

Robust Satellite Technique Detection of Extreme Heat Events in Italy: A 26-Year (2000–2025) Study of Non-Stationary Thermal Baselines

Mayowa Benjamin Lateef^{1,2,*} and Daniel Aderotoye^{2,3}

¹ Department of Engineering and Physics of the Environment, University of Basilicata, 85100 Potenza, Italy

² Center for Space Research and Applications, Federal University of Technology Akure, Akure 340252, Nigeria

³ Department of Geography, Oklahoma State University, Stillwater, OK 74078, USA

* Correspondence: lateefmayowa11@gmail.com

How To Cite: Lateef, M.B.; Aderotoye, D. Robust Satellite Technique Detection of Extreme Heat Events in Italy: A 25-Year (2000–2025) Study of Non-Stationary Thermal Baselines. *Urban and Building Science* **2026**. https://doi.org/10.53941/ubs.2026.100024

Received: 30 March 2026

Revised: 13 August 2026

Accepted: 14 August 2026

Published: 20 August 2026

Abstract: Extreme heat events pose significant socio-ecological risks across the Mediterranean region, with Italy being particularly vulnerable due to its complex topographies, microclimates, and non-stationary land surface temperature (LST) patterns driven by accelerating climate change. To overcome the limitations of fixed baseline thermal monitoring in non-stationary thermal environments, this study applies the Robust Satellite Technique (RST) to a 26-year record (2000–2025) of Moderate Resolution Imaging Spectroradiometer (MODIS) Terra daytime LST data to systematically detect and characterize extreme heat events across Italy. By deploying a leave-one-out baseline climatology and multi-criteria event definitions ($\Omega_{\text{SAT}} \geq 2.0$, minimum 3-day duration, and $\geq 10\%$ spatial coverage), we isolate thermal anomalies while excluding seismically active years (2008, 2009, 2013) that corrupt baseline statistics. Validation against major historical heat waves (2003, 2017, 2021) confirms that the framework reliably captures regional heat footprints, showing peak cumulative heat wave frequency concentrated across the Po Valley, southern Alpine foothills, and the Adriatic coastal corridor. Analysis of peak spatial events shows that while extreme anomalies can extend into spring (e.g., March 2001, covering 43% of land area) vulnerability remains most acute during summer. Although national seasonal mean anomalies display no statistically significant trend due to high interannual variability, pixel-wise trend analysis uncovers a localized July warming hotspot (Sen slope $> +0.03 \Omega_{\text{SAT}} \text{ year}^{-1}$, $p \leq 0.05$) across 8.0% of land pixels, heavily centered in the northeastern Po Valley. These findings highlight the strength of high-quality satellite remote sensing in delineating non-stationary sub-regional heat vulnerability and guiding targeted climate adaptation strategies across heterogeneous landscapes.

Keywords: extreme heat events; land surface temperature; robust satellite technique; thermal anomalies

1. Introduction

The frequency and intensity of extreme heat events have increased across Europe, causing a big threat to public health, agricultural yield, and ecosystem stability [1,2]. As anthropogenic climate change accelerates, Mediterranean heatwaves are becoming more frequent, longer-lasting, and geographically widespread, severely straining energy grids, water resources, and urban infrastructure [3]. Italy is particularly vulnerable to natural hazards and extreme phenomena, which are mostly temperature extremes, due to the geographical location of the country and the complex topography, as it is in the Mediterranean Basin, which permits heterogeneous



Copyright: © 2026 by the authors. This is an open access article under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Publisher's Note: Scilight stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

microclimatic conditions in the peninsula [4,5]. Over recent decades, the Italian peninsula has endured recurrent, severe heatwaves—most notably the historical events of 2003, 2017, and 2021—which resulted in acute heat-related mortality, severe soil moisture deficits, and major economic losses in agricultural sectors [6]. These compound hazards demonstrate that extreme thermal events are not merely uniform regional phenomena, but spatially variable hazards that interact directly with local terrain, land cover, and surface energy dynamics. The increasing recurrence and spatial expansion of these thermal extremes underscore the urgent need for high-resolution monitoring frameworks and spatial hazard mapping capabilities [7,8].

Ground-based conventional meteorological networks, although producing high temporal resolution data, are usually marred by spatial heterogeneity and sparse coverage, particularly over mountainous or remote regions [9]. As technology progresses in satellite remote sensing, spaceborne remote sensing is a valuable ancillary tool to ground-based measurements for observing land surface temperature (LST) variability at regional and continental scales [5,10]. Unlike point-based station measurements, spaceborne thermal infrared sensors provide continuous, spatially explicit observations of land surface temperature (LST), which reflects the direct radiative surface energy balance and serves as a key indicator of localized heat stress.

In particular, the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA Terra and Aqua satellites has been particularly suited to LST monitoring due to its provision of near-global coverage with high radiometric accuracy and temporal repetition since 2000, enabling long-term spatiotemporal analysis of land surface thermal dynamics at a 1 km spatial resolution [11].

The satellite observation and measurement of temperature anomalies are nowadays very trendy in various applications like climate change, agricultural monitoring, and natural hazard exploration [12,13].

Several algorithms have been developed to translate raw satellite observations into interpretable geophysical information. One of these is Robust Satellite Technique (RST), a change detection approach that identifies signals departing significantly from a long-term baseline computed from the same location, time of year, and observation conditions [14,15]. This approach utilizes statistical processing of multi-temporal satellite data to calculate standardized anomaly indices, enabling the identification of anomalous events that exceed historical means.

There have been recent achievements in the application of satellite-based anomaly detection techniques to investigate many phenomena, including pre-seismic thermal anomalies [16,17], oil spill detections [18] and the more recent studies on greenhouse gas anomalies [19]. Meanwhile, large-scale, long-term investigations of extreme heat events by Robust Satellite Technique (RST) methodology remain rare, particularly across the complicated terrain of Mediterranean nations like Italy, where heterogeneous land cover types pose unique challenges to thermal remote sensing.

Land surface temperature (LST) exhibits complex, non-stationary spatial and temporal patterns driven by ongoing climate change, localized surface-atmosphere feedbacks, and heterogeneous land cover dynamics. Existing thermal anomaly studies frequently rely on fixed historical baselines or static thresholds, which fail to account for these evolving, non-stationary thermal environments. Over multi-decadal time series undergoing secular warming, static baselines systematically introduce biases, either overestimating anomaly magnitudes in warmer recent years or failing to isolate transient meteorological heat stress from background climate trends. To address these critical research gaps, there is a strong motivation to adopt satellite remote sensing techniques that can handle dynamic surface conditions. Specifically, the Robust Satellite Technique (RST) establishes dynamic, spatially and temporally invariant baseline distributions (μ and σ) calculated over multi-year reference pools. By dynamically adjusting to local climatological backgrounds, RST effectively isolates true extreme heat anomalies from non-stationary background warming and localized microclimatic noise across heterogeneous topographies.

To address these gaps the primary objectives of this research are (1) to identify and characterize extreme heat events in Italy using RST anomaly detection over a 26-year record (2000–2025), (2) to analyze the spatiotemporal temperature anomaly distribution patterns across Italy's distinct topographies, and (3) to evaluate the feasibility of satellite-based approaches for operational heat event monitoring under ongoing background warming. The results will contribute to a greater understanding of Italian extreme temperature regimes and provide valuable observational evidence toward adaptation measures, public health policy, and agricultural planning.

2. Data and Method

2.1. Data

The study area (Italy), as seen in Figure 1, has a diverse landscape—ranging from low-lying alluvial basins like the Po Plain to elevated Alpine and Apennine Mountain chains—that creates complex surface-atmosphere interactions that yield distinct local microclimatic responses during extreme synoptic heat events. This study uses daily daytime land surface temperature (LST) retrieved from the Moderate Resolution Imaging Spectroradiometer

(MODIS) Terra satellite, specifically the MOD11A1 Version 6.1 product [20]. The Terra platform has been in continuous operation since its launch in December 1999, providing an uninterrupted daily LST record at 1 km spatial resolution from 24 February 2000 to the present. Version 6.1 was adopted exclusively because its predecessor, Version 6, was discontinued on 16 November 2022 following data loss associated with Terra's constellation exit maneuvers, rendering it unsuitable for analyses extending beyond that date. All data acquisition and preprocessing were performed within the Google Earth Engine (GEE) cloud computing platform [21] which provides direct access to the full MODIS archive without the need to download or locally store the raw imagery.

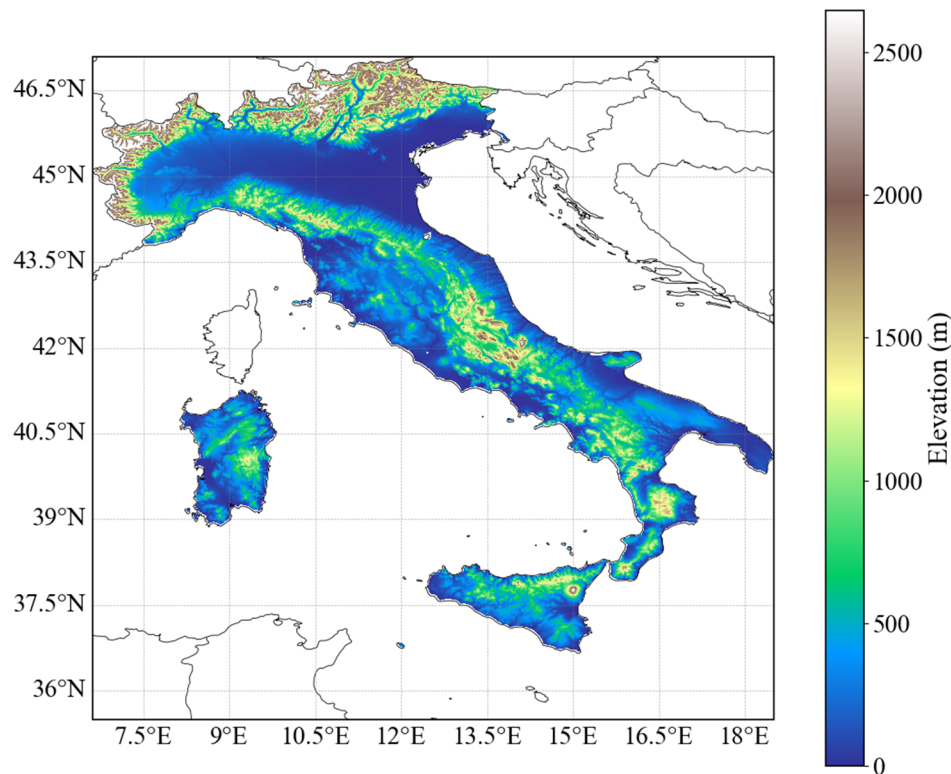


Figure 1. Topographic map of Italy displaying the digital elevation model (DEM) and the locations of major urban centers.

The study domain covers the Italian peninsula, bounded by 6–19° E and 36–48° N, a region of considerable climatological diversity spanning continental northern Italy to the semi-arid Mediterranean south. The analysis period runs from 2000 to 2025, representing the full available MODIS Terra record. Three years—2008, 2009, and 2013—were excluded from both the reference climatology and the study period. These years coincide with major seismic sequences in the central Apennines, including the L'Aquila (April 2009) alongside the Tuscany (June 2013) and Lazio (February 2013) events, during which thermally anomalous signals detected in satellite imagery have been attributed to seismic precursory processes rather than atmospheric heating [14,15]. Retaining these years would inflate the baseline mean and standard deviation, systematically suppressing anomaly magnitudes in unaffected years and introducing a source of bias that cannot be corrected post hoc. The resulting dataset comprises 23 valid study years.

Seasonal coverage was restricted to five periods: boreal spring (MAM: March–May), June, July, August, and boreal autumn (SON: September–November). June, July, and August were treated as individual monthly units rather than aggregated into a single summer season, following the approach of Perkins and Alexander [22], which preserves intra-summer variability in anomaly detection. Together, these seasons contribute 275 days per year. The degree to which cloud cover and QC masking affect data availability across seasons and years is illustrated in Figure 2, which shows the mean percentage of missing land-surface pixels per season for each study year. As expected, summer months (Jun–Aug) consistently exhibit the lowest missing-data fractions over Italy, confirming their suitability as the primary period for heatwave analysis.

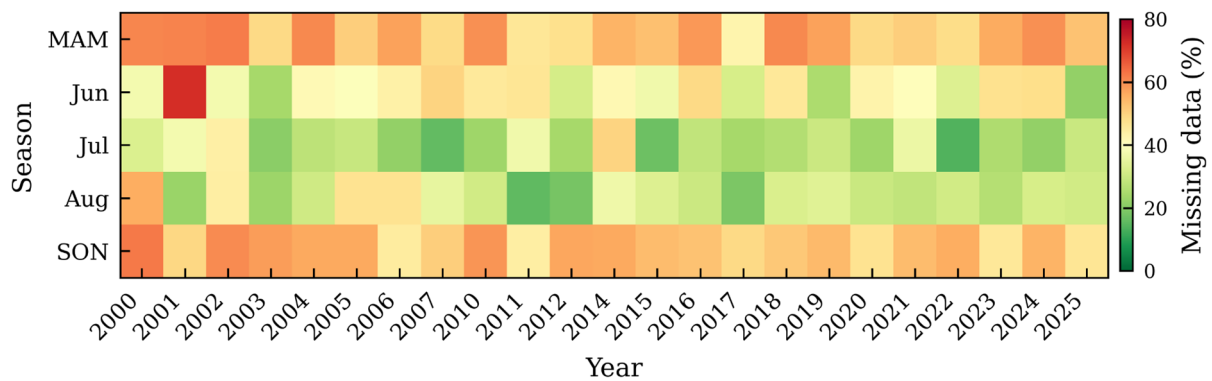


Figure 2. Mean percentage of missing land-surface pixels (LST band) per season per year over Italy (2000–2025). Green indicates low cloud cover; red indicates high cloud cover. Years 2008, 2009, and 2013 are excluded.

2.2. Methodology

LST quality control and preprocessing. Raw LST digital numbers were converted to Kelvin using the documented scale factor of 0.02. Each daily image was subjected to a two-stage quality mask prior to use. Bits 0–1 of the QC_Day bands were evaluated: pixels flagged as cloud-contaminated (value 10) or otherwise not produced (value 11) were discarded, while pixels classified as good quality (00) or acceptable quality (01) were retained. A physical range filter then removed any pixel outside 200–350 K to eliminate residual fill values and detector artifacts.

RST anomaly index. Anomalous thermal conditions were quantified using the Robust Satellite Technique (RST), originally proposed by Tramutoli [23] and subsequently formalized for hazard monitoring applications [24]. RST expresses each observation as a standardized departure from a location- and time-specific reference distribution. The Ω_{SAT} anomaly index for pixel location (x, y) on calendar day t is

$$\Omega_{\text{SAT}}(x, y, t) = \frac{\text{LST}(x, y, t) - \mu(x, y, t)}{\sigma(x, y, t)}$$

where μ and σ are the pixel-wise long-term mean and standard deviation of LST over the reference period, x, y, t are coordinate arguments specifying where the calculation is taking place. Ω_{SAT} is dimensionless and interpretable as a z-score: values exceeding +2 indicate a moderate positive anomaly, +2.5 a strong anomaly, and +3 an extreme anomaly relative to the local climatological background.

Baseline climatology. A leave-one-out design was adopted: for study year Y , the reference pool includes all years in the record except Y itself and the three seismically contaminated years, yielding a consistent baseline of 22 years for every study year. For each target calendar day, the reference pool was extended to include all cloud-free MODIS observations within a symmetric ± 7 -day window, the standard interval recommended by Tramutoli [24] and applied in recent RST validations [25]. For summer months over Italian land surfaces, this yields approximately 100–200 valid observations per pixel per baseline day—well above the minimum of 30 required for robust z-score estimation [25]. Pixel-wise μ and σ were computed using a combined GEE reducer applied to the pooled baseline image collection. A regularization constant $\varepsilon = 0.1$ K was added to σ to prevent division by zero in pixels with negligible thermal variability. Pixels with fewer than ten valid baseline observations were subsequently masked as statistically unreliable.

Heat wave detection. A heat wave event was defined as any period satisfying three simultaneous criteria considered in tandem with Perkins and Alexander [22] and Fischer and Schär [3]: Firstly, $\Omega_{\text{SAT}} \geq 2.0$ at each pixel on each qualifying day; secondly, the intensity criterion must hold for at least three consecutive days; and thirdly at least 10% of valid Italian land pixels must simultaneously satisfy first and second criterion. The three-day duration threshold is the standard minimum for a regional heat wave [22], while the 10% spatial extent criterion distinguishes regional events—affecting roughly 30,000 km² or more—from localized anomalies confined to a single climate zone or topographic setting, consistent with the spatial framing of Fischer and Schär [3].

Trend analysis. Long-term trends in seasonal mean Ω_{SAT} and annual heat wave frequency were assessed using the non-parametric Mann–Kendall test at the $\alpha = 0.05$ significance level, with trend magnitudes estimated by the Theil–Sen slope estimator [26], which is robust to outliers and non-Gaussian distributions. Pixel-wise Sen slopes were computed independently across all land pixels to produce spatial maps of Ω_{SAT} trend magnitude, with significance assessed via Kendall τ correlation.

3. Results

3.1. Validation of RST Heatwave Detection Using Known Heatwave Events

The RST Ω_{SAT} anomaly field was evaluated against three well-documented Italian heat wave events to assess the physical consistency of the detection framework. On 11 August 2003 (Figure 3a), 33.9% of valid Italian land pixels record $\Omega_{SAT} \geq 2.0$, with strong positive anomalies concentrated over the Po Valley, Apennine foothills, and Tyrrhenian coast, consistent with the geographic footprint of the 2003 European blocking anticyclone that caused approximately 20,000 excess deaths in Italy alone [27,28]. On 3 August 2017 (Figure 3b), 21.8% of pixels exceeded $\Omega_{SAT} \geq 2.0$, with the warm signal concentrated across central and southern Italy and a localized negative anomaly over the northern Po Valley attributable to convective cloud cover on that day, accurately reflecting the southward center of action of the Lucifer anticyclone prior to its northward propagation into the following days [28]. On 12 August 2021 (Figure 3c), 12.1% of pixels exceeded the threshold, marginally above the 10% spatial criterion adopted in this study, despite the event coinciding with the WMO-confirmed European all-time temperature record of 48.8 °C recorded near Floridia, Sicily, on 11 August [29,30]. The comparatively subdued Ω_{SAT} magnitude on this date is physically consistent with the leave-one-out baseline design, in which the reference climatology for 2021 is constructed from the full 2000 to 2025 record and therefore incorporates progressively warmer summers, compressing standardized anomaly magnitudes relative to what a fixed historical baseline would produce, a known property of RST applications under conditions of secular warming [25]. This confirms that the RST framework reliably detects well-documented heat wave events across a 26-year record, with detection strength broadly proportional to event intensity and spatial extent, and with baseline behavior that remains physically interpretable and scientifically consistent throughout the study period.

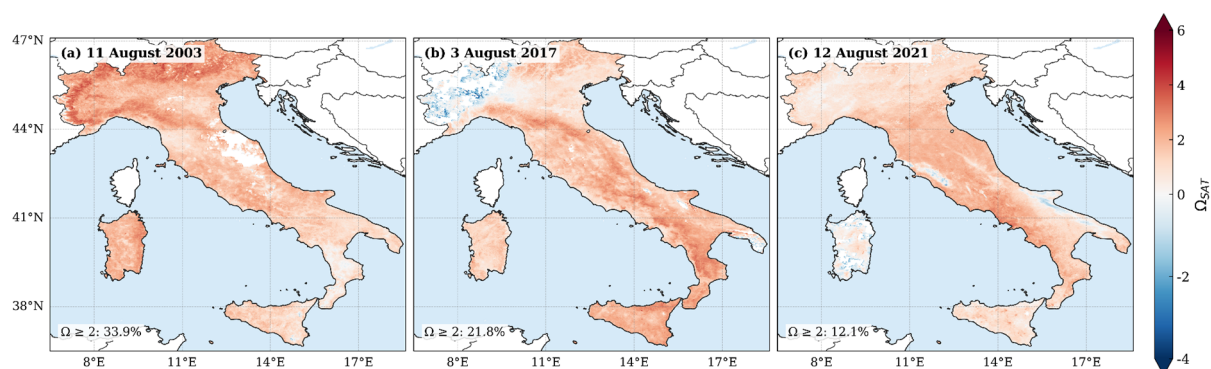


Figure 3. Spatial distribution of the RST anomaly index (Ω_{SAT}) over Italy on peak days of three documented heat wave events: (a) 11 August 2003, (b) 3 August 2017, and (c) 12 August 2021. The percentage of valid land pixels with $\Omega_{SAT} \geq 2.0$ is shown in the lower left of each panel.

3.2. Heatwave Frequency (HWF)

Figure 4 shows the cumulative count of days per pixel belonging to qualifying heat wave events over 2000–2025, where each counted day must form part of an episode satisfying all three detection criteria: $\Omega_{SAT} \geq 2.0$, at least three consecutive qualifying days, and simultaneous exceedance over 10% of Italian land pixels. The highest counts, reaching up to 20 days, are concentrated across the Po Valley, southern Alpine foothills, and the Adriatic coastal corridor from Emilia-Romagna through Puglia, indicating that these regions were most frequently and persistently embedded within large-scale heat wave episodes over the study period. Central Italy shows intermediate accumulations, while Sardinia, Sicily, and the southern interior record the lowest values, reflecting heat anomalies that, despite high absolute temperatures, are less spatially coherent and less sustained over consecutive days relative to the RST local baseline.

Figure 5 summarizes the annual heat wave statistics detected by the RST framework over Italy from 2000 to 2025. Between one and three events were detected per active year, with 2012 recording the highest count of three events and the greatest total heat wave duration of ten days, followed by 2003, 2011, 2024, and 2025, which each recorded seven or more total heat wave days. The maximum spatial extent, shown in Figure 5c, exceeds 40% of Italian land pixels in 2001, 2012, and 2017, indicating that the most spatially extensive events in those years affected nearly half the country simultaneously, well above the 10% classification threshold. Notably, several years, including 2004, 2007, 2008, 2009, 2013, 2018, 2019, and 2022, record no detected events, reflecting either the absence of qualifying anomalies or years excluded from the analysis due to seismic contamination, while the

clustering of active years around 2003, 2011 to 2012, 2015 to 2017, and 2023 to 2025 is broadly consistent with documented periods of anomalous heat stress across the Mediterranean.

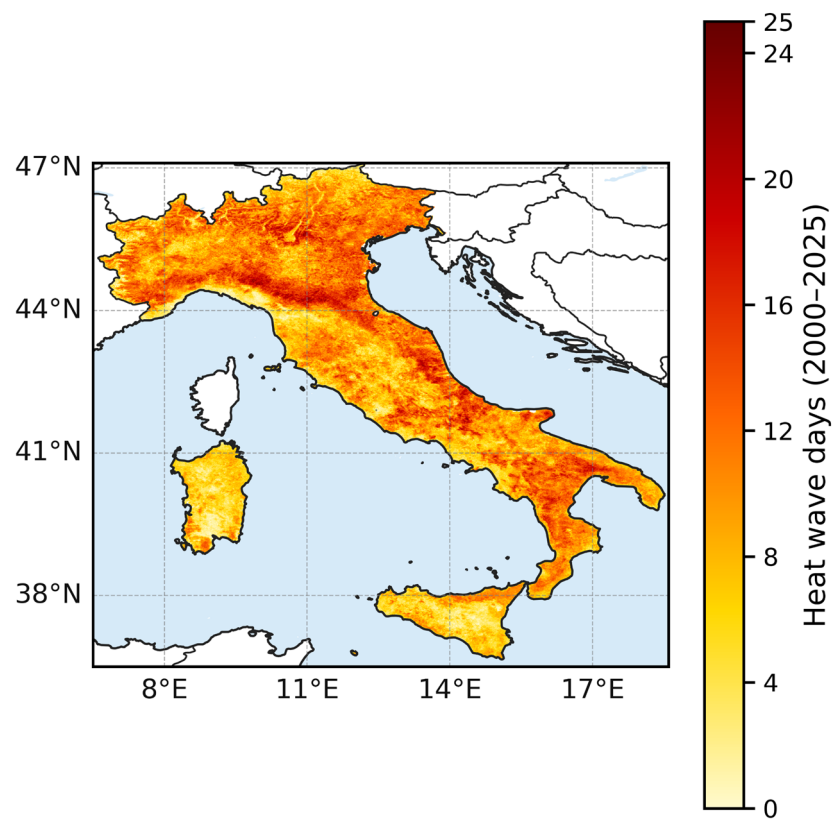


Figure 4. Per-pixel cumulative heat wave day frequency over Italy (2000–2025).

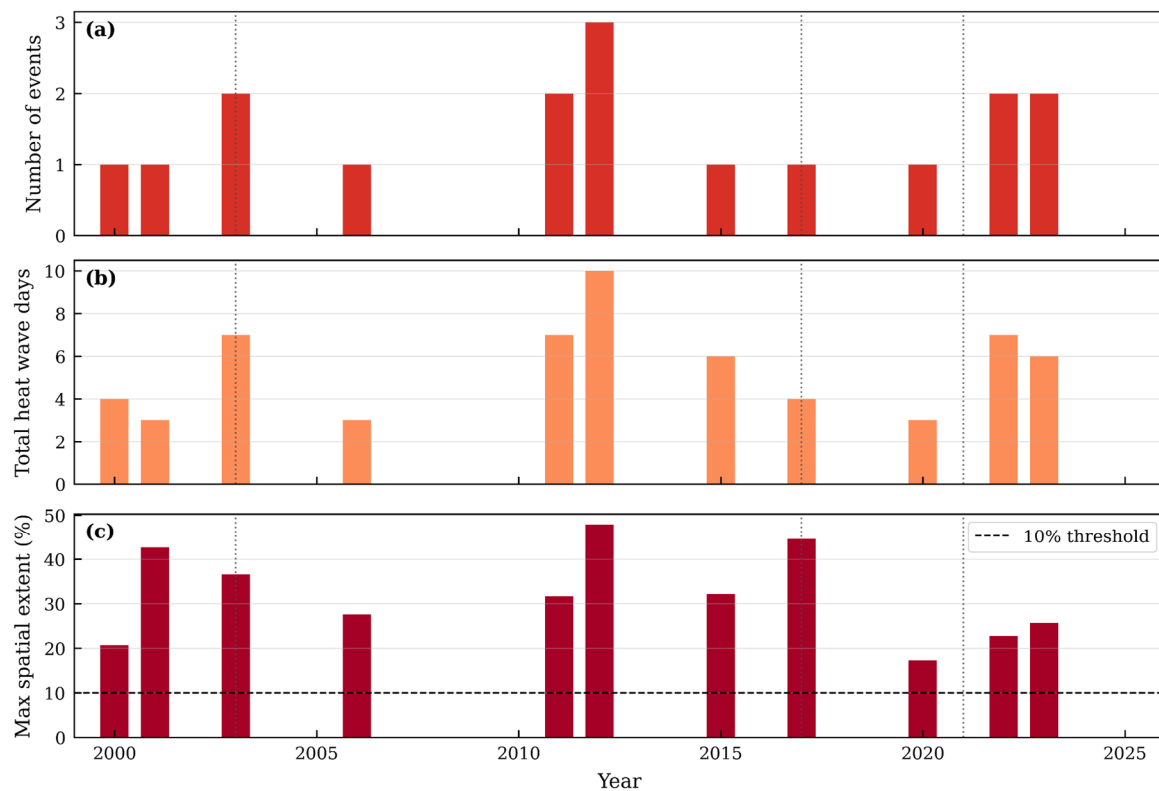


Figure 5. Annual heat wave statistics for Italy (2000–2025): (a) number of detected events per year, (b) total heat wave days per year, and (c) maximum spatial extent of the most spatially extensive event in each year. Dotted vertical lines mark the known heat wave years of 2003, 2017, and 2021. The dashed horizontal line in (c) indicates the 10% spatial extent threshold required for event classification.

Figure 6 presents the spatial distribution of Ω_{SAT} on the peak day of the five most spatially extensive heat wave events detected over Italy during 2000–2025, ranked by the percentage of land pixels simultaneously exceeding $\Omega_{SAT} \geq 2.0$. The most extensive event occurred in September 2012 (Figure 6a), affecting 48% of Italian land pixels on its peak day, with anomalies concentrated over southern Italy, Puglia, and Sicily, reflecting a late-season heat episode driven by warm air advection from North Africa into the central Mediterranean. The August 2017 Lucifer event (Figure 6b) ranks second with 45% coverage, showing broadly distributed warm anomalies across central and southern Italy, with the signal weakest in the northern Alps, where convective activity disrupted the surface heat signal. The March 2001 event (Figure 6c) is notably the only spring episode in the top five, with 43% coverage concentrated over central and southern Italy, indicating that anomalous warmth in early spring can produce spatially coherent RST signals comparable in extent to the most intense summer episodes. The May 2003 event (Figure 6d) precedes the catastrophic August 2003 heat wave by three months and covers 37% of Italian land pixels, suggesting that 2003 was anomalously warm across multiple seasons. The August 2003 event itself (Figure 6e) ranks fifth with 35% coverage, consistent with the broader validation result in Figure 3a, and shows the characteristic northern bias of the 2003 blocking anticyclone with the strongest anomalies over the Po Valley and Apennine foothills. The five events illustrate that the most spatially extensive RST-detected heat waves in Italy are not confined to summer and reflect a diversity of synoptic forcing mechanisms operating across the seasonal cycle.

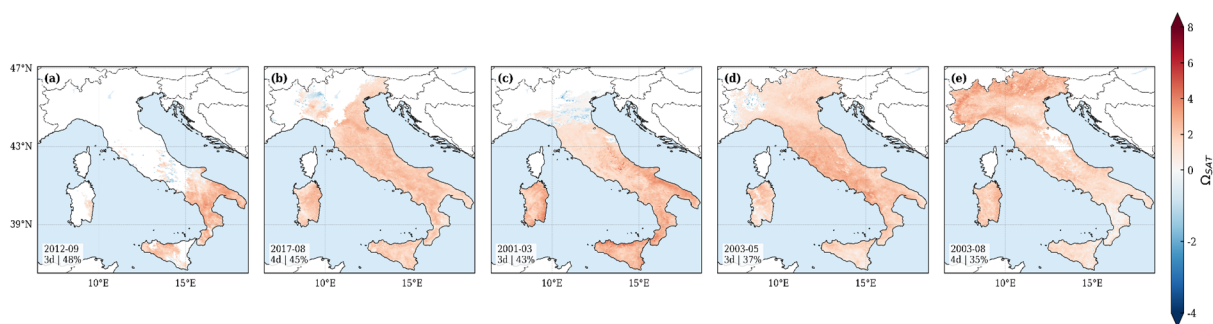


Figure 6. Ω_{SAT} anomaly maps on the peak day of the five most spatially extensive heat wave events detected over Italy (2000–2025), ranked by maximum spatial extent: (a) September 2012 (3-day duration, 48% spatial extent), (b) August 2017 (4 days, 45%), (c) March 2001 (3 days, 43%), (d) May 2003 (3 days, 37%), and (e) August 2003 (5 days, 35%). Panel annotations indicate the event year-month, duration in days, and peak spatial extent as a percentage of valid land pixels.

Figure 7 shows the time series of Italy-wide seasonal mean Ω_{SAT} from 2000 to 2025, assessed for monotonic trends using the Mann–Kendall test with trend magnitudes estimated by the Theil–Sen slope estimator. None of the five seasons exhibits a statistically significant trend over the study period, with p -values ranging from 0.113 in MAM to 0.751 in August, indicating that no season shows a detectable systematic shift in Italy-wide mean thermal anomaly at the 5% significance level. MAM and June show weak negative Sen slopes of -0.0125 and -0.0087 Ω_{SAT} year^{-1} , respectively, reflecting a slight tendency toward cooler spring and early summer anomalies relative to the leave-one-out baseline, while July, August, and SON show weak positive slopes ranging from $+0.0058$ to $+0.0098$ Ω_{SAT} year^{-1} , suggesting a marginal late-season warming tendency that nonetheless remains statistically indistinguishable from noise. The high interannual variability evident in all panels, with alternating positive and negative anomalies of comparable magnitude throughout the record, suppresses trend detectability over the 23-year effective sample. The known heat wave years of 2003, 2017, and 2021 do not consistently emerge as outliers across all seasons, confirming that the RST leave-one-out baseline effectively normalizes the anomaly relative to the evolving climatology and that individual extreme years contribute to but do not dominate the seasonal mean signal.

Figure 8 presents the spatial distribution of the Theil–Sen slope of July mean Ω_{SAT} computed independently for each land pixel across the 2000–2025 record, revealing considerable spatial heterogeneity in the direction and magnitude of thermal anomaly trends that is obscured in the Italy-wide seasonal mean shown in Figure 7c. Figure 8a shows that warming trends dominate the northern half of the country, with the strongest positive slopes exceeding $+0.03$ to $+0.04$ Ω_{SAT} year^{-1} concentrated along the eastern Po Valley, the Friuli–Venezia Giulia plain, and the pre-Alpine foothills bordering Austria and Slovenia. This northern signal is consistent with documented amplified warming over the Po Basin driven by reduced soil moisture feedback and urban heat island intensification in one of Europe’s most densely industrialized lowlands. Central Italy and the Tyrrhenian corridor show a more mixed pattern of weakly positive and weakly negative slopes, while southern Italy, Calabria, and

Sicily display predominantly negative trends, suggesting that July thermal anomalies relative to the local RST baseline have not intensified in the far south over this period, possibly reflecting a combination of increased cloud cover variability and the baseline compression effect discussed for 2021. Figure 8b retains only pixels where the trend is statistically significant at the 5% level and shows that only 8.0% of Italian land pixels meet this criterion, all concentrated in the northeastern Po Valley and pre-Alpine zone for warming and in scattered coastal areas of Puglia and Sicily for cooling. The spatially confined nature of statistically significant trends confirms the Figure 8 result that no Italy-wide July trend is detectable while simultaneously identifying the northeastern Po Valley as the sub-regional hotspot of emerging and statistically robust July thermal anomaly intensification within the study period.

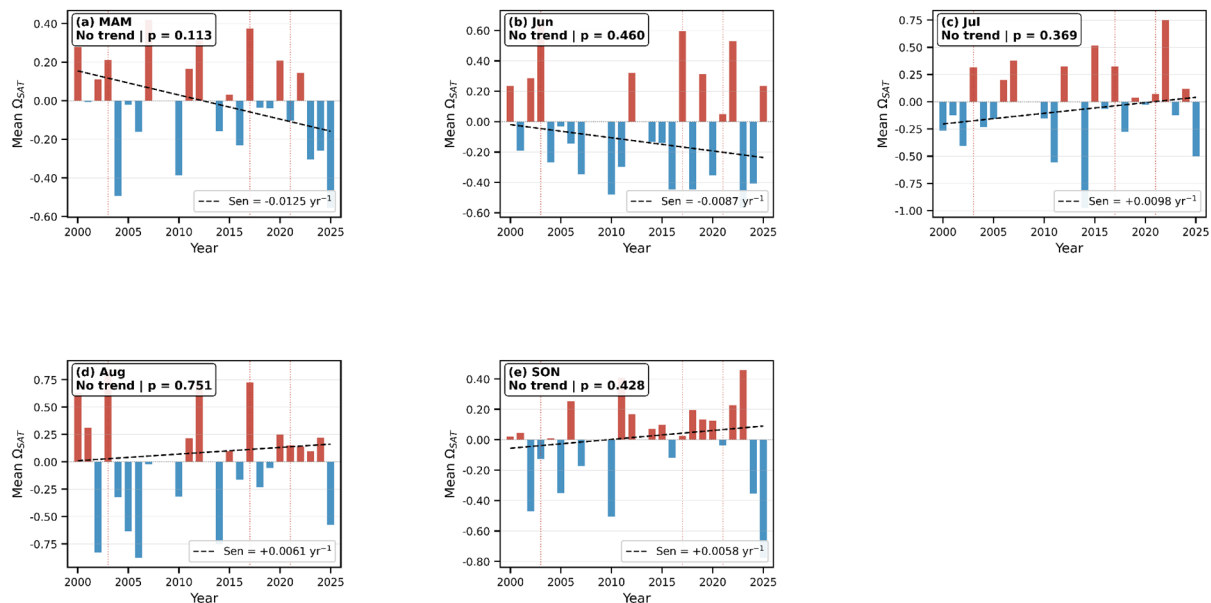


Figure 7. Annual mean Ω_{SAT} anomaly per season over Italy (2000–2025). Red bars indicate positive anomalies (warmer than baseline), and blue bars indicate negative anomalies (cooler than baseline). The dashed black line shows the Theil–Sen slope, and red dotted vertical lines mark the known heat wave years of 2003, 2017, and 2021. Mann–Kendall trend test results and Sen slope magnitudes are shown in each panel.

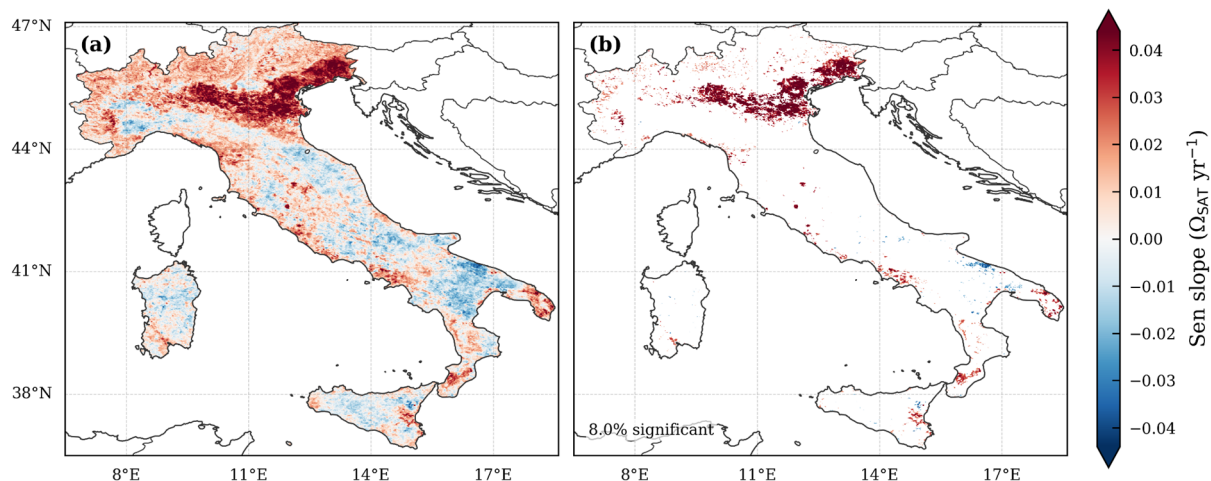


Figure 8. Pixel-wise Theil–Sen slope of July mean Ω_{SAT} over Italy (2000–2025): (a) all land pixels and (b) statistically significant pixels only ($p \leq 0.05$, Kendall τ test). Red indicates an increasing anomaly (warming trend), and blue indicates a decreasing anomaly (cooling trend).

4. Discussion

4.1. Synoptic Drivers and Mediterranean Climatological Context

The spatial and temporal patterns of thermal anomalies identified across Italy between 2000 and 2025 demonstrate the strong influence of Mediterranean-scale atmospheric circulation dynamics. To our understanding, major extreme heat events captured by the Robust Satellite Technique (RST), notably those of August 2003,

August 2017, and August 2021, were primarily driven by persistent subtropical anticyclonic ridges originating over North Africa and extending across the central Mediterranean Basin, as seen in [31,32]. These high-pressure systems induce intense atmospheric subsidence, upper-level ridge formation, and clear-sky conditions that maximize solar irradiance and radiative surface heating.

Results reveal that the spatial footprint of these events varies according to the trajectory and stability of the synoptic ridge. For instance, during the August 2003 event (Figure 3a), persistent omega-blocking displaced the core of the anomaly northward over the Po Valley and northern Apennine foothills. In contrast, events like the 2017 “Lucifer” heatwave (Figure 3b) exhibited a central-southern bias before propagating northward. This observed synoptic forcing was seen to interact directly with the complex topography of the Italian peninsula, where low-elevation interior basins experience rapid thermal buildup compared to surrounding mountainous terrain. These observed atmospheric processes align with recent investigations into urban microclimatic vulnerability and satellite-derived land surface temperature dynamics under Mediterranean climate regimes [33,34].

4.2. Spatial Heterogeneity and the Po Valley Hotspot

Although there was no Italy-wide seasonal anomaly meaning showing a statistically significant trend overall, as seen in our result (Figure 7), pixel-wise Sen slope analysis reveals critical sub-regional thermal trends. The most notable finding is the statistically significant July warming trend localized across 8.0% of Italian land pixels, concentrated heavily within the northeastern Po Valley and the adjacent pre-Alpine foothills (Figure 8).

This localized intensification ($\text{Sen slope} > +0.03 \Omega_{\text{SAT}} \text{ year}^{-1}$) reflects the distinct surface physical properties and low elevation of the Po Basin. As a flat, low-lying lowland bounded by the Alps and Apennines, the Po Valley experiences rapid daytime surface heating under clear-sky summer conditions. During prolonged high-temperature anomalies, the land surface undergoes enhanced sensible heat fluxes, amplifying satellite-retrieved daytime LST relative to the regional background. When combined with extensive urban and industrial surfaces across major metropolitan corridors (e.g., Milan, Venice, and Bologna), daytime LST values experience marked amplification relative to the local climatological background [35]. Conversely, southern regions (Calabria, Sicily) display stable or slightly negative trends relative to the local baseline (Figure 8a), reflecting both high interannual variability in convective cloud cover and baseline normalization dynamics.

4.3. Methodological Performance of RST and Baseline Dynamics

The RST framework (Ω_{SAT} index) proved highly effective at suppressing background noise and isolating statistically significant surface thermal anomalies, as also noted in [14]. By utilizing a leave-one-out baseline design with a ± 7 day temporal window, the methodology accounts for local microclimates and seasonal transitions without fixed climatological biases. Excluding seismically active years (2008, 2009, 2013) successfully prevented pre-seismic land surface thermal anomalies from artificially inflating the reference mean (μ) and standard deviation (σ), thereby preserving the sensitivity of the index to purely atmospheric heat stress.

However, the leave-one-out approach over a 26-year record undergoing secular climate warming introduces a “baseline compression” phenomenon. As recent summers (e.g., 2021–2025) become progressively warmer, the long-term baseline reference incorporates higher thermal values. Consequently, standardized z-scores (Ω_{SAT}) during recent extreme thermal events appear moderately lower than they would against a historical, fixed baseline (e.g., 1981–2010). This physical property explains why highly extreme absolute surface temperatures—such as the August 2021 Sicilian heatwave (Figure 3c)—yielded lower spatial anomaly percentages ($\Omega_{\text{SAT}} \geq 2.0$ over 12.1% of land pixels) compared to earlier historical benchmarks like August 2003 (33.9%). Understanding this baseline behavior is crucial when interpreting multi-decadal satellite anomaly time series under ongoing warming.

4.4. Study Limitations and Future Directions

Several limitations inherent to satellite remote sensing should be noted. First, MODIS Terra daytime LST retrievals are limited to cloud-free observations. Although cloud contamination is minimal during Italian summer months (Figure 2), convective cloud formation during heatwave decay phases can cause localized missing data. Second, land surface temperature (LST) responds directly to radiative surface energy balances and differs from near-surface air temperature (T_a , 2 m) recorded by meteorological networks. While satellite remote sensing provides high spatial coverage as demonstrated in this study, future research that does not explicitly utilize satellite observations should instead integrate ERA5-Land reanalysis or dense weather station networks to assess surface thermal stress and human comfort.

5. Conclusions

This study presented a high-resolution satellite assessment of extreme thermal events across Italy using a 26-year record (2000–2025) of MODIS Terra daytime Land Surface Temperature (LST) data. By implementing the Robust Satellite Technique (RST) with a leave-one-out baseline reference and strict quality-control bit-masking, the methodology effectively isolated surface heat anomalies while filtering out seismic contamination years (2008, 2009, 2013) that would otherwise skew baseline statistics. Deploying multi-criteria event thresholds ($\Omega_{\text{SAT}} \geq 2.0$, ≥ 3 -day duration, and $\geq 10\%$ national spatial extent) successfully captured iconic Mediterranean heatwaves, including August 2003, August 2017, and August 2021. The spatial cumulative frequency of these thermal anomalies was predominantly concentrated over low-elevation interior lowlands, particularly the Po Valley, the southern Alpine foothills, and coastal corridors along the Adriatic Sea.

Multi-temporal anomaly evaluations revealed that localized thermal anomaly intensification was heavily concentrated in the northeastern Po Valley—a region characterized by low elevation and dense anthropogenic land cover. Furthermore, the leave-one-out baseline design demonstrated how ongoing climate warming elevates the long-term reference mean (μ), leading to baseline compression. Under this relative normalization, recent extreme events exhibit lower standardized z-scores (Ω_{SAT}) relative to earlier historical benchmarks, underscoring the importance of contextualizing anomaly indices against evolving climatological baselines.

Overall, the RST framework proves to be a robust tool for mapping multi-decadal land surface heat dynamics across complex topography. While satellite observations excel at fine-scale spatial hazard mapping, future research where satellite remote sensing is not employed should integrate ERA5-Land reanalysis or dense weather station networks to evaluate near-surface air temperatures and human thermal comfort. The high-resolution hazard maps produced in this study provide essential observational evidence to inform targeted climate adaptation, urban planning, and heat vulnerability mitigation across heterogeneous Mediterranean environments.

Author Contributions

M.B.L.: Conceptualization, investigation, methodology, validation, visualization, writing—original draft, writing—review & editing; D.A.: Data acquisition and analysis, investigation, methodology, validation, visualization, writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite data utilized in this study are publicly available via NASA's Earthdata Search (<https://search.earthdata.nasa.gov/>, accessed on 9 January 2026).

Acknowledgments

D.A. would like to thank the Earth and Planetary Science Department at Johns Hopkins University for providing the computational resources used for the analysis done in this study during a summer internship with them in the summer of 2025. M.B.L. would like to thank the Earth Observations from Space: advanced technologies and applications (EO-SAT) programme, University of Basilicata, Italy, for the opportunity to be part of this initiative and for the resources and guidance provided to enhance the quality and impact of this research.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Russo, S.; Sillmann, J.; Fischer, E.M. Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environ. Res. Lett.* **2015**, *10*, 124003. <https://doi.org/10.1088/1748-9326/10/12/124003>.
2. Kovats, R.S.; Hajat, S. Heat stress and public health: A critical review. *Annu. Rev. Public Health* **2008**, *29*, 41–55. <https://doi.org/10.1146/annurev.publhealth.29.020907.090843>.
3. Fischer, E.M.; Schär, C. Consistent geographical patterns of changes in high-impact European heatwaves. *Nat. Geosci.* **2010**, *3*, 398–403. <https://doi.org/10.1038/ngeo866>.
4. Lionello, P.; Abrantes, F.; Gacic, M.; et al. The climate of the Mediterranean region: research progress and climate change impacts. *Reg. Environ. Change* **2014**, *14*, 1679–1684. <https://doi.org/10.1007/s10113-014-0666-0>.
5. Toreti, A.; Xoplaki, E.; Maraun, D.; et al. Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 1037–1050. <https://doi.org/10.5194/nhess-10-1037-2010>.
6. Abunywah, M.; Gajendran, T.; Erdiaw-Kwasie, M.O.; et al. The multidimensional impacts of heatwaves on human ecosystems: A systematic literature review and future research direction. *Environ. Sci. Policy* **2025**, *165*, 104024. <https://doi.org/10.1016/j.envsci.2025.104024>.
7. Lateef, M.B.; Elegba, O.G.; Adegoke, M.O.; et al. *Remote Sensing of Extreme Heat Events in Nigeria: A Multi-Index Study*; Springer Nature: Cham, Switzerland, 2026; pp. 169–192. https://doi.org/10.1007/978-3-032-11678-9_8.
8. Saber, A.; De Luca, C.; Pourzangbar, A.; et al. Heat wave risk assessment in Bologna using Spatio-temporal artificial intelligence: Leveraging LSTM enhanced by the hippopotamus optimization algorithm. *Sustain. Cities Soc.* **2025**, *131*, 106671. <https://doi.org/10.1016/j.scs.2025.106671>.
9. Beniston, M.; Stephenson, D.B.; Christensen, O.B.; et al. Future extreme events in European climate: An exploration of regional climate model projections. *Clim. Chang.* **2007**, *81*, 71–95. <https://doi.org/10.1007/s10584-006-9226-z>.
10. Lateef, M.B.; Ayanlade, O.S.; Adejebi, A.O.; et al. Machine learning-based projections of earth skin temperature anomalies in Nigeria using ERA5-land data. *Clim. Interact.* **2026**, *2*, 2624855. <https://doi.org/10.1080/29966876.2026.2624855>.
11. Wan, Z.; Zhang, Y.; Zhang, Q.; et al. Quality assessment and validation of the MODIS global land surface temperature. *Int. J. Remote Sens.* **2004**, *25*, 261–274. <https://doi.org/10.1080/0143116031000116417>.
12. Tramutoli, V.; Aliano, C.; Corrado, R.; et al. On the possible origin of thermal infrared radiation (TIR) anomalies in earthquake-prone areas observed using robust satellite techniques (RST). *Chem. Geol.* **2013**, *339*, 157–168. <https://doi.org/10.1016/j.chemgeo.2012.10.042>.
13. Tramutoli, V.; Corrado, R.; Filizzola, C.; et al. From visual comparison to robust satellite techniques: 30 years of thermal infrared satellite data analyses for the study of earthquake preparation phases. *Boll. Geofis. Teor. Appl.* **2015**, *56*, 167–202. <https://doi.org/10.4430/bgta0149>.
14. Tramutoli, V.; Di Bello, G.; Pergola, N.; et al. Robust satellite techniques for remote sensing of seismically active areas. *Ann. Geophys.* **2001**, *44*, 295–312. <https://doi.org/10.4401/ag-3596>.
15. Genzano, N.; Aliano, C.; Corrado, R.; et al. RST analysis of MSG-SEVIRI TIR radiances at the time of the Abruzzo 6 April 2009 earthquake. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 2073–2084. <https://doi.org/10.5194/nhess-9-2073-2009>.
16. Tramutoli, V.; Marchese, F.; Falconieri, A.; et al. Tropospheric and ionospheric anomalies induced by volcanic and saharan dust events as part of geosphere interaction phenomena. *Geosciences* **2019**, *9*, 177. <https://doi.org/10.3390/geosciences9040177>.
17. Peleli, S.; Kouli, M.; Vallianatos, F. Satellite-observed thermal anomalies and deformation patterns associated to the 2021, central crete seismic sequence. *Remote Sens.* **2022**, *14*, 3413. <https://doi.org/10.3390/rs14143413>.
18. Lacava, T.; Ciancia, E.; Coviello, I.; et al. A modis-based Robust Satellite Technique (RST) for timely detection of oil spilled areas. *Remote Sens.* **2017**, *9*, 128. <https://doi.org/10.3390/rs9020128>.
19. Zhang, Y.; Zhu, K.; Marchetti, D.; et al. Carbon monoxide anomalies for the 2013 Mw =6.7 lushan earthquake using MSSA-RST approach. *IEEE Trans. Geosci. Remote Sens.* **2024**, *62*, 4112420. <https://doi.org/10.1109/tgrs.2024.3492254>.
20. Wan, Z.; Hook, S.; Hulley, G. MODIS/Terra Land Surface Temperature/Emissivity Daily L3 Global 1 km SIN Grid V006. NASA Earthdata. Available online: <https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod11a1-006> (accessed on 20 July 2026).
21. Gorelick, N.; Hancher, M.; Dixon, M.; et al. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **2017**, *202*, 18–27. <https://doi.org/10.1016/j.rse.2017.06.031>.
22. Perkins, S.E.; Alexander, L.V. On the measurement of heat waves. *J. Clim.* **2013**, *26*, 4500–4517. <https://doi.org/10.1175/jcli-d-12-00383.1>.

23. Tramutoli, V. Robust AVHRR techniques (RAT) for environmental monitoring: theory and applications. In Proceedings of the Earth Surface Remote Sensing II, Barcelona, Spain, 21–24 September 1998; Volume 3496, pp. 101–113. <https://doi.org/10.1117/12.332714>.
24. Tramutoli, V. Robust Satellite Techniques (RST) for natural and environmental hazards monitoring and mitigation: Theory and applications. In Proceedings of the 2007 International Workshop on the Analysis of Multi-temporal Remote Sensing Images, Leuven, Belgium, 18–20 July 2007; pp. 1–6. <https://doi.org/10.1109/multitemp.2007.4293057>.
25. Filizzola, C.; Corrado, A.; Genzano, N.; et al. RST analysis of anomalous TIR sequences in relation with earthquakes occurred in Turkey in the period 2004–2015. *Remote Sens.* **2022**, *14*, 381. <https://doi.org/10.3390/rs14020381>.
26. Sen, P.K. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>.
27. Conti, S.; Meli, P.; Minelli, G.; et al. Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. *Environ. Res.* **2005**, *98*, 390–399. <https://doi.org/10.1016/j.envres.2004.10.009>.
28. Fink, A.H.; Brücher, T.; Krüger, A.; et al. The 2003 European summer heatwaves and drought—synoptic diagnosis and impacts. *Weather* **2004**, *59*, 209–216. <https://doi.org/10.1256/wea.73.04>.
29. *BREAKING NEWS* Italy Set a New European Heat Record as Siracusa, Sicily Peaks at +48.8 °C Today. Intense Heatwave Now Heads for Spain and Portugal This Weekend. Available online: <https://www.severe-weather.eu/europe-weather/record-heatwave-mediterranean-italy-spain-portugal-mk/> (accessed on 20 July 2026).
30. Sicily Records Europe's 'Highest Ever' Temperature as Fires Rage. Available online: <https://www.aljazeera.com/news/2021/8/12/italy-fires-spread-as-authorities-warn-of-record-temperatures> (accessed on 20 July 2026).
31. Almazroui, M.; Awad, A.M. Synoptic regimes associated with the eastern Mediterranean wet season cyclone tracks. *Atmos. Res.* **2016**, *180*, 92–118. <https://doi.org/10.1016/j.atmosres.2016.05.015>.
32. Samman, A.E. Synoptic and Dynamic Analyses of an Intense Mediterranean Cyclone: A Case Study. *Climate* **2025**, *13*, 126. <https://doi.org/10.3390/cli13060126>.
33. Cureau, R.J.; Balocco, C.; Pigliautile, I.; et al. On urban microclimate spatial-temporal dynamics: Evidence from the integration of fixed and wearable sensing and mapping techniques. *Environ. Res.* **2024**, *262*, 119795. <https://doi.org/10.1016/j.envres.2024.119795>.
34. Reiners, P.; Sobrino, J.; Kuenzer, C. Satellite-derived land surface temperature dynamics in the context of global change—A review. *Remote Sens.* **2023**, *15*, 1857. <https://doi.org/10.3390/rs15071857>.
35. Jia, K.; Sheng, Q.; Liu, Y.; et al. A framework for achieving urban sustainable development goals (SDGs): Evaluation and interaction. *Sustain. Cities Soc.* **2024**, *114*, 105780. <https://doi.org/10.1016/j.scs.2024.105780>.