SEISMIC PRECURSORS AND CLIMATE FLUCTUATIONS ASSESSMENT THROUGH TIME SERIES GEOSPATIAL AND IN-SITU MONITORING DATA

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ABSTRACT

Recent investigations suggest that climate change tends to exacerbate geo-disasters like as earthquake events. 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. Different criteria can be used to select the remote sensed earthquake pre-signals for which there is an evidence for anomalies in the geophysical observables. Rock microfracturing in the Earth's crust preceding a seismic rupture may cause local surface deformation fields, rock dislocations, charged particle generation and motion, electrical conductivity changes, gas emission, fluid diffusion, electrokinetic, piezomagnetic and piezoelectric effects as well as climate fluctuations. Space-time anomalies of Earth’s emitted radiation (thermal infrared radiation linked to air and land surface temperature variations recorded from satellite months to weeks before the occurrence of earthquakes, radon in underground water, soil and near the ground air, etc.), ionospheric and electromagnetic anomalies are considered as earthquake precursors. At land surface, energy fluxes interact instantaneously with each other in accordance with the prevailing meteorological conditions and the specific thermal and radiative characteristics of the soil surface. This paper aims to investigate seismic pre-signals variation (air and land surface temperature, and outgoing long-wave radiation) for some earthquakes recorded in Vranceaseismic active area in Romania. Based on local tectonic geology, hydrology and meteorology, such findings support lithosphere–ionosphere coupling theory.

INTRODUCTION

The geotectonic active areas like is Vrancea seismic zone in Romania are accompanied with crustal deformations and energy transfer, which must change the state of thermal radiation on the land surface. Thus it is possible to infer present-day geotectonic activities based on variations of the thermal radiation state on the land surface or near the ground derived from the satellite data. 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 satellite missions, their data can exhibit processes of spatio-temporal variation of geophysical parameters of seismic active regions.

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 (Rn^{222}), greenhouse gases (CO_2, CH_4, NO_2 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).

Different criteria can be used to select the remote sensed earthquake precursors for which there is an evidence of geophysical parameters anomalies. Rock microfracturing in the Earth's crust preceding a seismic rupture may cause local surface deformation fields, rock dislocations, charged particle generation and motion, electrical conductivity changes, gas emission, fluid diffusion, electrokinetic, piezomagnetic and piezoelectric effects as well as climate fluctuations. Space-time anomalies of Earth’s emitted radiation (thermal infrared radiation linked to air and land surface temperature variations recorded from satellite months to weeks before the occurrence of earthquakes, radon in underground water, soil and near the ground air, etc.), ionospheric and electromagnetic anomalies are considered as earthquake precursors.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 zoneand its surroundings is one of the most pronounced changes that can be detectedby space-borne sensors such as Advanced Very High Resolution Radiometer (NOAAAVHRR) and the Moderate Resolution Imaging Spectroradiometer(MODIS Terra/Aqua).In spite of some skepticism regarding earthquake prediction (1), early warning signs of earthquakes arediverse, fleeting and often subtle, and they can also be surprisingly strong, even formoderate earthquakes (2), (3).

VRANCEA SEISMIC REGION

Vrancea seismic region in Romania is structurally and seismically complex area, bounded by latitudes 45.6 °N and 46.0 °N and longitudes 26.5 °E and 27.5 ° E(Figure1).

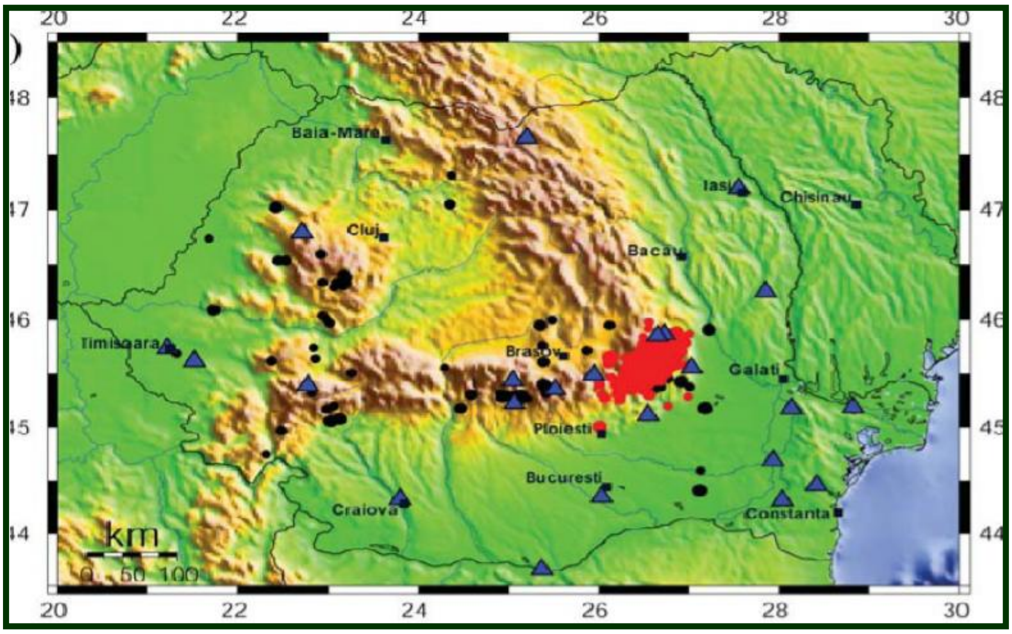

Figure 1. Vrancea active seismic region on Romania map(red zone)

Located at the sharp bend of the Southeastern Carpathians,is one of the most active intracontinental seismic areas in Europe, with 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) (4). A narrow, near-vertical focal volume subducted at intermediate depths (60 - 220 km), supposed to be in a relic stage at present, is the site of an unusually intense seismicity (an average frequency of 3 shocks with moment magnitude Mw> 7 per century).

Surrounding Vrancea, the several seismic stations belonging to the Romanian Seismic Network are recording seismic and other geophysical, geoelectromagnetic, geodinamic and meteorological parameters. This study investigated: the March, 4th, with moment magnitude Mw = 7.4, *H* = 94 km earthquake, 1986, August, 30th, with moment magnitude Mw = 7.1, *H* = 131 km earthquake;andOctober 27th 2004 earthquake, with moment magnitude Mw =5.9 and epicenter 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.

METHODS

Recent advances of information technology has allowed the development of tools and techniques to handle geological/geospatial data and/or derived. With differences in scales, datum, projections, formats, or resolution, the data are often difficult to handle and even more difficult to integrate.

During last decades the remote sensing data have been widely used for the assessment of prior and after strong earthquakes changes of several geophysical parameters as well as for the mapping of post earthquake damages (5).

As earthquakes (EQs) are large-scale fracture phenomena, associated fracture-induced physical fields allow a real-time monitoring of associated climate and geophysical variables anomalies in different spectral regions by satellite sensors.

These pre-signals suggest the existence of a strong coupling between the dynamics of lithospheric processes land atmospheric-ionospheric anomalies associated with seismic processes.

Based on multisensor satellite remote sensing continuous monitoring of land, ocean, atmosphere, and ionosphere parameters, have been strongly evidenced pre-earthquake changes in land, ocean, atmosphere, and ionosphere parameters (6), (7).
Through the analysis of different geophysical parameters and seismicity changestested over long periods of time, for earthquake prediction, scientists are continuing tosearch reliable precursory phenomena. Before a potential anomaly can be nominatedas a reliable precursor, it should pass or be proved by the following tests or analyses:whether it is an artificial anomaly, whether it correlates with an investigated event andwhether it is a random anomaly.
Satellite remote sensing applied for earthquake research can detect such phenomena, related with earthquakes, particularly the Earth's surface deformation, land and air surface temperatureand humidity, gas and aerosol content. Crustal deformations, both horizontal andvertical scaled from tens of centimeters to meters are recorded after the shock by the Interferometric Synthetic Aperture Radar (InSAR) technique withconfidence. Pre-earthquake deformations are rather small, on the order of centimeters. Some few cases ofdeformation mapping before the shock using satellite data in synergy with GPS data are known at present time. There are numerous observations of surface and near surface temperatureincreases of 3–5 °C prior to Earth crust earthquakes. Methods of earthquake prediction are developingusing thermal infrared (TIR) surveys. Have been reported also multiple evidence of gas and aerosol content changes before earthquakes are reported for in-situ observations. Satellite techniques allow also to measure the concentrations of gases in atmosphere: O_3, CH_4, CO_2, CO, H_2S, SO_2, HCl and aerosols. However thespatial resolution and sensitivity of modern systems restricts the application of satellite gas observationin seismology and the first promising results have been obtained only for ozone, aerosol andair humidity.
Natural phenomena and satellite data availability stimulated the analysis of the long time series of thermalimages in relation to earthquake hazard.
Climate oscillations have significantly contributed to the planet's evolution, including seismic and volcanic activity. Generally, geotectonic instability can be inferred from detailed geophysical, geological, andstructural studies of a seismic active area, but the triggering mechanism hasbeen always difficult to infer.

Data from satellite sensors, such as AVHRR on board the National Oceanic andAtmospheric Administration (NOAA) series satellites andMODIS Terra/Aqua on board the NASA Terra and AquaEarth Observation System satellitesprovide LST products retrieved for a specific area with a spatial resolution of about1 km, whereas the Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensoron board the METEOSAT Second Generation (MSG) series geostationary satellitesretrieves LST at a lower spatial resolution (about 3 km).

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 oftime provided by Oak RidgeNationalLaboratoryDistributedActiveArchiveCenter(ORNL DAAC) (http://daac.ornl.gov/MODIS/modis.html). MODIS/Terra LST/EDaily L3 Global 1 km SIN Grid satellite data were used for comparison of the results.

In addition, NOAA-AVHRR data-derived land surface temperature (LST), air temperature and outgoing longwave radiation (OLR) provided by the NOAA/ESRL Physical SciencesDivision, Boulder, CO, USA (http://www.esrl.noaa.gov/psd/) have been used.

Meteorological data around Vrancea region in Romania and anomaly were provided by the National Administration of Meteorology, in addition, in-situmeteorological data were compared with satellite data. Land surface temperature anomalies were obtained by subtracting the multi-year mean from the area-averaged values and dividing by multi-year mean values.

Outgoing Longwave Radiation (OLR) 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. OLR is a NOAA polar-orbiting satellite derived measurement of the radiative character of energy radiated from the warmer earth surface to 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/m^2) originally observed by polar orbiting NOAA are based on dedicated developed algorithms. Maximum and minimum OLR values ranges including other parameters were defined in the analyzed earthquake case

RESULTS

Space-time anomalies of Earth's emitted radiation (radon in underground water and soil, thermal infrared in spectral range measured from satellite months to weeks before the occurrence of earthquakes etc.), and electromagnetic anomalies are considered as pre-seismic signals. This energy transformation 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) (8). This paper presents observations made using time series NOAA-AVHRR and MODIS satellite data–derived land surface temperature (LST) and outgoing long-wave radiation (OLR) as well as air temperature anomalies recorded for selected earthquakes to be analyzed in seismic Vrancea region, Romania, using anomalous TIR signals as reflected in LST rise and high OLR values which followed similar growth pattern spatially and temporally. In all analyzed cases, starting with almost one week prior to a moderate or strong earthquake a transient thermal infrared rise in LST of several Celsius degrees (^{o}C) and the increased OLR values 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.

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, Landsat TM/ETM can produce such information. 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.

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 in South-Eastern Europe region centered on RomanianearbyVranceaepicenter prior to this earthquake was observed withonemonth before the main shock (Figure 3) and on Vrancea (Figure 4).

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.

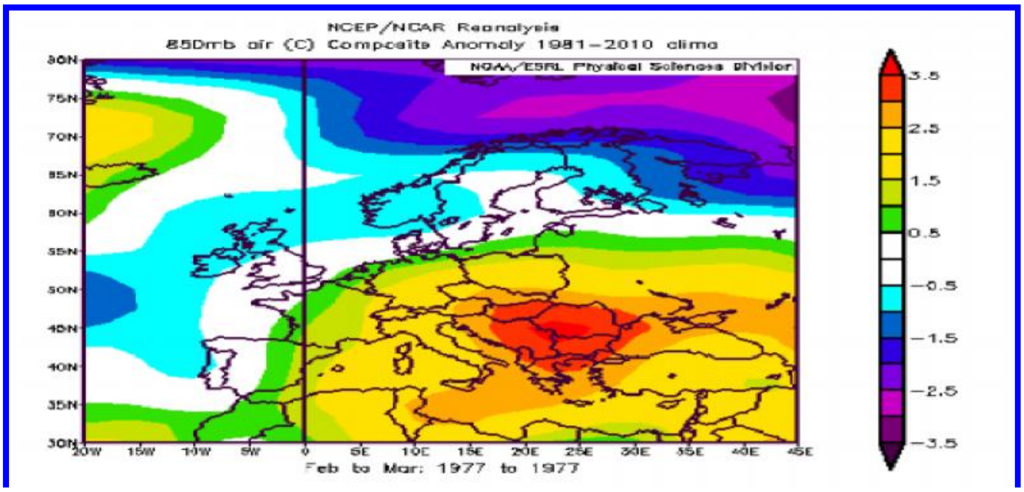

Figure3.Air temperature anomaly over large area in South-Eastern Europe around Vrancea seismic region prior one month before March, 4th, Mw = 7.4, H = 94 km earthquake

It is known that satellite thermal survey has a relatively long history of applications in seismology. Most of its advantages and limits are well known. Two main problems limit thermal data utilization: cloud penetration and geological situation. Surface conditions such as vegetation and climate conditions like as precipitations, wind, etc. also strongly influence thermal effects.

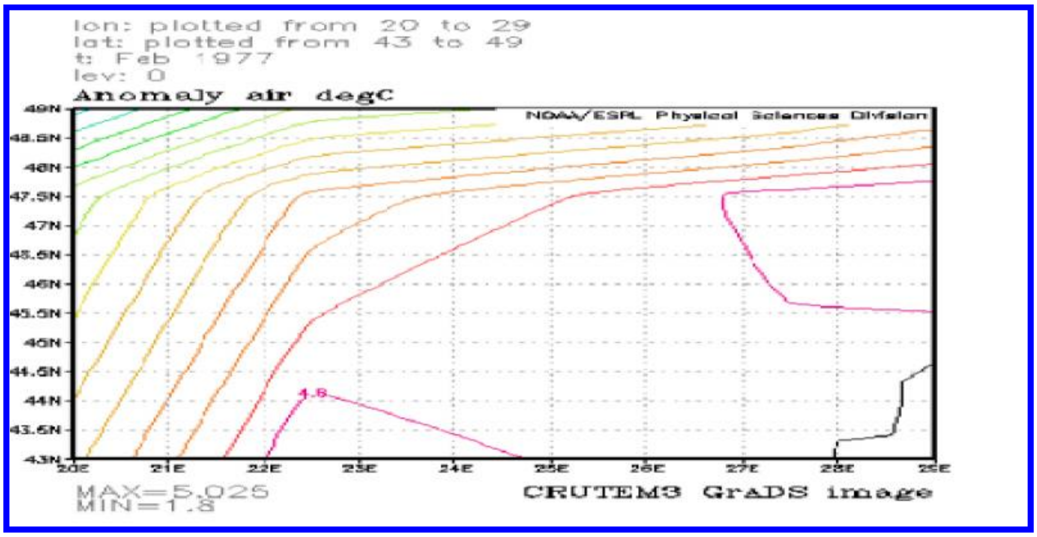

Figure4.Air temperature anomaly over Vrancea region one month before

March, 4th, Mw = 7.4, H = 94 km earthquake

One month before ofVrancea1986, August, 30thearthquake, with moment magnitude Mw = 7.1, *H* = 131 kmearthquake have been recorded surface air temperature anomalies (Figure 5).

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^{o} C- 8^{o} C during 24-27 October 2004 (Figure 6), 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.

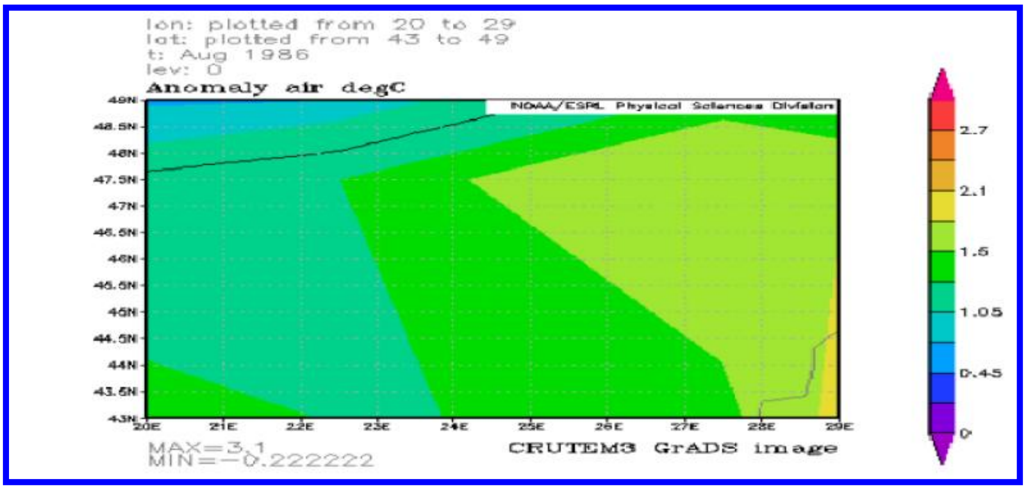

*Figure5.Air temperature anomaly over Romania one month before*Vrancea1986, August, 30th

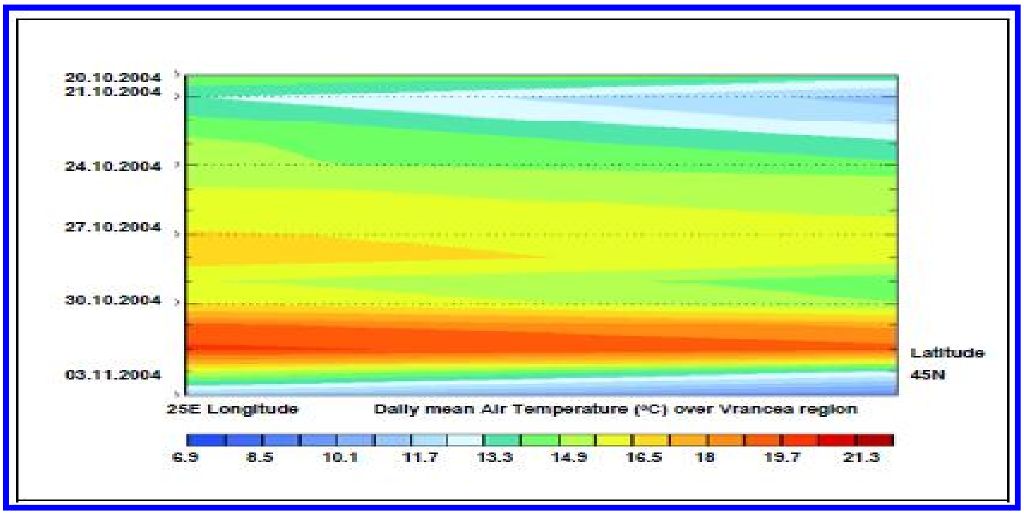

Figure6.Daily MEAN air temperature over Vrancea region before and after Vrancea 2004,Oktober 27th earthquake

Outgoing Longwave Radiation (OLR)

Thermal anomalies before strong earthquakes are observed at different levels, starting from the ground surface up to the top of clouds altitude. The most promising presignal is the Outgoing Longwave Radiation (OLR) anomaly measured at the top of clouds level. Its advantage is that it is measured within the infrared transparency window of 8–12 μ m and does not separate clouds.

For October 27th 2004, Mw =5.9, and epicenter depth of *H* =96 km in Vrancea area the thermal anomalies of OLR have been developed with about 4–7 days or more prior to the main event function of magnitude and focal depth and disappeared after the main shock. OLR registered anomalies ranged 32–48 W/m^2 higher than the normal values for the same period of time and ten years of measurements.

Figure 7 presents daily means OLR variationbetween 20 October 2004 till 3November 2004, which evidenced gradually increase of the outgoing long-wave radiation OLR emitted by land surface in Vrancea epicentral area before 5.9 M_w earthquake registered on October 27th 2004.The magnitude of the recorded mean OLR anomalies increased firstly starting from 24 October 2004, with a maximum value between 25-26 Octobers and then decreased gradually till 27^{th} October in the morning, after that increased again between middle of the day 27^{th} October and 30^{th} 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.

The interpolated OLR data are continuous spatially as well as temporally. The estimates of interpolated OLR values (W/m^2) originally observed by polar orbiting NOAA are based on dedicated developed algorithms. Maximum and minimum OLR values ranges including other parameters were defined in each analyzed earthquake case.

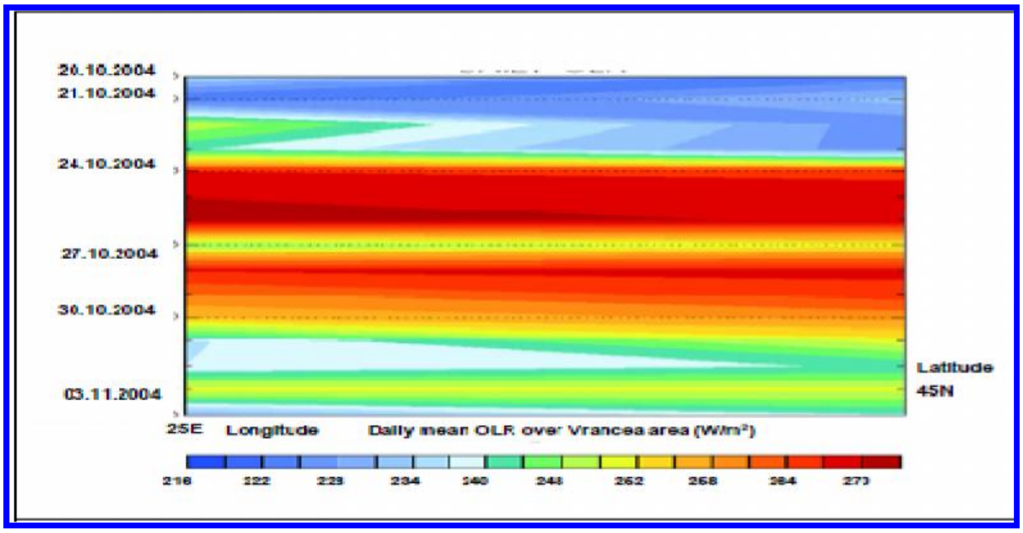

Figure7. Dailymean OLR over Vrancea region before and after Vrancea 2004, October 27^{th} earthquake

The increase in air and land surface temperature as well as of OLR near epicentral areas can be attributed to enhanced 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. OLR is dependent of local meteorological parameters temperature and humidity and changes in these variables may be responsible for anomalous OLR values.

CONCLUSIONS

Geo-hazards such as earthquakes, landslides, and weather related hazards are among the strongest sudden impacts on modern life and property in Romania. The assessment, surveillance and mitigation of geo-hazards in Romania are a mandatory task of the geosciences community. Seismic precursors assessment in the most active seismic area Vrancea in Romania are multifold and combine investigations of recurrence intervals or probability of occurrence of events together with their probable impact on life and property, and the investigation of deformation and rates within different time scales, including geological studies, paleoseismology, and the monitoring of seismicity and currently accumulating deformation. The present results show existence of coupling between lithosphere-atmosphere associated with preparation and seismic event occurring. Such results of pre-earthquake signals are promising and can contribute significantly in the future towards forecasting the impending earthquakes in tectonically active region Vrancea, which represents a real seismic hazard for South-Eastern Europe. Thermal anomalies research in Vranceaseismic active area is developing in the direction of seismic activity monitoring and close integration with ground observations.The anomalies of air and land surface temperatures as well as of outgoing longwave radiation observed some days to weeks before main seismic shocksprovide 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 nature of air and land surface temperature as well as outgoing longwave radiation anomalies still remains unclear. 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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