

One of the more elusive goals in seismology is short-term earthquake forecasting. The selection of the earthquake precursory observables must be based on the existence of credible scientific evidence for anomalies in the geophysical parameters prior to at least some earthquakes and the accepted physical models to explain the existence of the precursors (1). Due to its theoretical and experimental complexity, the scientific research on medium to strong seismic events prediction still represents one of the most challenging questions in the scientific community.

In an active geotectonic focal region as is the case of Vrancea zone the increasing accumulation of strain can cause dilatancy of rocks. This phenomenon of dilatancy consists in the formation and propagation of cracks inside a rock as stress reaches a critical value .If the rocks in the epicentral zone and surrounding volumes are saturated with fluids, the voids generate pressure gradients. Hence, fluids invade the newly opened voids and flow until the pressure balances inside the whole system of interconnected pores. During the fluid invasion the condition of rock hardening can be reached: the rock suddenly weakens and the earthquake is triggered. Therefore the dynamical structure of the presignals is linked to the structure of the seismic focal zone, and its variability can convey useful information about the geotectonic dynamics.

According to 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. It seems that Vrancea region in Romania is fitting such a model. Seismic events are associated with ongoing deformation along the main active geologic faults. Crustal deformation produces a wide variety of landforms at the surface of the Earth and their size depends on the duration of the process involved in their formation. Co- and post-seismic deformations take place over periods of a few seconds to several days, and produce fault scarps

and surface displacement ranging from a few centimeters to several meters in magnitude. Along active deformation zones, earthquakes cause short-term and localized topography changes which may present additional hazards, but at the same time permit, to quantify stress and strain accumulation, a key control for seismic hazard assessment (1).

Earthquake science has entered a new era with the development of space-based technologies to measure surface geophysical parameters and deformation at the boundaries of tectonic plates and large faults.

Geospatial data proved the ability to identify and monitor the specific variations at ground surface associated with approaching severe earthquakes which appear several days or weeks before the seismic shock over the seismically active areas. Satellite time-series data, coupled with ground based observations where available, can enable scientists to survey pre-earthquake signals in the areas of strong tectonic activity. Cumulative stress energy in seismic active regions under operating tectonic force manifests various earthquakes' precursors. Space-time anomalies of earth's emitted radiation (thermal infrared in spectral range measured from satellite months to weeks before the occurrence of earthquakes, radon in underground water and soil, etc.), and electromagnetic anomalies are considered as pre-seismic signals. As earthquake preparing is a transient dynamic process accompanied with energy transfer and material movements, which are responsible of thermal radiation state change on the ground, it is possible to monitor the thermal radiation state on the ground from thermal infrared satellite data.

Several studies performed in the last years suggested the existence of anomalous space-time transients, in the thermal infrared (TIR) radiation emitted by the Earth, possibly related to earthquake preparatory phenomena. Among different theories about their origin, the abrupt increase in radon gas (Rn222), greenhouse gases (CO2, CH4, NO2 etc) emission rates has been also proposed to explain the appearance of anomalous TIR precursory signals in some relation with the place and the time of earthquake occurrence in geotectonic active areas. Geospatial data, coupled with ground-based observations where available, enable scientists to survey pre-earthquake signals in areas of strong tectonic activity.

Natural radioactivity (in particular, radon Rn-222) is considered to be a possible trigger for atmospheric increased ionization and electrical conditions anomalies in the lower atmosphere (atmospheric conductivity and the electric field) and upper atmosphere (ionospheric TEC –Total Electron Content anomalies). The mosaic pattern of the strain field in the epicentral zones creates a specific obstacle to the detection of precursory events and determination of the spatial scale of the earthquake preparation zone. Obviously, the size of the zone largely depends on the earthquake magnitude. A change in the thermal regime of the epicentral zone and its surroundings is one of the most pronounced changes that can be detected by space-borne sensors such as Advanced Very High Resolution Radiometer (NOAA AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS Terra/Aqua). In spite of some skepticism regarding earthquake prediction, early warning signs of earthquakes are diverse, fleeting and often subtle, and they can also be surprisingly strong, even for moderate earthquakes (2), (3). Thus, the analysis of derived geophysical parameters from time series satellite data can provide precursory patterns for medium and large earthquakes of Vrancea zone, in Romania.In particular, can be assessed a reasonable probability that an earthquake larger than a certain threshold to be recorded in the future (4).

STUDY AREA AND DATA USED

Vrancea tectonic active zone is one of the most active intracontinental seismic areas in Europe located between latitudes 45.6 °N and 46.0 °N and longitudes 26.5 °E and 27.5 ° E (Figure 1).

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. 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.

It has a high potential seismic hazard associated to a few strong intermediate depth earthquakes (1940, November, 10th, Mw = 7.7, h = 150 km; 1977, March, 4th, Mw = 7.4, h = 94 km; 1986, August, 30th, Mw = 7.1, h = 131 km; 1990, May, 30th, Mw = 6.9, h = 91 km; 1990, May, 31st, Mw = 6.4, h = 87 km; 2004, October 27th, Mw =5.9, h =96 km). Surrounding Vrancea, the several seismic stations belonging to the Romanian seismic network are recording seismic and other geophysical, electromagnetic, geodynamic and meteorological parameters. This study investigated: the March, 4th, with moment magnitude Mw = 7.4, h = 94 km; and October 27th 2004 earthquake, with moment magnitude Mw =5.9 and epicentre depth of h =96 km. The strength of an earthquake is usually measured on different magnitude scales, but the moment magnitude (mw) is regarded as the most representative value of the seismic source (5).

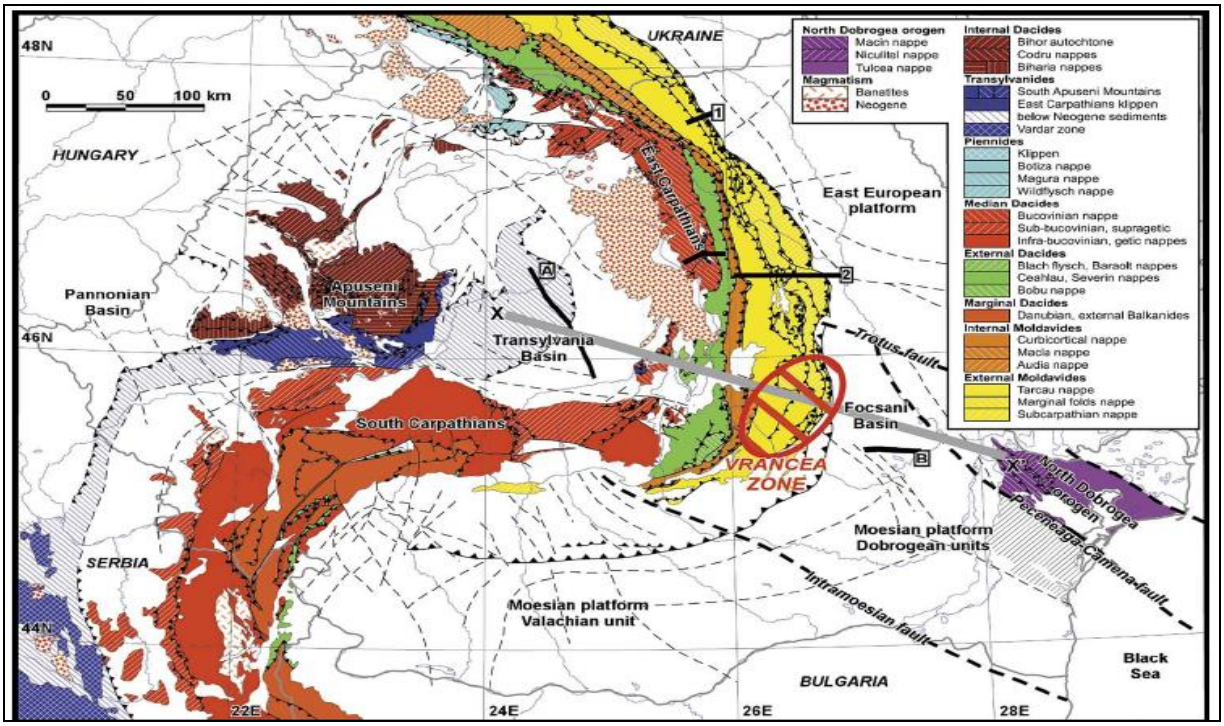

Figure 1. The study test site Vrancea geotectonic active area in Romania

This study used time series products of MODIS/Terra land surface temperature/emissivity (LST/E) 8-Day L3 Global 1 km SIN Grid MOD11A2 LST_Day_1 km 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). MODIS/Terra LST/E Daily L3 Global 1 km SIN Grid satellite data were used for comparison of the results.

In addition, have been used NOAA-AVHRR data-derived land surface temperature (LST) and air temperature (AT) provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO, USA (http://www.esrl.noaa.gov/psd/). Meteorological data around Vrancea region in Romania and anomaly were provided by the National Administration of Meteorology, in addition, in-situ meteorological data were compared with satellite data.

RESULTS

This paper presents observations made using time series NOAA-AVHRR and MODIS satellite data–derived land surface temperature (LST) and air temperature (AT) anomalies recorded for the two selected earthquakes (1977 and 2004) recorded in Vrancea seismic region, Romania, using anomalous TIR signals as reflected in LST and AT values rise which followed similar spatio-temporal growth pattern. In both analyzed cases, starting with almost one week prior to a moderate or strong earthquake a transient thermal infrared rise in LST and AT of several Celsius degrees (°C) higher than the normal have been recorded around epicentral areas, function of the magnitude and focal depth, which disappeared after the main shock. As Vrancea area has a significant regional tectonic activity in Romania and Europe, the joint analysis of geospatial and in-situ geophysical information is revealing new insights in the field of hazard assessment. In order to implement an efficient and robust system for earthquake prediction, the precise anomaly detection in a nonlinear time series of earthquake precursors seems to be a critical issue.

Land Surface Temperature

The ability to detect land surface temperatures from space is well developed, and there have been some reports of surface temperature changes prior to earthquakes. These may involve changes in the circulation patterns of groundwater bringing water of different temperature to the surface. This possible precursor is interesting from the remote-sensing viewpoint. TIR (thermal infrared) spectral bands of different satellites like MODIS, NOAA AVHRR, ASTER, and Landsat TM/ETM can produce such information (6). The analysis of the time series LST (Land Surface Temperature) maps for different seismic regions prior strong earthquakes, evidenced building up of thermal anomalies. Based on time-series MODIS/Terra Land Surface Temperature/Emissivity (LST) 8-Day L3 Global 1km SIN Grid, MOD11A2/LST_Day_1km was represented land surface temperature variation during 2004 year over Vrancea region (Figure 2) centered on earthquake of 27th October 2004 epicenter (45.787 N, 26.622 E), 101 km x 101 km surface area .

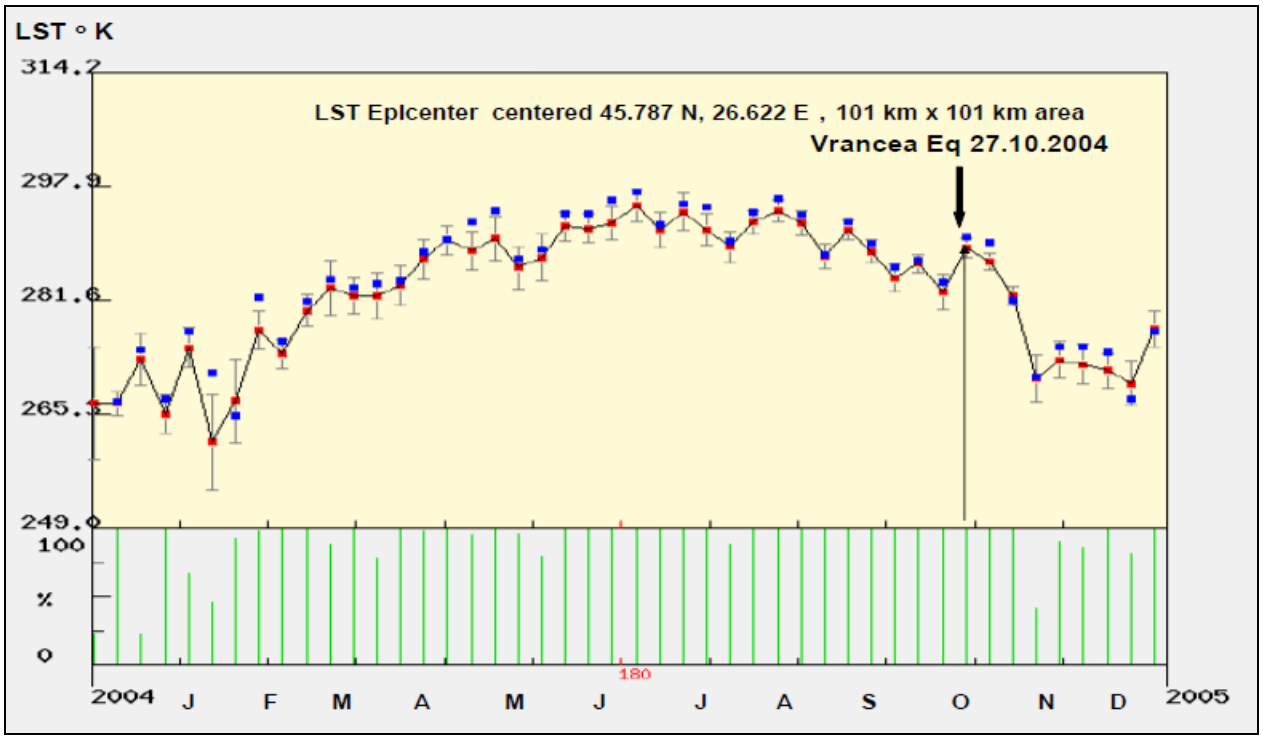

Figure 2. Land surface temperature (LST) variation during 2004 year over epicentral Vrancea region based on MODIS Terra time series data.

Land surface temperature anomalies were detected by subtracting the multi-year mean from the area-averaged values and dividing by multi-year mean values (7). Time series satellite data analysis revealed increase of land surface temperatures LST around epicentral area ranging 5–10°C. 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". A clear rise of land surface temperature in epicentral area and surroundings was recorded by MODIS time series satellite data. For October 27th 2004, Mw =5.9, and epicenter depth of *H* =96 km in Vrancea area the thermal anomalies of land surface temperature have been developed with about 4–7 days or more prior to the main event depending upon the magnitude and focal depth and disappeared after the main shock.

Air Temperature

Thermal observations from NOAA AVHRR satellites, NCEP/NCAR Reanalysis, based on climate data 1981-2010 indicate a significant change of the air temperature and near-surface atmosphere layers for strong earthquake March, 4th, Mw = 7.4, *H* = 94 km earthquake in Vrancea region. Significant surface air temperature anomaly over Vrancea epicenter region prior to this earthquake was observed with one month before the main shock (Figure 3).

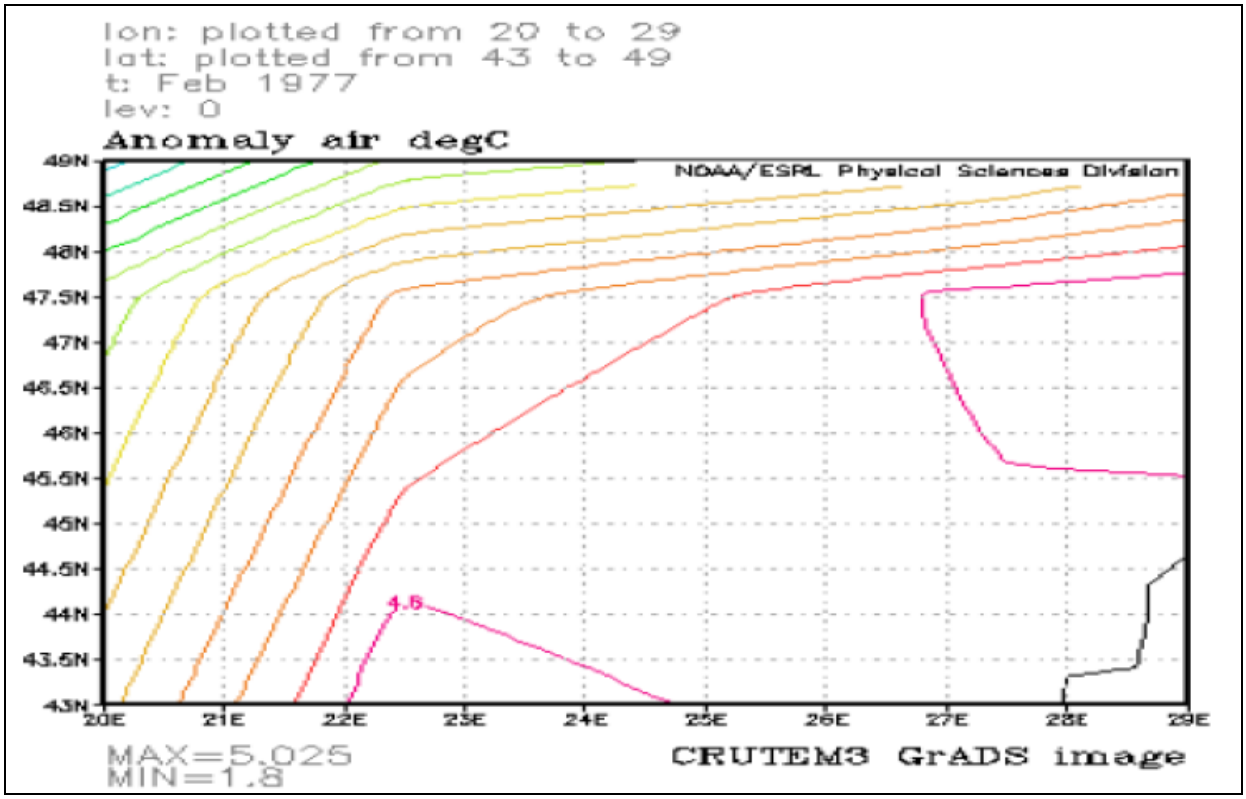

Figure 3. Air temperature anomaly over Vrancea region one month before March, 4th, Mw = 7.4, H = 94 km earthquake

Immediately after the shock March, 4th, this anomaly continued more several days. Ground observations confirmed satellite data: air and land surface temperature changed simultaneously with thermal anomaly variation. Ten years of Meteosat TIR observations have been analyzed in order to characterize the TIR signal behavior at each specific observation time and location. Space-time TIR signal transients have then been analyzed, both in the presence (validation) and in the absence of seismic events, looking for possible space-time relationships. In order to study the

relationship between the air temperature and 27th October 2004 earthquake, have been analyzed time-series of mean daily air temperature and anomaly data for period of 15 October -15 November 2004, on the base period of normals 1981-2010 around 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 a rise of around 4.8° C- 8° C during 24-27 October 2004 (Figure 4), in good correlation with in-situ measurements, which revealed a pronounced increase of air temperature over Vrancea region. 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 between 30 October and 3 November.

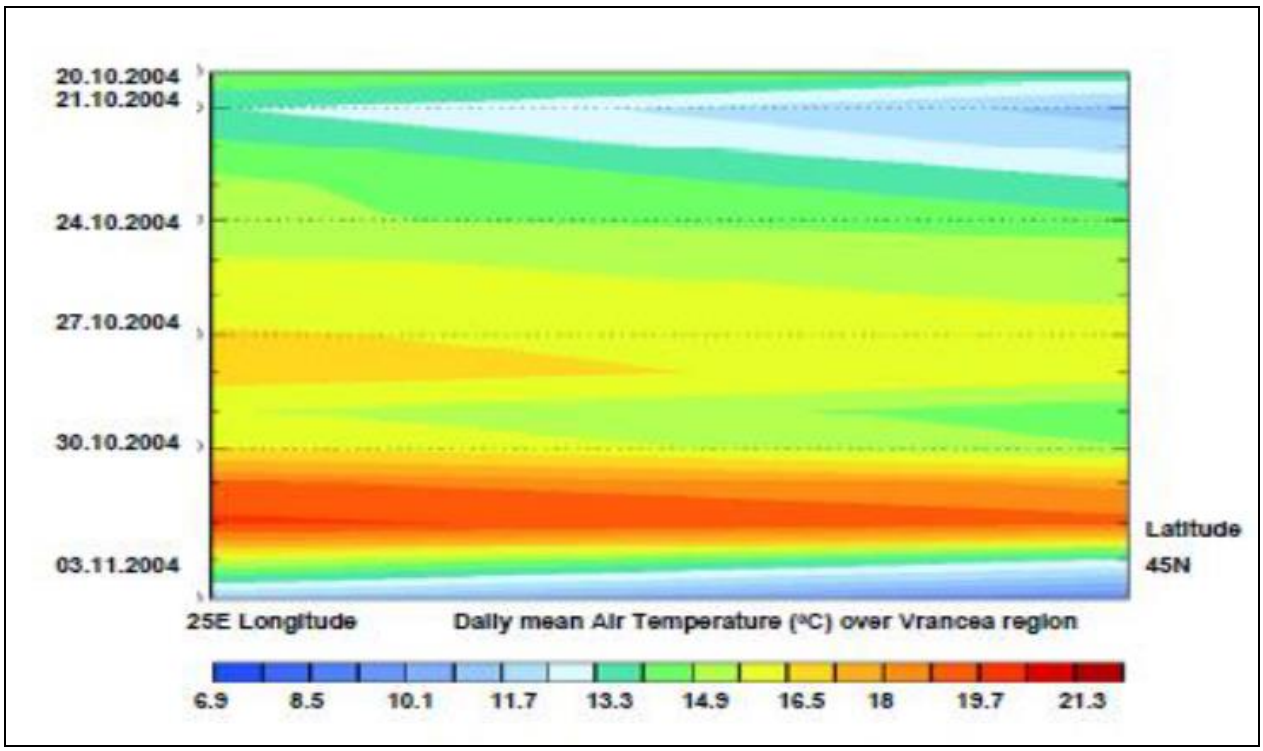

Figure 4. Daily mean air temperature over Vrancea region before and after Vrancea 2004, October 27th earthquake

CONCLUSIONS

Earthquake preparation is a transient dynamic process which can be monitored in real time from geospatial data validated with in-situ monitoring. Due to new advanced satellite multispectral sensors and high temporal and spatial resolutions of NOAA AVHRR and MODIS Terra/Aqua satellite missions, their data can exhibit processes of spatio-temporal variation of Land Surface Temperature parameter of Vrancea active seismic region in Romania.

Earthquake thermal anomalies research in Vrancea area is developing in the direction of seismic activity monitoring and close integration with ground observations. The thermal anomalies of land surface temperature observed some days to weeks before main seismic shocks provide early warning signals in all analyzed earthquake test cases. The present results show existence of coupling between lithosphere-atmosphere associated with preparation and seismic event occurring. Such observations demonstrate promising results, but new data accumulation is required. The joint analysis of geospatial and in-situ geophysical information will reveal new insights in the field of earthquake hazard assessment.

ACKNOWLEDGEMENTS

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