Seismic Surveillance of Vrancea Active Region in Romania by Time Series Satellite Data Anomalies

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ABSTRACT

The Vrancea zone in Romania located at the bending of the South-Eastern Carpathians is one of the high-risk seismic zones in Europe, characterized by a high occurrence of intermediate-depth earthquakes, confined in a 60–200 km depth lithospheric volume. For continuous surveillance of the Vrancea seismic active area in Romania, this study developed and implemented an advanced integrated methodology of multi-field time series satellite- and ground-based observational data of seismic precursors and lithosphere-atmosphere coupling modeling, for new seismic increased activity indicators design. Based on the seismic records in synergy with atmospheric and land surface pre-seismic anomalies detection from Land Surface Temperature (LST) from the time series MODIS Terra/Aqua and NOAA AVHRR along with Air Temperature at 2m height (AT), this study found significant correlations with moderate seismic events of moment magnitude $M_w \geq 5$ on Richter scale for 2012-2023 period. It was observed also a high correlation between air temperature AT at 2m height and land surface temperature LST, the Spearman rank correlation coefficient was ($r= 0.95$; $p<0.01$). Also, there is a high correlation between the moment magnitude of the six moderated earthquakes recorded in the Vrancea area from 2012 to 2023 years and LST values ($r=0.65$; $p<0.01$). The findings of this study aim to improve, by cross-validating, the methodologies for seismic hazard assessment in Romania due to the Vrancea source and detect preparatory seismic phases and precursors. Early detection and monitoring of induced geophysical anomalies can help decision-makers mitigate the impact and improve disaster response efforts. This will contribute to promoting an EOS for Romania in the frame of ESA Copernicus. The investigation of the seismo-associated phenomena from space is a challenge for Earth Observation and earthquake forecasting, with a high impact on SDGs as well as the Natural Hazard Directive in the EU.

Keywords: seismic precursors, time series satellite data, Vrancea geotectonic active area, Romania

1. INTRODUCTION

Earthquakes (EQs) attributed to brittle failure of the lithosphere, can be a devastating natural disaster, causing extensive damage to infrastructure and loss of lives. Early detection and monitoring of seismic precursors can help mitigate the impact and improve disaster response efforts using satellite data. As a result of energy release due to the accumulation of stress during the seismic preparation period around the epicenters, the EQ events significantly affect the Earth's crustal deformation, as well as lower and high atmosphere by inducing variations in the different layers above the seismic preparation zone[1]. The seismic preparation period possessed several anomalies of the satellite recorded geophysical/geochemical parameters, known as seismic precursors that have been observed not only on the surface of the Earth but also in the atmosphere and ionosphere from different satellites. Is considered that only short-term earthquake prediction is a useful and meaningful form for protecting human lives and social infrastructures [2]. Several studies during the last decades demonstrated that a few weeks/days before moderate and strong earthquakes the specific anomalies of some geophysical and geochemical parameters emerge within the earthquake preparation zones. The mechanical processes of earthquake preparation are always accompanied by deformations associated with complex short- or long-term precursory phenomena. It seems that the Vrancea region in Romania fits such a model. 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 quantification stress and strain accumulation, a key control for seismic hazard assessment [3].

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Tenth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2024), edited by
A. Christofe, S. Michaelides, D. Hadjimitsis, C. Danezis, K. Themistocleous, N. Kyriakides, G. Schreier,
Proc. of SPIE Vol. 13212, 132120B · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3035001

Earthquake preparation, as a transient dynamic process, can be surveyed in real-time from geospatial validated in-situ data. The study of earthquakes will probably increase due to global urbanization, as millions of people are exposed to earthquakes in geotectonic active areas. Satellite remote sensing techniques, both spaceborne and airborne, can bring a highly effective contribution[4]. While thermal infrared imagery can be used for earthquake prediction, In-SAR (Interferometric Synthetic Aperture Radar) and GPS networking data are useful for measuring Earth's surface deformation. Optical, LiDAR (Light Detection and Ranging) data can also be used for building damage assessment after earthquakes, especially in the response and recovery phases [5,6].

Besides geodetic measurements and field observations, which have limitations in completeness and quantity, numerical models can improve significantly the understanding of the driving physics of seismic cycles and increase accuracy in seismic hazard assessment. Recently, many improvements were made in the modeling and cross-validation of seismic hazards worldwide. Based on the new approaches that have been modeled various geophysical, geochemical, and geodetical, variables linkages with seismic cycles and crustal movements, considering complex spatial and temporal distribution of earthquakes in convergent [7, 8].

Also, previous studies have attempted to test possible statistical significance between pre-seismic anomalies in various geophysical parameters worldwide. In terms of their altitude and time interval, these precursors can be categorized into several categories: Land Surface Temperature (LST) as Surface Variables, followed by Air Temperature at 2m height (AT), Relative Humidity (RH), Air Pressure (AP), and Outgoing Longwave Radiations (OLRs) and Latent surface heat flux (SLHF) as Atmospheric variables, Aerosol Optical Depth (AOD), seismic tectonic clouds, and Crustal Deformation Variables [9, 10]. According to the literature in the field of seismic precursors, the use of geospatial data in many studies worldwide was done for the characterization and mapping of geologic lineaments changes from different satellite sensors onboard at VIS wavelengths of Landsat, Sentinels, but not for seismicity in Romania [11, 12].

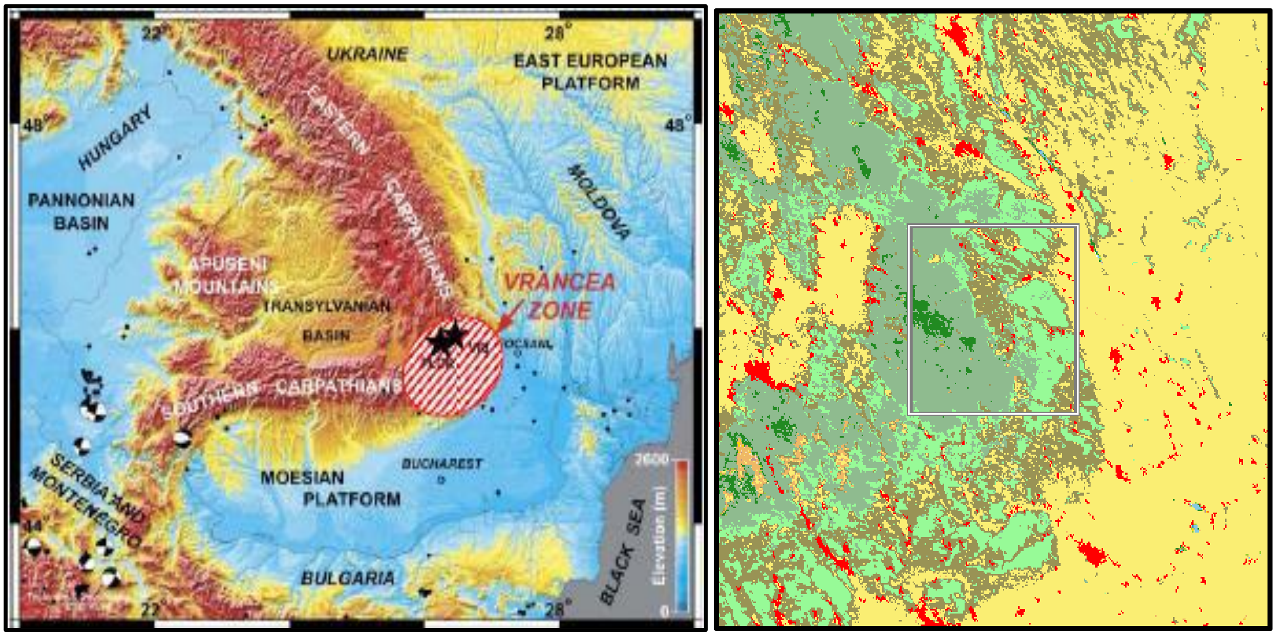
The Global Earth Observation System of Systems (GEOSS) is providing more and more observations or revisits of the planet Earth, especially on the surface sphere, which is the lithosphere-atmosphere interface. The surface sphere acts as a very active layer of the LSAIC (Lithosphere-Surfacesphere-Atmosphere-Ionosphere) coupling system. The LSAIC model explains the linkage between the buildup of tectonic stresses, migration of soil gases, fault activation, fluctuation of surface latent heat flux, atmospheric and ionospheric perturbations, and the occurrence of seismic events. Great uncertainty exists till now regarding the nature of the processes that could produce such signals, both inside the Earth's crust and at the surface. Based on the seismic records in synergy with atmospheric and land surface pre-seismic anomalies detection from land surface temperature (LST) from the time series MODIS Terra/Aqua and NOAA AVHRR along with air temperature (AT), relative humidity (RH), air pressure (AP) and outgoing longwave radiations (OLR), this study found for Vrancea active geotectonic region significant correlations with moderate seismic events of moment magnitude $m_w \geq 5$ on Richter scale for 2012-2023 period. To get some insights into the complex phenomenon of earthquake preparation, a systematic multi-precursor approach and the integrated analysis of ground geophysical and satellite data are needed to study the slow process of earthquake preparation. Based on local tectonic geology, hydrology, and meteorology, such findings support the LSAIC coupling theory.

2. VRANCEA SEISMO-TECTONIC SETTING

Vrancea geotectonic active seismic region in Romania is located at the Eastern Carpathian Arc Bend and bounded by latitudes 45.6 °N and 46.0 °N and longitudes 26.5 °E and 27.5 ° E (Figure 1).

It is one of the most active intracontinental tectonic areas in Europe, with high seismic hazard potential associated to a few strong intermediate-depth earthquakes, that span diverse topography features, several active faults, and present-day crustal deformation. The Seismogenic Vrancea region in Romania features a complex geologic structure characterized by a sharp relief. From the seismo-tectonic viewpoint, the Vrancea geotectonic active zone in Romania located in the curvature sector of the Eastern Carpathians (Romania) presents a peculiar source of seismic hazard related to the subcrustal earthquakes located at the sharp bend of the Southeast Carpathians, and at the intersection of the East-European plate (North and North-West) with the Moesian (South) and Intra-Alpine (West) sub plates, Vrancea region is considered one of the most seismically active areas in Europe, with a high seismic risk for the neighboring countries (Bulgaria, Hungary, Serbia, Republic of Moldavia, Ukraine). It is characterized by the occurrence of low moment magnitude (Mw) crustal (0-40 km depth) earthquakes (Mw<5.5 and moderate seismic activity), and intermediate depth (70-200 km) strong earthquakes ($6 \leq Mw \leq 8$) in a narrow epicentral and hypocentral region [13].

Located at the border of the great East-European Platform, Romanian territory is an area of complex geological structure dominated by the presence of the Alpine Orogenic Belt of the Carpathian Mountains. The compressive stress field due to the subduction of the Black Sea Sub-Plate under the Pannonian Plate generates faulting processes. The resulting fault plane is approximately parallel North Eastern-South Western-oriented to the Carpathian Bend. A deep crustal fracture with dextral slip, the Peceneaga- Camera Fault is considered to be the North-Eastern boundary of the Moesian Platform. However, the Eastern unit of the Moesian Sub-Plate is described by a series of principal faults with a North-Western orientation and by a secondary system of North Eastern-South Western-orientated faults. East of the Peceneaga-Camena Fault North-Western are trending crustal fractures.



(a) (b)

Figure 1. Location of Vrancea seismic zone: (a) on geomorphologic map of Romania; (b) on MODIS Terra classification map.

The Black Sea Sub-Plate has a North-Western displacement along the “markers” formed by the Moesian and Eurasian Sub-Plates. Due to its peculiar tectonic regime and geodynamic processes, during the last 300 years, the Vrancea seismogenic region featured 13 earthquakes with moment magnitudes (Mw) above 7, out of which seven events had Mw above 7.5 and three between 7.7 and 7.9 on Richter scale. Due to higher permeability and porosity relative to surrounding rocks, crustal faults, and fractures are the main migration channels for carrier gases and radon gas from the deep layers of the crust to the surface [14].

3. METHODS AND DATA USED

Seismic information for the test study area Vrancea in Romania was obtained from the ROMPLUS catalog of NIEP (National Institute of R&D for Earth Physics) and USGS www.infp.ro/romplus and www.usgs.gov. All the moderate earthquakes of moment magnitude Mw ≥ 4 occurring in the region from the 1st January 2012 till 31st December 2023 have been selected from the catalogs and displayed in Figure 2.
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. To assess thermal anomalies, for defined Vrancea area by 45.6 ºN – 46.0 ºN , and longitude 26.5 ºE -27.5 ºE, and centered on 45.6 ºN and 27.0 ºE, this study used in-situ monitoring data and time series satellite 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 provided by Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)(http://daac.ornl.gov/MODIS/modis.html)[15,16]. With state-of-the-art technology Moderate Resolution Imaging Spectroradiometer (MODIS) data have an absolute accuracy of 1º K for LST

products at 1 km spatial and daily temporal resolution by utilizing the bands 31 and 32 observations with the generalized split window algorithm.

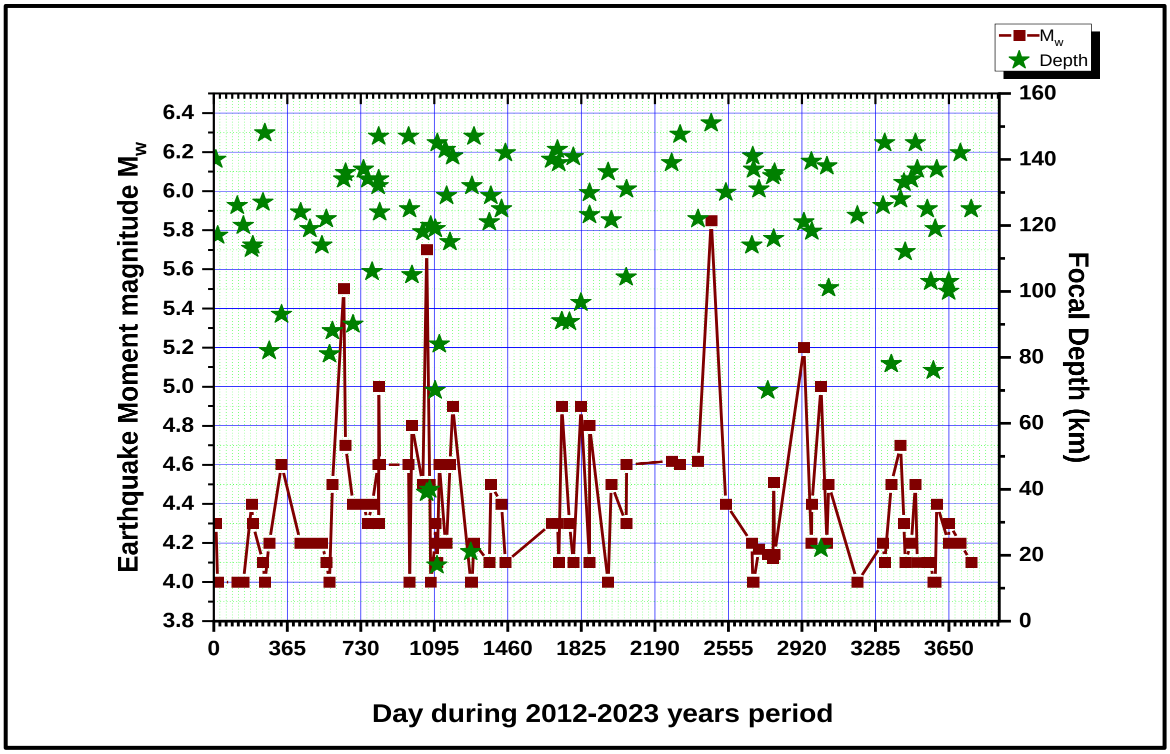


Figure 2. Vrancea seismic events of moment magnitude Mw ≥ 4 recorded during 2012-2023 period

In addition, NOAA-AVHRR data-derived land surface temperature (LST), air temperature, and outgoing longwave radiation (OLR) provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO, USA (http://www.esrl.noaa.gov/psd/). Meteorological data around the Vrancea region in Romania were provided by the National Administration of Meteorology, and in-situ meteorological data were compared with satellite data. this study used Spearman cross-correlation analysis and non-parametric test coefficients as well as linear regression analysis. For assessment of the normality of the LST and AT averaged daily time-series data sets, Kolmogorov-Smirnov Tests of Normality. ORIGIN 10.0 software version 2021 for Microsoft Windows was used for data processing. For satellite data processing ENVI 5.7 software was used. Also, ORIGIN 10 software has been used for time series data analysis.

4. RESULTS

To detect the possible thermal anomalies of land surface temperature LST and air temperature AT geophysical parameters identified as seismic precursors were used the following steps: firstly, we analyzed thermal infrared information provided by MODIS Terra/Aqua and NOAA AVHRR 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. Also, we studied the relationship between tectonic strain and thermal exchange through theoretical analysis, and we analyzed in-situ available data provided by the seismic network in the Vrancea area as well as available data from meteorological stations. Finally, we compared the ground surface and satellite data and established the possible relationship between these observations.

To set accurate, precise, and stand-alone criteria for earthquake prediction, the simultaneous integration of several precursor parameters that reduce the parameter uncertainty must be considered. Using time-series remote sensing observations, this paper examines spatio-temporal variations of land surface temperature, and mean air temperature several weeks to several days before the investigated moderate earthquakes [17, 18, 19]. The increase in land surface temperature LST 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 [20]. Also, LST is dependent on local meteorological parameters temperature, and humidity, and changes in these variables may be responsible for low anomalous LST values [20, 21, 22]. We applied a methodology that allows us to detect subtle, localized spatiotemporal fluctuations in hyper-temporal, geostationary-based geophysical parameters data and statistically evaluate our findings concerning distance from the epicenter and temporal coincidence with earthquakes. Figure 3 presents derived satellite MODIS Terra land surface temperature variation (ºC) during the 2012- 2023 period over earthquake geotectonic active Vrancea region, showing few LST anomalies related to the six seismic events of moment magnitude $M_w \geq 5.0$. Space-time TIR signal transients have then been analyzed, both in the presence (validation) and the absence of seismic events, looking for possible space-time relationships.

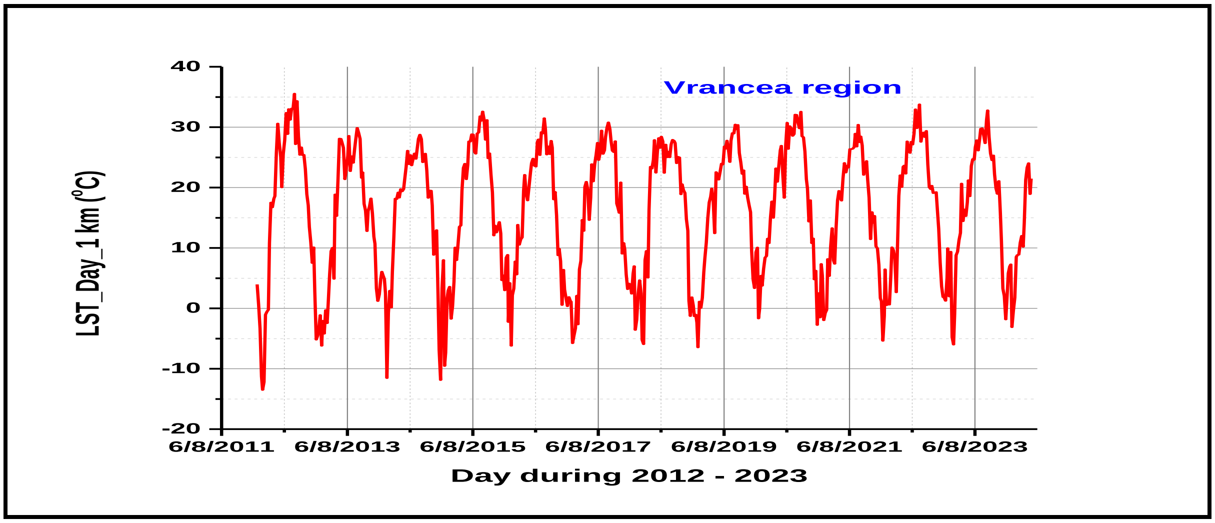


Figure 3. Land Surface Temperature MODIS Terra LST_Day_1km temporal pattern over Vrancea seismic area during 2012-2023.

Like other reported thermal anomalies, due to a high increase of cumulative tectonic stress and enhanced transient thermal infrared (TIR) emission from the crust in the Vrancea active geotectonic area, the thermal pre-signals of moderate earthquakes have been detected through satellites equipped with MODIS Terra thermal sensors. These short-term pre-signals defined by sudden rises in land and air surface temperature a few days or weeks before the earthquake occurrence can provide useful information on seismic hazards in the study area. Due to possible changes in physical properties that reflect the dilated or undilated state of the region, the occurrence of moderate earthquakes may well change the response to tectonic stress in the Vrancea region. Also, observed changes in some other geophysical and geochemical parameters in that area are attributed to changes in the crustal elasticity of the region [8]. It was observed also a significant correlation between air temperature AT at 2m height and land surface temperature LST. Spearman rank correlation coefficient was (r= 0.95; p<0.01). Also, there is a high correlation between the moment magnitude of the six moderated earthquakes recorded in the Vrancea area from 2012 to 2023 years and LST values (r=0.65; p<0.01).
The present results support the existence of coupling between lithosphere-surface sphere-atmosphere associated with the 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 regions.
To study the relationship between the air temperature and Vrancea earthquakes have been analyzed time-series mean daily air temperature anomalies, around the Vrancea zone in Romania provided by NOAA satellite data and in-situ monitoring at seismic station Vrancea during the 2012 - 2023 period. A good positive correlation between AT anomalies and recorded seismic events during the same period was demonstrated by Spearman correlation coefficient R^2=0.89. For some analyzed earthquakes, starting with ten days up to one week before a moderate earthquake has been recorded transient thermal infrared rise in AT (2-10ºC) and LST (10-15 ºC) higher than the normal values, a function of the magnitude and focal depth, which disappeared after the main shock.
Before the seismic events, the earthquake precursors appear at different distances and heights over the active seismogenic areas [23, 24, 25]. It seems that the earthquake preparation area on grounds [26, 27] can be estimated according to the relation:

$$R = 10^{0.43M_w} \quad (1)$$

where R is the radius of the preparation zone in Km and Mw is the earthquake moment magnitude [21, 22, 23]. For Vrancea earthquake of 22 November 2014 with Mw =5.7, the corresponding calculated radius would be $R \approx 282.5$ km in the latitudinal and longitudinal directions from the epicenter, for earthquake 6 October 2013, moment magnitude M_w=5.5, the corresponding calculated radius would be $R \approx 231.7$ km, while for earthquake 29 March 2014 earthquake, moment magnitude M_w=5.0 the corresponding calculated radius would be $R \approx 141.3$ km in the latitudinal and longitudinal directions from the epicenter [14, 28, 29].

Analysis of time series satellite and in-situ monitoring data show that the anomalous disturbances of thermal fields in Vrancea area usually appear 2 to 11 days before the occurrence of moderate earthquakes. Our results show that the earthquake-related thermal anomalies are mainly concentrated within 150 to 170 km to the southeast and northeast of the epicenter. With the increase in earthquake magnitudes, the anomalies tend to appear earlier and are distributed more widely. The results for seismic precursors monitoring of this study could be integrated for continuous and distributed monitoring and surveillance of earthquake hazard/risk in Romania due to the Vrancea source, having a high impact on the seismicity monitoring for SDGs as well for Natural Hazard Directive in the EU.

As the mechanism of earthquakes is very complex, based on new geospatial sensor data new anomaly detection approaches need to be developed and verified, considering also local and regional pre-signal anomaly patterns in different seismically active regions. Synergy use of geospatial, geophysical, and geological information is revealing new insights for Vrancea zone seismicity understanding in Romania. With new geospatial observation data, accurate seismic activity monitoring and surveillance of active geotectonic areas offers significant socioeconomic benefits and improvements to forecasting capability are imperious needed. However, the investigation of the seismo-associated phenomena from space is a challenge for the present and near future Earth observation and earthquake forecasting.

5. CONCLUSION

Investigation of land and air surface temperature from satellite remote sensing TIR seismic precursory anomalies, and their anomalies in air near the ground is an important issue in the field of earthquake short-term forecasting of Vrancea moderate or strong earthquakes in Romania. Seismic multi-precursor monitoring through space-based remote sensing in synergy with in-situ data can help to solve the earthquake prediction dilemma allowing broad areas of observation of the Earth's surface, where strong earthquakes can be expected to occur. The present results support the existence of coupling between lithosphere-surface sphere-atmosphere associated with the preparation and seismic event occurring. Such observations demonstrate promising results, but new data accumulation is required. It can be concluded that some of the short-term anomalies of selected variables can be correlated with seismic events when they have magnitudes of $M_w \geq 5$ or greater. The association between recorded anomalies of these investigated parameters and major tectonic faults in the Vrancea region could result from mechanical cracks in the rocks or too slow crack growth determined by the local strain of the media. Efforts to advance understanding of earthquake prediction in Romania require detailed observation of all phases of the earthquake cycle (pre-, co-, and post-seismic), across multiple fault systems and tectonic environments, with integrated knowledge of all geophysical, geochemical, geological, seismological, and geodynamic parameters. Due to its particular features and geotectonic setting, the Vrancea seismic structure in Romania appears to be an excellent experimental laboratory for prediction research. The detection of land and air temperature anomalies in the Vrancea active zone can serve as medium and short-term forecasting for an effective early warning system applied to moderate and strong earthquakes in active continental plates. However, a deep systematic approach based on novel satellite observations of several anomalies associated with pre-earthquake activity will be useful for seismic hazard assessment in the Vrancea area.

ACKNOWLEDGEMENTS

This work was supported by the Romanian Ministry of Research, Innovation and Digitalization, through Program 1-Development of the national research-development system, Subprogram 1.2 - Institutional performance - Projects to finance the excellent RDI, Contract no. 18PFE/30.12.2021; This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no.

PN 23 05; This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS-UEFISCDI, project number PN-III-P4-PCE-2021-0585, within PNCDI III.

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