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Original scientific paper

Statistical Assessment of Land Surface Temperature Anomalies Associated with $M_w \geq 5$ Earthquakes in Türkiye Using MODIS and ERA5

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Since many reported anomalies related to earthquakes are heavily influenced by environmental and meteorological variability, identifying trustworthy precursory signals of earthquakes continues to be one of the most difficult problems in geophysics. Despite ongoing debates regarding its statistical robustness and physical interpretation, land surface temperature (LST) remains an interesting dataset for studying remotely sensed phenomena and their potential relationship with earthquakes. In this study, we statistically evaluate the pre- and post-earthquake surface temperature behavior in relation to 93 earthquakes ($M_w \geq 5.0$) that occurred in Türkiye between 2001 and 2024. To improve interpretability and reduce meteorological bias, daily surface temperature data from MODIS satellite measurements were combined with ERA5 reanalysis skin temperature data. Standardized z-scores within a 90-day time frame consisting of 60 days before and 30 days after each event were used to identify anomalies. This asymmetric time window was selected to better capture pre-earthquake signals, which are often weak, intermittent, and less persistent than post-earthquake responses. In general, the results indicate that, particularly for earthquakes with $M_w \geq 6.5$, post-earthquake thermal anomalies tend to be more consistent and more clearly distinguishable than those observed beforehand. However, the associated effect sizes are small (Cohen's $d < 0.1$), suggesting that although the differences are statistically detectable, they remain limited in magnitude. Pre-earthquake anomalies can still be distinguished from background variability, but they typically remain subtle and close to the noise level. Similar temporal behavior observed in both MODIS and ERA5 datasets further suggests that short-term atmospheric variability alone is unlikely to explain the detected patterns. Taken together, these results imply that land surface temperature anomalies, when considered in isolation, are not sufficient for reliable earthquake prediction. Nevertheless, they may provide useful complementary information when integrated with other geophysical observations. By combining a long-term, multi-event statistical approach with independent meteorological data, this study provides a more robust and balanced assessment of earthquake-related thermal behavior in a tectonically active region. This interpretation is further supported by a representative spatiotemporal case study, which highlights the transition from weak and spatially heterogeneous pre-earthquake anomalies to more coherent patterns following the earthquake.

Keywords: Earthquake-related anomalies, Land surface temperature, MODIS, ERA5, Statistical analysis, Spatiotemporal analysis, Türkiye.

1. Introduction

Because tectonic processes are complex and nonlinear, earthquake prediction remains a long-standing unresolved scientific problem (Saraf et al., 2009). Despite significant advances in seismology, there is no widely accepted technique for accurately predicting earthquakes (Bhardwaj et al., 2017). Therefore, identifying potential earthquake-related anomalies in various geophysical, geochemical, and atmospheric parameters that can provide indirect information about the accumulation and release of crustal stress has become a focus of significant research efforts (Pulinets and Ouzounov, 2011; Zhang and Meng, 2019; Pavlidou et al., 2019).

Over the past few decades, land surface temperature (LST) derived via satellite remote sensing has attracted increasing attention among these parameters (Tronin, 1996; Bhardwaj et al., 2017). Anomalous thermal signals before or after moderate to large earthquakes have been recorded in a number of studies, suggesting potential links between surface thermal behavior and tectonic activity (Rawat et al., 2011; Zoran, 2012; Chen et al., 2020; Semlali et al., 2024). Increased gas emissions, changes in surface emissivity, microfractures, and variations in stress-induced thermal conductivity are among the proposed causes (Saraf et al., 2009). However, since surface temperature is largely influenced by meteorological conditions, seasonal cycles, and long-term climate variability, the validity of surface temperature anomalies as earthquake-related indicators remains debatable (Pavlidou et al., 2019; Zhao et al., 2019).

Previous studies on earthquake-related thermal anomalies do not always lead to consistent conclusions. In general, they can be grouped into two broad approaches. Some studies report statistically significant thermal variations prior to earthquakes and suggest that these signals may have potential as precursors (Panda et al., 2007; Zhu et al., 2019; Shah et al., 2021; Semlali et al., 2023). In contrast, other studies have shown that similar thermal patterns can also occur during seismically quiet periods, raising concerns about false positives and possible overinterpretation (Pavlidou et al., 2019; Zhao et al., 2019). Taken together, these contrasting findings highlight how challenging it is to distinguish tectonic signals from background environmental variability. Because research is often limited to individual earthquakes or short time periods, it is difficult to generalize the results or assess statistical significance across multiple events (Barkat et al., 2018). In addition, a significant obstacle in interpreting satellite-derived thermal signals has been shown to be the inability to adequately separate tectonic effects from atmospheric effects (Kancherla et al., 2018; Shah et al., 2021). Recent studies have highlighted the importance of long-term, multi-event statistical analyses combined with independent meteorological datasets to address these issues (Shah et al., 2021; Hafeez et al., 2022; Semlali et al., 2023). In addition to providing physically consistent depictions of atmospheric and surface conditions, reanalysis

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products such as ERA5 offer a useful opportunity to assess whether detected thermal anomalies are largely due to meteorological processes or linked to seismic activity. Therefore, the robustness of anomaly identification and interpretation can be improved by combining satellite observations with reanalysis data (Semlali et al., 2024).

Türkiye's high seismic activity and well-documented earthquake database make it an excellent natural laboratory for such studies. Located at the confluence of the African, Arabian, Eurasian, and Anatolian plates, the region is characterized by active fault systems and complex tectonic interactions (Reilinger et al., 2006; Emre et al., 2018). In the last few decades, numerous medium and large-scale earthquakes have occurred in the region. Despite this, comprehensive and long-term assessments of surface temperature anomalies associated with earthquakes in Türkiye are still limited.

This study presents a comprehensive statistical analysis of land surface temperature anomalies associated with earthquakes of magnitude $M_w \geq 5.0$ that occurred in Türkiye between 2001 and 2024. Using daily MODIS land surface temperature data and ERA5 skin temperature data, pre- and post-earthquake thermal behavior was analyzed within a standardized temporal context. This study has three objectives: (i) to measure the statistical properties of land surface temperature anomalies before and after earthquakes; (ii) to compare satellite-derived anomalies with reanalysis-based temperature fields; and (iii) to determine how the observed thermal responses are dependent on earthquake magnitude. By emphasizing statistical robustness rather than deterministic prediction, this study aims to contribute to the current discussion on earthquake-related thermal anomalies in a more unbiased and reliable way. This study also provides one of the largest multi-event LST–earthquake statistical assessments specifically for Türkiye.

2. Data and Methodology

This study examined 93 $M_w \geq 5.0$ earthquakes that happened in Türkiye between 2001 and 2024. In order to minimize the influence of long-term climatic trends and capture potential pre-seismic and post-seismic thermal activity, a temporal window ranging from 60 days prior to 30 days following each earthquake was established. Previous studies have shown that pre-earthquake anomalies in thermal, atmospheric, and electromagnetic parameters are generally low-intensity and occur intermittently rather than as continuous signals (Xiong and Shen, 2017; Ouzounov et al., 2018). Therefore, a longer pre-earthquake time interval was preferred to improve statistical robustness and reduce the impact of short-term environmental variability. Earthquake epicenter coordinates, occurrence times, and magnitudes were obtained from the United States Geological Survey (USGS)

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earthquake catalog (https://earthquake.usgs.gov/), which provides standardized and internationally consistent seismic event information.

Land Surface Temperature (LST) data were acquired from the MODIS Terra/Aqua LST products (MOD11A1/MYD11A1), offering daily global LST at a spatial resolution of 1 km. To reduce cloud-derived contamination, pixels marked as low-quality were eliminated before analysis. Quality control was performed using the MODIS LST Quality Assurance (QA) layer. Only pixels flagged as 'good quality' (mandatory QA = 0) and with an estimated LST error ≤ 1 K were retained, while pixels affected by clouds, high emissivity uncertainty, or poor retrieval conditions were excluded following the MODIS LST user guide (Wan, 2008). Days with less than 50% valid pixel coverage within the analysis window were excluded to minimize cloud-induced sampling bias. On average, about 39% of the pixels within the 100 km buffer satisfied the quality criteria and were retained for analysis. The proportion of valid pixels was slightly higher before the earthquakes (≈40%) than after (≈38%), although this difference remains relatively small. This suggests that data availability is generally consistent across the analysis window and is unlikely to introduce a systematic bias between pre- and post-earthquake comparisons. Similar levels of data availability have been reported in previous MODIS-based LST studies, where cloud contamination and retrieval limitations often reduce the proportion of usable observations (Kancherla et al., 2018; Pavlidou et al., 2019; Shah et al., 2021).

The reanalysis-based skin temperature data were obtained from the ERA5 dataset, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), which offers hourly surface temperature fields with a spatial resolution of approximately 0.25° (Hersbach et al., 2020). ERA5 skin temperature represents a model-consistent surface variable rather than a true satellite-derived LST. The same spatial and temporal configuration was used to examine ERA5 data. A comparison of satellite-derived thermal anomalies against a physically consistent meteorological background is facilitated by the combined use of MODIS and ERA5.

LST values were spatially averaged within a fixed 100 km radius around each earthquake epicenter. This choice reflects a balance between capturing localized tectonic signals and reducing short-scale spatial variability, and is broadly in line with approaches adopted in earlier multi-event statistical studies. Using a fixed radius also helps maintain methodological consistency across all events, which is important in an ensemble-based framework. At the same time, it should be noted that fault systems in Türkiye, including the North Anatolian Fault, display considerable spatial variability. As a result, a uniform buffer may not fully capture the scale-dependent nature of thermal responses associated with different fault geometries or earthquake magnitudes.

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It should be noted that the earthquake catalog used in this study may include events that are not fully independent in a strict statistical sense. In particular, some earthquakes occur close to each other in space and time, forming aftershock sequences or clustered activity (e.g., the 2023 Kahramanmaraş sequence). For the purposes of this analysis, earthquakes were treated as independent samples within an ensemble-based framework, as the main goal was to identify general patterns of thermal behavior rather than establish event-specific causal relationships. This approach enables the use of large-sample statistics, but it may also introduce a certain degree of spatiotemporal autocorrelation. To account for this, the results are interpreted primarily at the ensemble level, focusing on average tendencies instead of individual event responses. Accordingly, the reported statistical significance should be viewed as reflecting collective behavior, rather than strictly independent realizations.

2.1. Anomaly Detection and Statistical Analysis

A standardized z-score method was used to detect thermal anomalies (Ouzounov et al., 2011; Wilks, 2011). Anomalies were calculated for each earthquake-centered time series as follows:

$$Z = \frac{T - \mu}{\sigma} \tag{1}$$

Here, μ and σ represent the mean and standard deviation of the reference period, and T represents the daily temperature. The reference mean (μ) and standard deviation (σ) were computed individually for each earthquake using the full 90-day analysis window (−60 to +30 days). It should be noted that defining both the reference statistics and anomaly detection within the same analysis window introduces a certain level of dependency between the baseline and the evaluated signal. This choice was made to preserve a locally adaptive normalization, helping to reduce seasonal influences and maintain comparability across different events. At the same time, this approach may slightly attenuate anomaly amplitudes. However, it also provides a more conservative framework, lowering the risk of false-positive detections.

An anomaly was detected when Z exceeded a predetermined threshold. To capture low-amplitude thermal fluctuations that could be indicative of pre-earthquake processes, and to avoid overly restrictive thresholds (such as ±2 or ±2.5) that could suppress weak but systematic signals, a threshold of ±1.5 was chosen as a balance between sensitivity and robustness. Although the number of anomalies was lower, sensitivity tests with different thresholds (±2.0) revealed qualitatively similar temporal patterns, indicating that the baseline results were threshold-independent (Figure S1).

To determine whether the observed temperature fluctuations differed significantly from background conditions, paired statistical tests were used to

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compare pre- and post-earthquake periods. To investigate the relationship between thermal behavior and earthquake magnitude, anomaly occurrence rates were calculated for various magnitude classes. All analyses were conducted using the Google Earth Engine platform, within a uniform and reproducible framework (Gorelick et al., 2017).

3. Results

In this section, the changes in LST data of selected earthquakes are statistically analyzed. The spatial distribution of the 93 earthquakes examined across Türkiye is shown in Figure 1. The main tectonic formations where events are concentrated are the North Anatolian Fault (NAF) and East Anatolian Fault (EAF) regions. This distribution provides a representative dataset for evaluating earthquake-related thermal behavior in various geological settings and reflects the dominant seismic regimes of the region. Detailed information on the earthquakes used is given in Table 1.

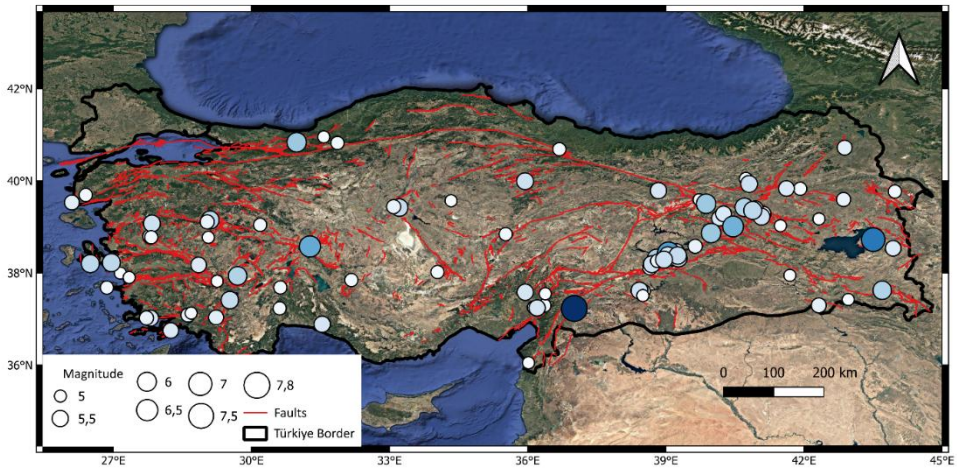

Figure 1. Spatial distribution of the analyzed earthquakes across Türkiye.

Statistical tests were performed for both MODIS and ERA5 data in the pre- and post-earthquake periods. In the first stage, LST time series of 93 earthquakes were combined, and basic descriptive statistics were calculated by analyzing the pre- and post-earthquake periods separately for MODIS and ERA5 data. These values, including mean, median, standard deviation, maximum, and minimum values, are presented in Table 2. The values presented in Table 2 are based on summary statistics derived from the original temperature data, rather than normalized z-scores. Although anomaly detection in this study relies on normalized values, the purpose of Table 2 is to provide a general overview of temperature variability across different events. For this reason, comparisons between events should be approached

with some caution, as the reported values reflect aggregated conditions rather than standardized anomaly measures.

Table 1. The list of analyzed earthquakes.

#	Date	Lat, Lon	Mag	#	Date	Lat, Lon	Mag	#	Date	Lat, Lon	Mag
1	25.06.2001	37.238, 36.206	5.5	32	12.11.2008	38.841, 35.524	5.1	63	10.09.2018	37.230, 30.613	5.1
2	10.07.2001	39.832, 41.623	5.4	33	17.02.2009	39.107, 29.039	5.2	64	20.02.2019	39.692, 26.401	5.1
3	26.08.2001	40.951, 31.573	5	34	17.06.2009	36.047, 36.020	5	65	20.03.2019	37.408, 29.531	5.7
4	31.10.2001	37.249, 36.136	5.1	35	20.06.2009	37.680, 26.860	5.1	66	4.04.2019	38.300, 39.163	5.2
5	3.02.2002	38.573, 31.271	6.5	36	30.07.2009	39.588, 39.726	5	67	8.08.2019	37.935, 29.700	5.9
6	27.01.2003	39.500, 39.878	6.1	37	8.03.2010	38.864, 39.986	6.1	68	22.01.2020	39.072, 27.839	5.6
7	10.04.2003	38.221, 26.958	5.8	38	11.11.2010	37.899, 27.343	5	69	24.01.2020	38.431, 39.061	6.7
8	1.05.2003	39.007, 40.464	6.4	39	19.05.2011	39.149, 29.103	5.8	70	28.01.2020	39.106, 27.875	5
9	3.05.2003	36.884, 31.536	5.5	40	23.06.2011	38.578, 39.640	5.2	71	14.06.2020	39.423, 40.707	5.9
10	13.07.2003	38.288, 38.963	5.6	41	22.09.2011	39.785, 38.842	5.5	72	25.06.2020	38.533, 43.941	5.4
11	23.07.2003	38.172, 28.853	5.4	42	23.10.2011	38.721, 43.508	7.1	73	26.06.2020	38.790, 27.793	5.2
12	25.03.2004	39.930, 40.812	5.6	43	26.03.2012	39.171, 42.330	5	74	28.06.2020	36.748, 28.248	5.4
13	1.07.2004	39.766, 43.979	5.1	44	3.05.2012	39.175, 29.092	5.2	75	4.08.2020	38.188, 38.698	5.6
14	3.08.2004	37.020, 27.720	5.2	45	14.06.2012	37.294, 42.325	5.3	76	20.09.2020	38.018, 34.042	5.1
15	11.08.2004	38.377, 39.261	5.7	46	22.07.2012	37.546, 36.384	5	77	3.12.2020	37.946, 41.697	5
16	10.01.2005	37.017, 27.804	5.5	47	5.08.2012	37.421, 42.965	5	78	27.12.2020	38.456, 39.230	5.5
17	25.01.2005	37.622, 43.703	5.9	48	17.09.2013	39.023, 41.492	5	79	25.06.2021	39.187, 40.167	5.4
18	14.03.2005	39.354, 40.890	5.8	49	24.11.2013	40.821, 31.869	5.1	80	31.08.2021	39.042, 30.189	5.1

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Table 1. Continued.

#	Date	Lat, Lon	Mag	#	Date	Lat, Lon	Mag	#	Date	Lat, Lon	Mag
19	6.06.2005	39.220, 41.080	5.6	50	24.08.2014	37.683, 30.629	5.1	81	8.11.2021	37.843, 32.171	5.1
20	30.07.2005	39.437, 33.089	5.2	51	9.10.2015	40.685, 36.690	5.1	82	19.11.2021	39.827, 41.922	5.1
21	17.10.2005	38.200, 26.500	5.8	52	2.12.2015	39.283, 40.255	5.4	83	9.04.2022	38.116, 38.662	5.3
22	26.11.2005	38.260, 38.814	5.1	53	10.01.2016	39.565, 34.337	5	84	12.06.2022	38.737, 43.507	5.2
23	10.12.2005	39.394, 40.946	5.4	54	7.02.2017	39.528, 26.099	5.3	85	14.08.2022	37.995, 27.151	5
24	21.01.2007	39.592, 42.863	5.2	55	2.03.2017	37.616, 38.431	5.6	86	27.09.2022	40.719, 42.888	5.3
25	9.02.2007	38.390, 39.043	5.5	56	13.04.2017	37.125, 28.691	5	87	11.10.2022	37.261, 36.234	5
26	21.02.2007	38.318, 39.275	5.7	57	21.04.2017	38.771, 29.064	5	88	23.11.2022	40.836, 30.983	6.1
27	25.08.2007	39.282, 41.124	5.3	58	11.05.2017	40.038, 40.742	5.1	89	6.02.2023	37.226, 37.014	7.8
28	29.10.2007	37.033, 29.233	5.3	59	27.05.2017	38.773, 27.823	5.1	90	20.02.2023	36.162, 36.025	6.3
29	20.12.2007	39.417, 33.212	5.7	60	24.11.2017	37.085, 28.622	5.2	91	25.07.2023	37.579, 35.948	5.5
30	25.04.2008	37.819, 29.256	5	61	24.04.2018	37.596, 38.514	5.2	92	18.04.2024	39.989, 35.945	5.6
31	3.09.2008	37.507, 38.503	5	62	19.08.2018	37.290, 36.364	5.1	93	16.10.2024	38.312, 38.806	6

Table 2. Mean, median, standard deviation, maximum, and minimum values of MODIS LST and ERA5 skin temperature data for the pre- and post-earthquake periods.

	MODIS (°C)		ERA5 (°C)	
	Pre-EQ	**Post-EQ**	**Pre-EQ**	**Post-EQ**
Mean	21.65	22.39	12.31	12.91
Median	23.37	23.86	12.7	13.78
Standard Deviation	14.83	14.91	11.4	11.53
Max. Value	54.37	53.12	35.91	32.22
Min. Value	-28.03	-19.77	-27.33	-21.46
p-value	0.0365		0.0283	
Cohen's d	0.0497		0.0522	

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An independent samples t-test was conducted to determine whether there was a statistically significant difference between LST values in the pre- and post-earthquake periods. Accordingly, the p-value was found to be 0.0365 for MODIS and 0.0283 for ERA5. Here, the p-value indicates the level of statistical significance, and generally, a p-value < 0.05 indicates a significant difference between the groups (Wilks, 2011). The obtained values show a significant difference in both datasets in the pre- and post-earthquake periods. According to commonly used interpretation guidelines, Cohen's d values below 0.2 are generally considered to represent very small effect sizes. This suggests that, although the observed differences are statistically significant, their practical magnitude remains limited. It should also be noted that statistical significance was interpreted at the ensemble level rather than assuming strict event independence.

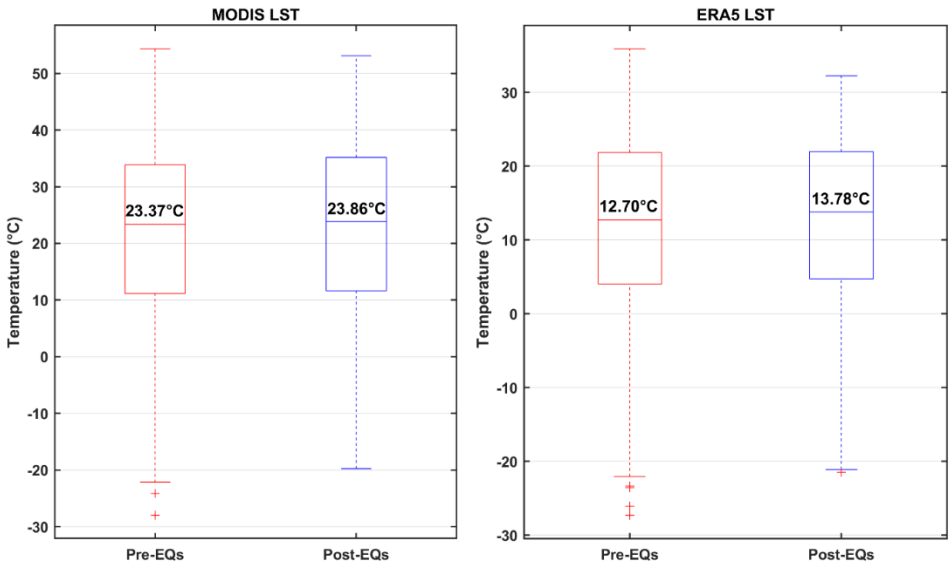

Figure 2. Boxplots of land surface temperature obtained from MODIS and ERA5 data for the pre- and post-earthquake periods. Whiskers represent 1.5× IQR, and plus symbols (+) indicate statistical outliers. Median values are explicitly shown on the boxplots.

Figure 2 shows boxplots of pre- and post-earthquake surface temperature (LST) values obtained from MODIS and ERA5. The original temperature values shown in the figure are intended to provide a descriptive overview, while anomaly detection and statistical comparisons are performed using normalized data. Both MODIS and ERA5 data show an increase in median temperature (approximately 1°C) after the earthquakes. The consistency between both datasets supports the idea that short-term atmospheric variability is not the main driver of the observed post-earthquake thermal

changes, and that small-scale changes in surface temperature during the earthquake period may reflect earthquake-related surface thermal variability. It should be noted that these changes may manifest as either warming or cooling anomalies depending on local environmental conditions, as also illustrated in the case study (Figure 6).

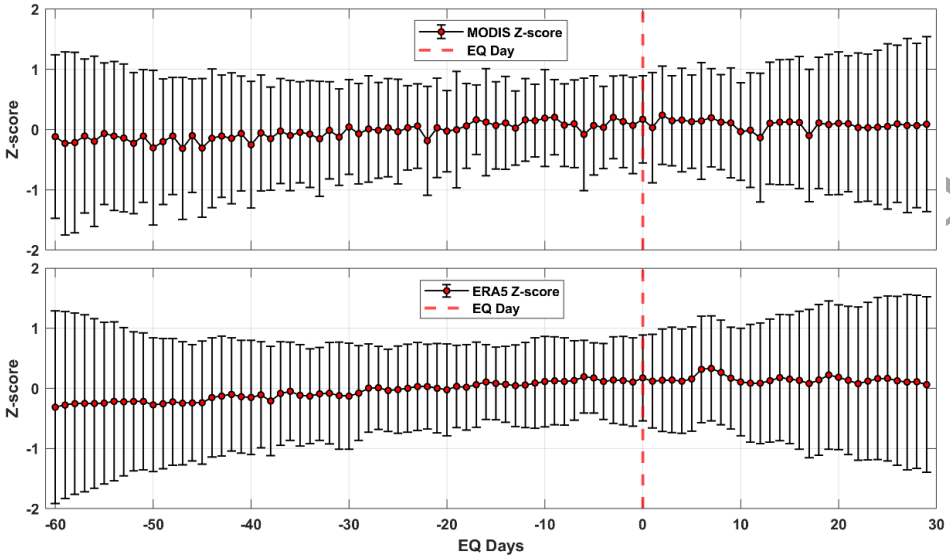

Figure 3. Average temporal evolution of standardized LST anomalies (z-scores) focused on earthquake occurrence (day 0). Curves represent average MODIS and ERA5 anomaly time series, showing the relative behavior of thermal responses before and after earthquakes. Shaded areas represent ±1 standard error of the mean.

Figure 3 shows the mean z-score time series of LST anomalies focusing on the time of earthquake occurrence. Thermal anomalies show a slow increase in the days following earthquakes, with a clearer peak observed in ERA5 data, while MODIS exhibits a more gradual response. Pre-earthquake anomalies typically remain around the background variability and are weaker and less persistent. The robustness of the observed thermal responses is supported by consistent temporal patterns seen in both MODIS and ERA5. Although statistically significant, the amplitude of the averaged z-score anomalies remains small ($|Z| < 0.5$), indicating modest effect sizes rather than strong deterministic signals.

Figure 4 compares the frequency of thermal anomalies recorded in the pre- and post-earthquake periods. In the entire dataset, post-earthquake anomalies are more common than pre-earthquake anomalies. Both datasets show a significant increase in anomaly frequency after seismic events. Specifically, the frequency of post-earthquake anomalies increased from 9.8%

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to 14.6% in MODIS and from 10.9% to 15.4% in ERA5 compared to pre-earthquake levels. In the pre-earthquake period, the ratio of negative anomalies to positive anomalies is higher. In the post-earthquake period, positive anomalies become more dominant, indicating a systematic change in thermal patterns. The proportions shown in Figure 4 quantitatively illustrate this shift in anomaly polarity between the pre- and post-earthquake periods.

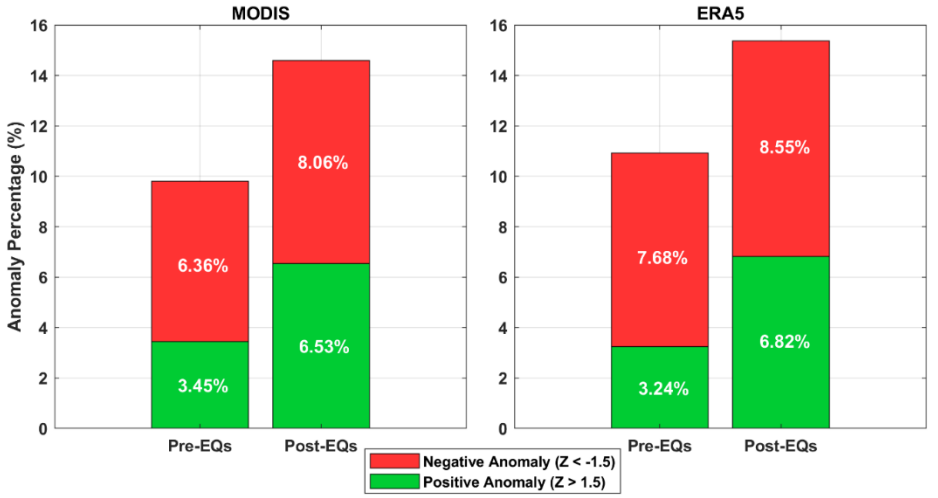

Figure 4. Comparison of thermal anomaly frequencies during pre-seismic and post-seismic periods.

Figure 5 illustrates how anomaly occurrence rates vary across different earthquake magnitude classes for both the MODIS and ERA5 datasets. Overall, there is a tendency for post-earthquake anomaly rates to increase with magnitude. For smaller events (M_w 5.0–6.0), the difference between pre- and post-earthquake anomaly rates remains limited, suggesting relatively weak and less distinguishable thermal responses. In contrast, larger earthquakes tend to show a clearer separation between pre- and post-earthquake conditions in the aggregated results. It should be noted, however, that the number of events in the highest magnitude class (M_w > 6.5) is quite small. In the MODIS dataset, only four earthquakes fall into this category, and they do not exhibit a consistent pattern: two show higher post-earthquake anomaly rates, while the other two display the opposite behavior. This variability likely reflects the influence of the limited sample size and indicates that the observed trend should be interpreted with caution. Even so, the overall tendency toward higher post-earthquake anomaly rates remains visible at the ensemble level across both datasets, suggesting a general relationship between earthquake magnitude and anomaly occurrence, although some variability remains.

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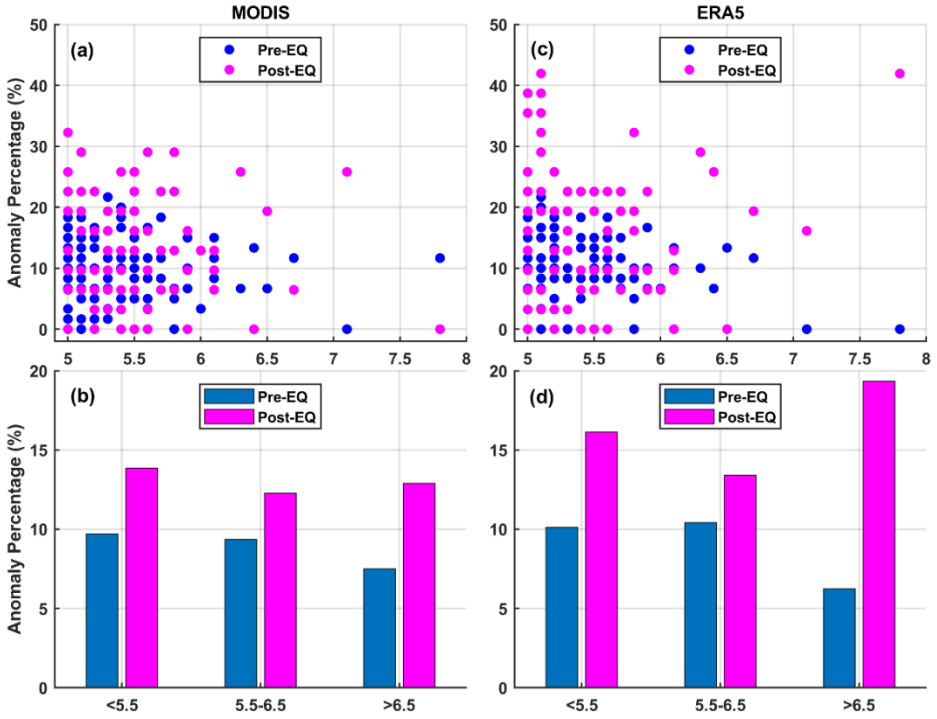

Figure 5. The relationship between earthquake magnitude and anomaly occurrence rates. Earthquakes are grouped according to magnitude class, and the bars show the corresponding frequency of detected anomalies. (a-b) MODIS and (c-d) ERA5.

To further illustrate how thermal anomalies evolve over time, Figure 6 shows daily ERA5-derived LST anomaly maps for the 10 days before and after the 2023 Kahramanmaraş earthquake (M_w 7.8). Before the earthquake, anomalies appear relatively weak and spatially scattered, without a clear or persistent pattern. After the event, however, the anomalies become more pronounced and spatially coherent, particularly near the fault system. In this case, post-earthquake anomalies are mostly negative, pointing to a relative cooling signal rather than warming. This suggests that earthquake-related surface responses do not follow a single direction, but may appear as either positive or negative thermal deviations depending on local environmental and atmospheric conditions. In this sense, the magnitude and spatial coherence of anomalies seem to provide more reliable indicators than their sign.

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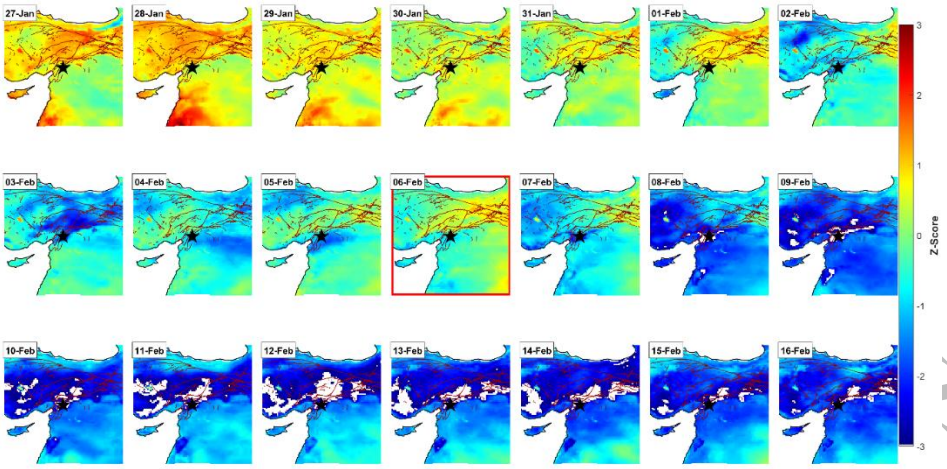

Figure 6. Daily ERA5-derived land surface temperature anomaly maps (z-scores) for the period spanning 10 days before and 10 days after the 2023 Kahramanmaraş earthquake (M_w 7.8). The earthquake occurred on 6 February 2023 (highlighted panel). The epicenter is indicated by a black star, and major fault lines are shown in red. Warmer colors represent positive anomalies, while cooler colors indicate negative anomalies. The temporal sequence highlights the transition from weak and heterogeneous pre-earthquake anomalies to more coherent post-earthquake patterns.

Overall, this example is consistent with the statistical results, showing that post-earthquake anomalies tend to be stronger and more organized than those observed beforehand. At the same time, it also highlights that individual events can vary in both the sign and magnitude of anomalies. For this reason, interpreting the results at the ensemble level remains important for identifying more robust and consistent patterns.

4. Discussion

The results indicate that LST anomalies associated with earthquakes in Türkiye are more pronounced in the post-earthquake period compared to the pre-earthquake period. This result is consistent with ERA5 reanalysis data and MODIS satellite measurements, suggesting that short-term atmospheric variability may not be the sole cause of the observed thermal responses (Zoran, 2012; Zhu et al., 2019; Semlali et al., 2024).

Physical processes associated with earthquakes provide a useful context for interpreting the observed asymmetry between pre- and post-earthquake thermal signals. In particular, the more pronounced and consistent anomalies observed after earthquakes are likely linked to processes that occur directly following rupture. These may include stress redistribution, surface deformation (Nath et al., 2024), changes in soil moisture, and enhanced heat transfer associated with fracturing and increased permeability (Saraf et al.,

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2009; Kancherla et al., 2018). Together, these processes can alter near-surface thermal properties and promote heat exchange between the subsurface and the atmosphere, resulting in more spatially coherent and detectable temperature anomalies. At the same time, these associations should not be interpreted as direct causal relationships, but rather as statistically consistent surface responses to seismic activity. In contrast, pre-earthquake thermal anomalies tend to be weaker and less persistent. Mechanisms such as microfracturing, gas emissions, or stress-induced changes in thermal conductivity (Saraf et al., 2009; Bhardwaj et al., 2017; Chen et al., 2020) may occur prior to rupture, but they are often intermittent, localized, and strongly influenced by environmental conditions. As a result, their amplitudes usually remain close to the noise level of surface temperature measurements, even when they can be statistically distinguished from background variability, particularly for larger magnitude events (Panda et al., 2007; Semlali et al., 2023). This interpretation is consistent with the growing view that pre-earthquake thermal signals, if present, are generally weak and difficult to isolate without long-term datasets and robust statistical approaches (Barkat et al., 2018; Shah et al., 2021; Hafeez et al., 2022). Overall, the contrast between pre- and post-earthquake processes provides a plausible physical explanation for the temporal patterns identified in this study. While post-seismic mechanisms tend to produce stronger and more spatially integrated responses, pre-seismic signals are more subtle and can easily be masked by environmental variability. The relatively small effect sizes observed here further emphasize the need to carefully control false positives in potential operational applications.

A key strength of this study is the combined use of MODIS and ERA5 data, which enhances the reliability of anomaly detection. It is important to emphasize that ERA5 represents a model-based reanalysis constrained by observations, whereas MODIS provides direct satellite-derived surface measurements. The agreement between these fundamentally different data sources strengthens the robustness of the observed temporal patterns, despite their large spatial resolution mismatch (1 km vs ~25 km). Both datasets show consistent temporal anomaly patterns surrounding seismic events, despite differences in spatial resolution, acquisition technique, and physical characteristics (Semlali et al., 2024; Guo et al., 2025). The agreement between these different data sources indicates that the observed thermal changes are not a result of sensor-specific noise or data processing decisions (Kancherla et al., 2018; Shah et al., 2021). An important resource for assessing the effect of atmospheric forcing is ERA5, which integrates various meteorological measurements into a physically consistent model. The similarity in MODIS and ERA5 anomaly timings suggests that at least some of the observed thermal response may be due not only to meteorological fluctuations but also to surface-atmosphere interactions caused by or modified by seismic activity (Zhang and Meng, 2019; Zhao et al., 2019). However, the slightly higher

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variability found in MODIS data underscores the need for cautious interpretation and demonstrates how sensitive satellite-derived surface temperature is to surface features (Pavlidou et al., 2019).

The results of this study are broadly in line with previous research reporting weak or ambiguous pre-earthquake thermal signals alongside more pronounced post-earthquake responses (Blackett et al., 2011; Rawat et al., 2011; Zoran, 2012; Kancherla et al., 2018; Chen et al., 2020; Semlali et al., 2024). Some studies have identified statistically significant thermal anomalies prior to major earthquakes and suggested their potential as precursors (Panda et al., 2007; Barkat et al., 2018; Zhu et al., 2019; Semlali et al., 2023). At the same time, other work, particularly Pavlidou et al. (2019), has shown that similar thermal patterns may also occur during seismically quiet periods, raising concerns about their reliability as predictive signals. In this context, the findings of the present study help to bridge these differing interpretations. Consistent with Pavlidou et al. (2019), pre-earthquake anomalies are generally weak and remain close to background variability, which limits their predictive usefulness. At the same time, by using a long-term, multi-event statistical framework and incorporating ERA5 reanalysis data to account for meteorological influences, the analysis reveals weak but statistically distinguishable patterns at the ensemble level. This suggests that individual pre-earthquake signals may not be reliable indicators on their own, but subtle tendencies can still emerge when a sufficiently large dataset and an appropriate normalization approach are applied. Rather than contradicting earlier studies reporting negative results, these findings refine them by indicating that any pre-earthquake thermal signals are likely to be small in magnitude and detectable only under robust statistical conditions. Overall, this perspective highlights the importance of large-sample approaches when evaluating subtle geophysical signals.

This study employs a long-term, multiple-event statistical approach, in contrast to many previous studies that have focused on single events or short observation periods (Bhardwaj et al., 2017; Barkat et al., 2018). This approach reduces the possibility of false positives due to seasonal variations or transient meteorological conditions (Saraf et al., 2009; Chen et al., 2020). Since stronger earthquakes cause more extensive crustal deformation and surface change, the magnitude-dependent increase in the frequency of post-earthquake anomalies seen here is consistent with physical expectations (Saraf et al., 2009; Pavlidou et al., 2019). The limited number of large-magnitude events ($M_w > 6.5$) introduces some uncertainty when interpreting this trend. Within this small subset, contrasting anomaly behaviors are observed, suggesting that variability between individual events remains significant. For this reason, the apparent magnitude-dependent pattern should be interpreted with caution.

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According to the findings, LST anomalies should not be considered definitive earthquake precursors (Saraf et al., 2009; Bhardwaj et al., 2017). Rather, they may be part of a larger group of environmental responses to earthquakes (Ouzounov and Freund, 2004; Zhang and Meng, 2019). The stronger and more consistent post-earthquake anomalies in this study demonstrate that thermal signals are more consistently linked to post-fracture processes rather than an impending earthquake (Kancherla et al., 2018; Zhu et al., 2019; Semlali et al., 2024). From a practical standpoint, these results suggest that LST-based analyses are more suitable for retrospective investigations and post-event assessments rather than operational earthquake prediction (Zhao et al., 2019; Shah et al., 2021). However, thermal anomalies, when combined with other geophysical, geochemical, or ionospheric observations within a multiparameter framework, can offer complementary information compared to the weak pre-earthquake signals seen for higher magnitude events (Pulinets and Ouzounov, 2011; Semlali et al., 2024; Guo et al., 2025).

Several limitations should be considered. Residual meteorological influences on LST cannot be fully removed, even with the inclusion of ERA5 data. In addition, the proportion of valid LST pixels after quality filtering remains relatively low due to cloud contamination and retrieval constraints, with an average coverage of about 39%. This reduces the effective spatial sampling. At the same time, the similar data availability observed before and after earthquakes suggests that this limitation does not introduce a systematic bias into the comparison. Instead, it mainly affects the signal-to-noise ratio and should be taken into account when interpreting the magnitude of detected anomalies.

Surface characteristics represent another important source of uncertainty. Factors such as vegetation cover, soil type, urbanization, and elevation can significantly influence LST and introduce spatial variability unrelated to tectonic processes. Although ERA5 helps to constrain large-scale atmospheric effects, it does not resolve fine-scale surface heterogeneity. As a result, some of the observed anomalies may partly reflect local environmental conditions rather than purely seismic effects. That said, the large number of events and the ensemble-based statistical approach reduce the likelihood that these influences systematically bias the overall results. Future work could improve on this by incorporating land cover information, topographic corrections, or stratified analyses based on surface properties.

It should also be noted that the values presented in Table 2 are based on descriptive statistics derived from raw temperature data. These values may still be affected by seasonal differences between events occurring at different times of the year. Although the event-centered analysis window helps to limit within-event variability, it does not completely remove seasonal differences between events. For this reason, the values in Table 2 are best interpreted as

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complementary indicators rather than directly comparable normalized metrics.

A further limitation relates to spatial averaging. Thermal responses associated with specific fault segments may be partially obscured when averaged over a fixed buffer. The use of a 100 km radius ensures methodological consistency, but it may not fully capture differences in fault geometry or rupture scale. Larger and more complex earthquakes may produce broader thermal responses, whereas smaller events are likely to remain more localized. Adopting adaptive spatial windows based on magnitude or fault characteristics could improve sensitivity in future studies.

Finally, subsurface processes occurring at depth are not always reflected in surface temperature measurements. The use of a shared temporal window for both baseline estimation and anomaly detection also introduces a degree of dependency, since the same data contribute to both steps. This may slightly reduce anomaly amplitudes and make the detection more conservative. Even so, given the relatively short time window and the focus on ensemble-level behavior, this effect is expected to remain limited and does not alter the overall conclusions.

Future studies could address these limitations by incorporating additional environmental factors such as soil moisture or gas emissions, adaptive spatial windows based on fault geometry, and higher-resolution thermal datasets (Kancherla et al., 2018; Pavlidou et al., 2019; Zhang and Meng, 2019). Complementary frameworks for identifying spatial patterns in LST anomalies can be provided by advanced methodological tools such as contrast boundary concentration techniques (Nikulin et al., 2024). Furthermore, it may be possible to isolate small seismic signals from background variability by combining machine learning techniques with physically informed constraints (Hafeez et al., 2022).

Another aspect to consider is the possible presence of spatiotemporal autocorrelation in the dataset. Some earthquakes occur close to each other in both space and time, forming aftershock sequences or clustered activity. This can lead to overlapping thermal responses, making it difficult to attribute anomalies to individual events. The use of a fixed 100 km spatial buffer may further contribute to this issue, as neighboring earthquakes can partially share the same analysis area, especially in regions with dense seismicity. Although the analysis is based on aggregate statistical behavior rather than strict event-level independence, such clustering effects may still influence the effective sample size and should be taken into account when interpreting statistical significance. Future studies could address this more directly by applying declustering methods or spatiotemporal filtering approaches based on established seismicity models, such as Omori-type decay.

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5. Conclusions

This study statistically evaluated land surface temperature anomalies associated with 93 earthquakes ($M_w \geq 5.0$) in Türkiye between 2001 and 2024 using MODIS satellite measurements and ERA5 reanalysis data. The results show that thermal responses are more pronounced and stable during the post-earthquake period, while pre-earthquake anomalies remain weak and close to background variability. The occurrence of anomalies increases with magnitude, particularly for earthquakes with $M_w > 6.5$. The consistent behavior observed in both MODIS and ERA5 datasets indicates that the detected thermal signals are not solely driven by short-term meteorological variability. These findings indicate that land surface temperature anomalies alone are insufficient for reliable earthquake prediction but can provide complementary information when integrated with other geophysical observations within a multiparameter framework. To our knowledge, this study represents one of the largest multi-event statistical assessments of earthquake-related LST anomalies conducted for Türkiye, both in terms of temporal coverage and number of analyzed events. Furthermore, the proposed statistical framework provides a robust basis for future multi-parameter earthquake monitoring and retrospective analyses. Considering both the ensemble-based results and the event-scale case analysis together further strengthens these findings, showing that post-earthquake anomalies tend to be more coherent and pronounced than those observed before the earthquake.

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Supplementary Materials – Figure S1: Sensitivity tests with different z-score threshold.

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SAŽETAK

Statistička procjena temperaturnih anomalija površine kopna povezanih s potresima magnitude $M_w \geq 5$ u Turskoj primjenom MODIS-a i ERA5-a

Erman Şentürk[1] i Abdullah Çağlar Fındıkcıoğlu [1]*

Prepoznavanje pouzdanih predkazatelja potresa i dalje predstavlja jedan od najtežih izazova u geofizici, budući da su brojne zabilježene anomalije povezane s potresima pod utjecajem promjenjivih okolišnih i meteoroloških uvjeta. Unatoč raspravama o statističkoj robusnosti i fizičkoj interpretaciji temperature površine kopna (LST – land surface temperature), ona i dalje predstavlja zanimljiv skup podataka za proučavanje pojava zabilježenih daljinskim istraživanjima i njihove moguće povezanosti s potresima. U ovom istraživanju statistički je analizirane su promjene u temperaturi površine kopna prije i nakon potresa za 93 potresa ($M_w \geq 5{,}0$) koji su se dogodili u Turskoj između 2001. i 2024. godine. Kako bi se unaprijedila interpretacija i smanjila pristranost uzrokovana meteorološkim podacima, dnevni podaci o temperaturi površine kopna dobiveni satelitskim mjerenjima MODIS uspoređivani su s podacima o temperaturi površine tla iz reanalize ERA5. Za prepoznavanje anomalija korištene su standardizirane z-vrijednosti unutar vremenskog perioda od 90 dana, koji obuhvaća 60 dana prije i 30 dana nakon svakog potresa. Ovaj asimetrični vremenski prozor odabran je kako bi se bolje zabilježile pojave prije potresa, koje su često slabe, povremene i manje postojane od onih nakon potresa. Rezultati pokazuju da su, osobito kod potresa magnitude $M_w \geq 6{,}5$, temperaturne anomalije nakon potresa konzistentnije i jasnije uočljive od onih zabilježenih prije samog potresa. Međutim, pripadajuće veličine učinka su male (Cohenov $d<0{,}1$), što ukazuje na to da, iako su razlike statistički mjerljive, njihov je intenzitet i dalje ograničen. Anomalije prije potresa ipak se mogu razlikovati od pozadinskog šuma, no one su vrlo suptilne i blizu razine šuma. Sličan obrazac uočen je i u MODIS i u ERA5 skupovima podataka, što dodatno upućuju na to da sama kratkotrajna promjenjivost u atmosferskim uvjetima teško može objasniti uočene uzorke. Gledajući u cjelini, ovi rezultati ukazuju na to da anomalije temperature površine kopna, ako se promatraju izolirano, nisu dovoljne za pouzdano predviđanje potresa. Unatoč tome, mogu pružiti korisne dodatne informacije kada se uzmu u obzir i druga geofizička opažanja. Uzimajući u obzir dugoročni, multi-događajni statistički pristup s neovisnim meteorološkim podacima, ovo istraživanje pruža robusniju i uravnoteženiju procjenu toplinskog ponašanja povezanog s potresima u tektonski aktivnoj regiji. Ovu interpretaciju dodatno potkrepljuje reprezentativna prostorno-vremenska studija, koja ističe prijelaz sa slabih i prostorno heterogenih anomalija prije potresa na koherentnije uzorke nakon potresa.

Ključne riječi (keyword in Croatian): Anomalije povezanee s potresima, temperature površine kopna MODIS, ERA5, statističke analize, prostorno-vremenske analize, Turska

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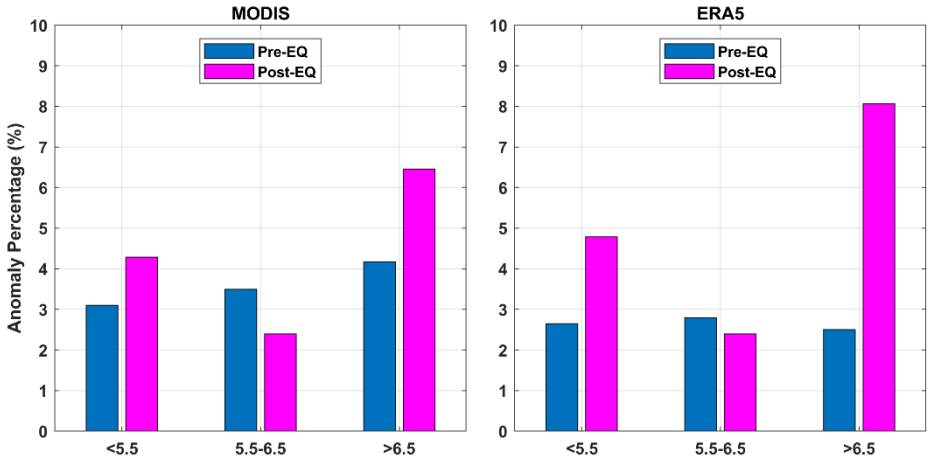

Figure S1. The relationship between earthquake magnitude and anomaly occurrence rates. Anomalies were identified using a Z-score with a threshold of ±2.0.

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