

Article

Territorial Stress Index (TSI): A Spatial Approach to Climate Change in Gran Canaria, Spain and Its Implications for Emergency Management

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Abstract

Climate change does not manifest homogeneously across a territory, especially on oceanic islands where the complexity of the terrain can generate significant climatic gradients over short distances. This study analyzes the spatial evolution of maximum temperature (TMAX) and precipitation in Gran Canaria during the period 1991–2025 and explores its implications for land use planning and emergency management. For this purpose, homogenized monthly series from Spain's State Meteorological Agency (AEMET) were used, analyzed on the basis of a sectorization of the island into seven climatic zones and the use of different statistical procedures for estimating and contrasting trends. Additionally, an exploratory Territorial Stress Index (TSI) was developed to synthesize the relative intensity of thermal and pluviometric change. The results show a generalized and statistically significant warming, although with significant spatial differences, while precipitation exhibits greater heterogeneity and shows no significant trend for the island as a whole. At the climatic zone scale, TMAX trends range between 0.149 and 0.408 °C per decade, while precipitation trends vary both in magnitude and direction. The highest TSI value (90.0) was obtained for the leeward mid-slopes, where intense warming coincides with a reduction in precipitation, creating a warming–drying scenario. Other areas with relatively high values exhibit warming–wetting configurations, indicating that climate stress does not follow a single territorial trajectory. The TSI does not constitute a risk index but facilitates the identification of spatial differences in the evolution of climate stressors that can serve as a basis for subsequent assessments incorporating hazard, exposure, vulnerability, and response capacity. These results highlight the importance of incorporating intra-island climate differentiation into adaptation strategies, land use planning, and emergency management.

Keywords: climate change; territorial stress; territorial stress index; emergency management; territorial planning; Gran Canaria



Academic Editor: Srivatsan V. Raghavan

Received: 17 August 2026

Revised: 4 October 2026

Accepted: 14 October 2026

Published: 23 October 2026

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1. Introduction

Recent climate variability and the intensification of extreme phenomena are altering the environmental conditions of numerous territories. The increase in temperatures, the

alteration of precipitation regimes, and the greater recurrence of extreme events are some of the most evident manifestations of climate change observed over the past decades [1]. These changes do not occur homogeneously, but rather exhibit marked spatial and temporal variability, especially in island territories, where the complexity of the terrain, the limited availability of resources, and the high concentration of population and infrastructure increase vulnerability to climate alterations [2,3].

This concern extends to island regions worldwide. Evidence of climate change has been documented across small islands in the Pacific, Indian Ocean, Caribbean, eastern Atlantic, and Mediterranean, although the magnitude and expression of the observed changes differ considerably among regions. In particular, warming constitutes a widespread signal across small-island regions, whereas changes in precipitation tend to show greater spatial and seasonal heterogeneity [4].

Traditionally, climate research has focused much of its efforts on quantifying the magnitude of warming or identifying trends in precipitation, using these variables as the main indicators of climate evolution [1,5]. Although such analyses are essential, on their own they do not fully facilitate an understanding of their territorial implications. In addition to knowing whether temperature and precipitation vary significantly, it is necessary to analyze how these changes are distributed in space, as the intensity of their increase or decrease can vary significantly between nearby territories and generate differentiated environmental conditions [6,7]. This spatial dimension is particularly relevant for territorial planning and emergency management. This circumstance is especially important for risk management, as background climatic conditions influence various environmental processes that determine the preparation, prevention, and territorial allocation of resources [8,9].

An especially relevant example concerns wildfires. The availability and dryness of plant fuel, the duration of the seasons in which the danger is greater, preventive planning, and the activation of certain operational devices are determined by the prevailing meteorological and climatic conditions [10–12]. Therefore, a sustained increase in temperatures, especially when coinciding with a reduction in precipitation, can favor environmental conditions compatible with an increase in water stress, greater vegetation dryness, and contexts that favor the occurrence and spread of fires. However, these climatic conditions do not solely determine the risk as, in addition to factors such as fuel and topography, land use, exposure, and vulnerability must also be taken into account.

The availability of water is also a central element in this process [6,8]. In island territories, where water resources are limited and highly dependent on precipitation, changes in rainfall and temperature patterns can impact urban supply, agriculture, ecosystems, and the adaptive capacity of the territory [1,3,7]. These pressures do not act in isolation, but rather interact with each other, progressively increasing the complexity of territorial management [8,13].

Given the above, these processes can be examined from the perspective of territorial stress, understood here as the spatially differentiated pressure that environmental changes may exert on a territory's resources and functions. This study addresses its climatic dimension by jointly examining the magnitude and direction of maximum temperature and precipitation trends and the spatial patterns emerging from their combination. This working definition draws on conceptual contributions from vulnerability and resilience research. Adger [13] identifies exposure to stress, sensitivity, and adaptive capacity as central dimensions of vulnerability. Turner et al. [14] propose a framework linking environmental disturbances to the sensitivity and resilience of coupled human–environment systems across scales. Cutter et al. [15] introduce the disaster resilience of place (DROP) model to support comparisons of resilience at local and community levels. These contributions provide a basis for interpreting climatic pressures within their territorial context, while

recognizing that climatic trends alone do not establish vulnerability, loss of functional capacity, or observed damage.

Under these considerations, the present research analyzes the trends of maximum temperature and precipitation in Gran Canaria (Canary Islands, Spain) during the period 1991–2025. The choice of this island as a study area is justified by its complex orography, its notable topoclimatic diversity, and the strong territorial differentiation it presents over short distances.

The methodological novelty of this study lies in combining an intra-island analysis of temperature and precipitation trends with the exploratory Territorial Stress Index (TSI). The proposed approach jointly considers the relative intensity and direction of thermal and pluviometric changes, allowing contrasting climatic trajectories, such as warming–drying and warming–wetting configurations, to be distinguished within the same island. This approach therefore provides a spatially differentiated interpretation of climate change that cannot be captured by island-wide aggregated trends alone.

In accordance with this objective, the following research questions are posed: (i) What changes occurred in terms of maximum temperatures and precipitation behavior in Gran Canaria during the period 1991–2025? (ii) To what extent do the magnitude and direction of these changes vary among the different climatic zones and regional units of the island? and (iii) How can the different combinations of thermal and pluviometric trends be interpreted in terms of territorial stress, and what implications might they have for planning and emergency management?

2. Study Area

2.1. Geographical Location

The scope of the study is limited to the island of Gran Canaria, located in the north-eastern Atlantic Ocean, approximately 200 km off the northwest coast of Africa. The island forms part of the Canary archipelago and the Macaronesia region, which includes the Azores, Madeira, and Cape Verde archipelagos (Figure 1). With an area of approximately 1560 km² and a maximum diameter of around 50 km, Gran Canaria constitutes a small island territory characterized by an extraordinary topographical and climatic diversity, resulting from the interaction between its volcanic origin, the complexity of the relief, and the influence of subtropical atmospheric circulation [16].

Gran Canaria occupies a central position in the archipelago and presents significant physiographic complexity, with a rugged terrain that exceeds 1900 m in altitude [16,17]. Most of the population and economic activity is concentrated in the coastal strip, especially in the metropolitan area of Las Palmas de Gran Canaria and in the tourist municipalities in the south of the island [18]. This territorial distribution increases the pressure on natural resources, particularly on water resources, and heightens the exposure of the population and infrastructure to the effects of climate variability and extreme phenomena [3,19].

2.2. Environmental and Climatic Characteristics

The climate of Gran Canaria is conditioned by the interaction between the subtropical atmospheric circulation, the Azores High, the trade winds, and a complex orography of volcanic origin. The seasonal position and intensity of the Azores High play a major role in controlling the atmospheric circulation affecting the Canary Islands and the associated north-easterly trade-wind regime. Figure 2 shows the mean synoptic configuration of the North Atlantic at the annual scale and for January and June, illustrating the seasonal variability of this subtropical high-pressure system. The combination of atmospheric circulation and the complex island topography generates significant topoclimatic diversity

within a territory of small dimensions, favoring important spatial contrasts in temperature, precipitation, and humidity [15,17].

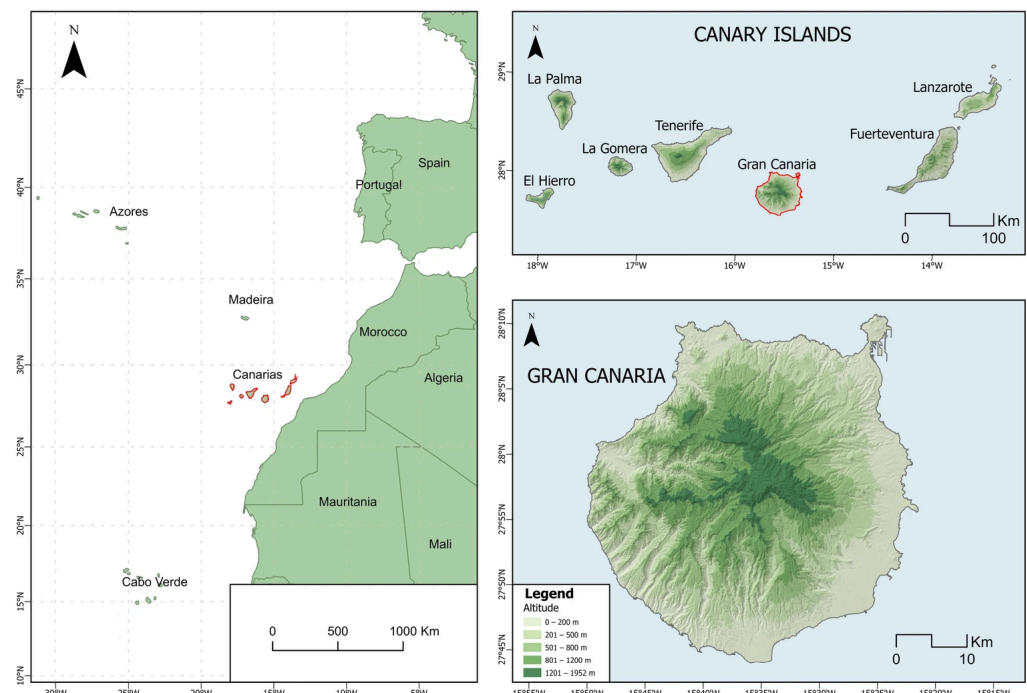


Figure 1. Geographical location of the Canary Islands within Macaronesia. The map also shows the Azores, Madeira, and Cape Verde archipelagos. Source: Own elaboration based on cartographic data from ArcGIS Hub ver. 3.6 (World Countries Generalized) and Grafcan, S.A. (Island and Municipalities).

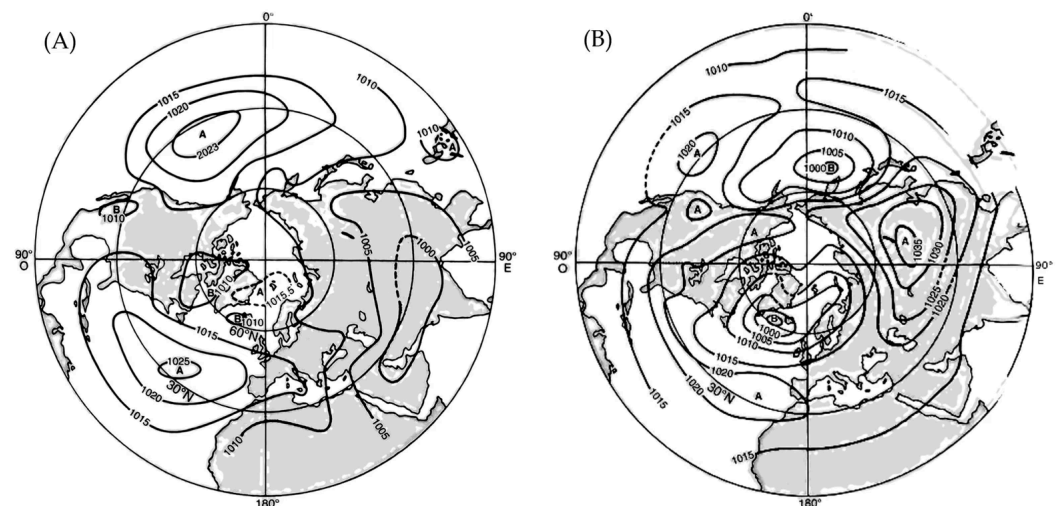


Figure 2. Mean Northern Hemisphere sea-level pressure patterns in (A) January and (B) July, illustrating the seasonal displacement and reorganization of the North Atlantic subtropical high-pressure system [20].

The northern slope, directly exposed to the trade winds, experiences relatively humid conditions associated with orographic cloud formation and the stratocumulus layer known as the “sea of clouds”. Mean annual precipitation reaches 700–800 mm in the north of the island, compared with less than 100 mm on the southern coast of the island, where rain-shadow conditions contribute to a drier environment for much of the year [17,21,22]. Mean annual temperature also varies spatially, ranging from 12.5 °C in the highest sections of the island to 22 °C on the southern coast of the island [22].

This climatic diversity is illustrated in Figure 3, which shows the Köppen climate classification for Gran Canaria [22]. Most of the island is characterized by a hot desert climate (BWh), whose main features are low precipitation, mild winters, and hot summers. This climate type covers 36.0% of the island's surface area and is mainly found in coastal areas and lower-elevation zones exposed to the southern and western sectors. These areas are bordered by hot and cold semi-arid climates (BS), characterized by mild winters and hot to very hot summers. Depending on whether the mean annual temperature is above or below 18 °C, these are classified as BSh, covering 30.0% of the island, or BSk, covering 5.4%. Temperate climates with dry and warm or hot summers (C climates) occur mainly at mid and higher elevations. Within this group, Csa climates, characterized by hot summers with a mean temperature above 22 °C in the warmest month, are found primarily in the mid-elevation areas of the southern, eastern, and northeastern sectors of the island and cover 18.8% of its surface area. In contrast, Csb climates, characterized by cooler summers in which the mean temperature of the warmest month does not exceed 22 °C, account for 9.8% of the island's territory.

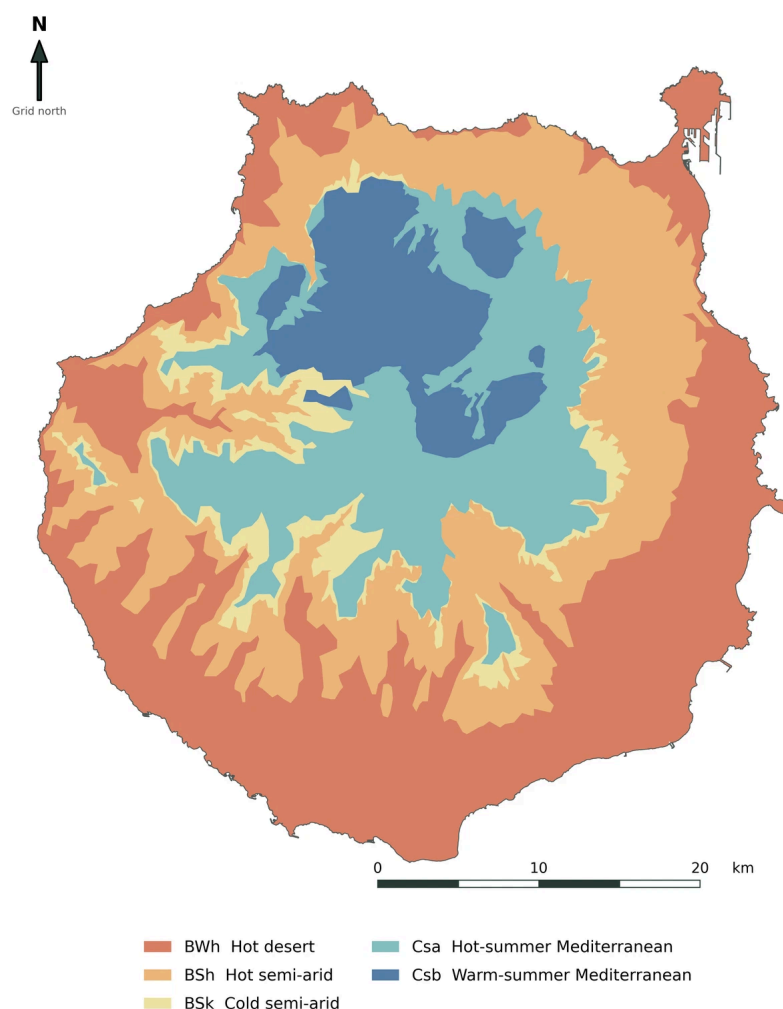


Figure 3. Köppen climate classification of Gran Canaria (1991–2020). Source: authors' cartographic elaboration using the official vector dataset from the Government of the Canary Islands' Climate Atlas (SITCAN Open Data; CC BY 3.0). The atlas methodology is described in Luque et al. [22].

These climatic contrasts directly impact the availability of water resources. The absence of permanent river courses means that the supply fundamentally depends on volcanic aquifers, regulation through dams and reservoirs, and increasingly on unconventional resources such as desalination and the reuse of treated wastewater [19]. Despite the

technological advances that have been developed and implemented, water availability remains closely linked to the evolution of rainfall and temperature.

In recent decades, various studies have documented an increase in the frequency and intensity of extreme heat episodes, along with growing uncertainty about the future evolution of precipitation in the Canary Islands [1,23]. Previous climate research has also documented a clear warming signal, although with marked spatial differences associated with the complex topography of the archipelago. In Gran Canaria, Luque et al. [24] identified a long-term warming trend of approximately 0.09 °C per decade, increasing to 0.17 °C per decade when the analysis was restricted to the period since 1970, while also identifying differences between coastal and mid-altitude windward areas. Precipitation has shown a less spatially consistent evolution, with previous research highlighting considerable variability and heterogeneous trends across the archipelago [25]. More recently, high-resolution climate mapping of the Canary Islands has confirmed the importance of analyzing temperature and precipitation at island and intra-island scales, showing a predominantly positive temperature trend but substantially more heterogeneous and frequently non-significant precipitation trends [22]. These findings reinforce the need for spatially differentiated climate analyses in small, topographically complex islands such as Gran Canaria.

3. Data and Methods

The analytical approach was designed to distinguish four complementary aspects of climate change: (i) deviations from a shared climatological baseline; (ii) the direction and magnitude of long-term trends; (iii) changes in the recurrence of extremely warm monthly conditions; and (iv) the spatial differentiation of those signals across the island. Monthly records were transformed into annual indicators to eliminate the seasonal cycle and facilitate comparison between regions with very different baseline climates. The analysis used the fixed 1991–2020 reference period throughout, in accordance with World Meteorological Organization guidance on standard climatological normals, so that the post-2020 observations could be directly compared with the earlier part of the series and not assessed against a moving baseline [26]. The study period was therefore defined as 1991–2025, providing a 35-year observational window consistent with this reference period. Although meteorological records prior to 1991 are available for some stations in Gran Canaria, extending the analysis to earlier decades would require reassessing the temporal completeness and spatial representativeness of the station network. The selected period was intended to maintain a consistent balance between temporal length and the spatial coverage required for the intra-island analysis.

3.1. Meteorological Data and Quality Control

Before the statistical analysis, the research team performed quality control, missing-data estimation, and homogenization using Climatol version [4.4-0]. Homogenization using Climatol involved comparing each individual value from every station and making weighted comparisons based on altitude, distance and a prescribed value of 35 from a Standard Normal Homogeneity Test (SNHT). The SNHT value was lifted from the prescribed 25 to 35 in order to account for the more variable and extreme climate in the island. The change in SNHT was conducted following guidance in the Climatol manual to adapt this variable according to the area of study. In the case of this investigation, increasing the SNHT value made it more tolerant to accept greater variabilities in meteorological conditions, which is an aspect characteristic of the climate in the Canary Islands [27]. This process allowed to identify at a given point in time whether a value in a selected station was inhomogeneous with similar stations or with its own previous data. If this change persisted in time, indicating that it was not an isolated anomalous value and that the data

was deemed inhomogeneous, Climatol applied a correction. This phenomena could arise due to changes in instrumentation, station location, exposure, or observation practices, which may distort climatic trend estimates [28,29]. Comparing a station to a group of similar ones, and checking their homogeneity, also allowed Climatol to build a synthetic dataset for the instances where there were missing data points. However, this was only performed when there were sufficient stations to construct the synthetic data.

A post-homogenization control was then applied when several inhomogeneous sections were identified in a single station within a period of less than two years, as it was deemed unrealistic that a meteorological station would be moved several times in this time span. Furthermore, considering the number of movements the station would have experienced, it was uncertain whether the coordinates of its position would be precise. In the same fashion, stations with corrections of 0.5 °C or more were eliminated as it was deemed that if a station was moved to a similar representative location the change should be smaller, meaning that for such a considerable change to happen, the coordinates of the position must have changed but there was a lack of access to the information of that new location. Following this process, the homogenisation is repeated with the reduced dataset. Of the 49 TMAX stations and 131 precipitation stations available after homogenization, 29 and 34, respectively, met the requirement of at least eight years of data within the 1991–2025 study period. These stations were selected to construct the climatic-zone reference series, which were used in the subsequent statistical analyses. Figure 4 shows the spatial distribution of the 41 stations considered for climatic-sector assignment. The final analytical subsets comprised 29 TMAX stations and 34 precipitation stations.

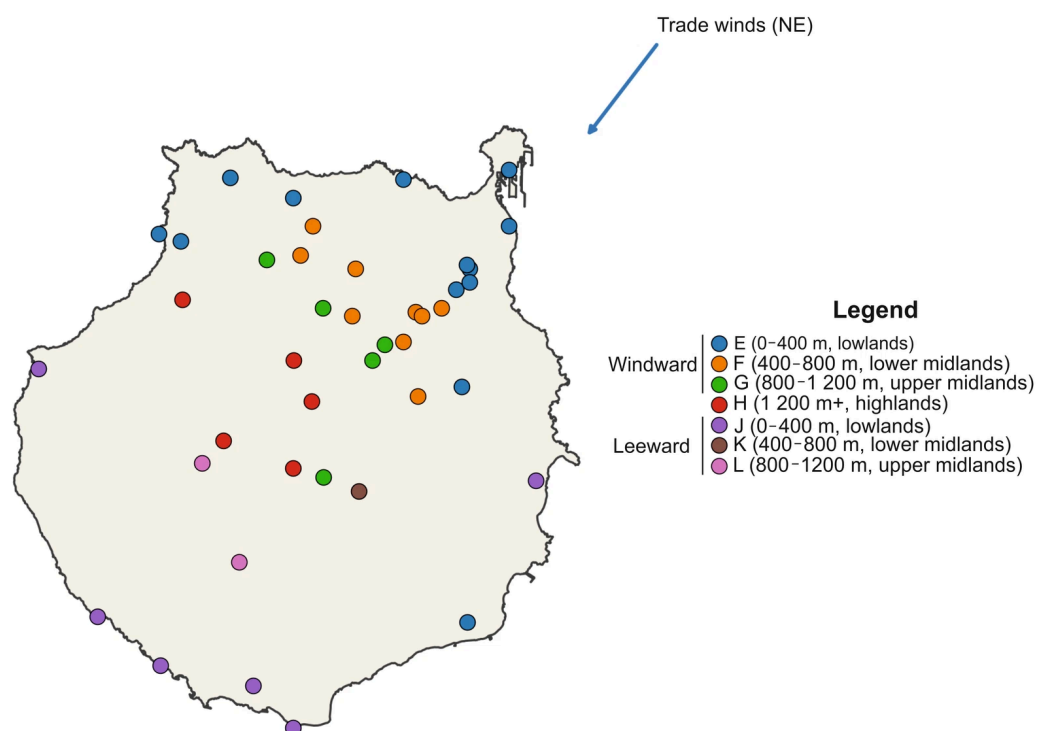


Figure 4. Spatial distribution of the 41 AEMET meteorological stations considered for assignment to the seven climatic sectors of Gran Canaria. Colours indicate windward lowlands (E), windward mid-slopes (F), upper windward slopes (G), the summit area (H), leeward lowlands (J), leeward mid-slopes (K), and upper leeward slopes (L). The final analytical subsets comprised 29 TMAX stations and 34 precipitation stations. The arrow indicates the prevailing north-easterly trade winds.

3.2. Climatic Regionalization and Regional Aggregation

The steep relief of Gran Canaria and its exposure to the prevailing north-easterly trade winds result in strong altitudinal and windward–leeward climatic gradients over short distances. To represent this heterogeneity, the stations were grouped into seven climatic zones according to altitudinal band and exposure: windward lowlands (0–400 m), windward mid-slopes (400–800 m), upper windward slopes (800–1200 m), the summit area (>1200 m), leeward lowlands (0–400 m), leeward mid-slopes (400–800 m), and upper leeward slopes (800–1200 m). This classification is consistent with the climatic effects of elevation, trade-wind clouds, and the leeward rain shadow described for Gran Canaria [17,24]. Figure 5 shows the spatial delimitation of these zones and their regional groupings.

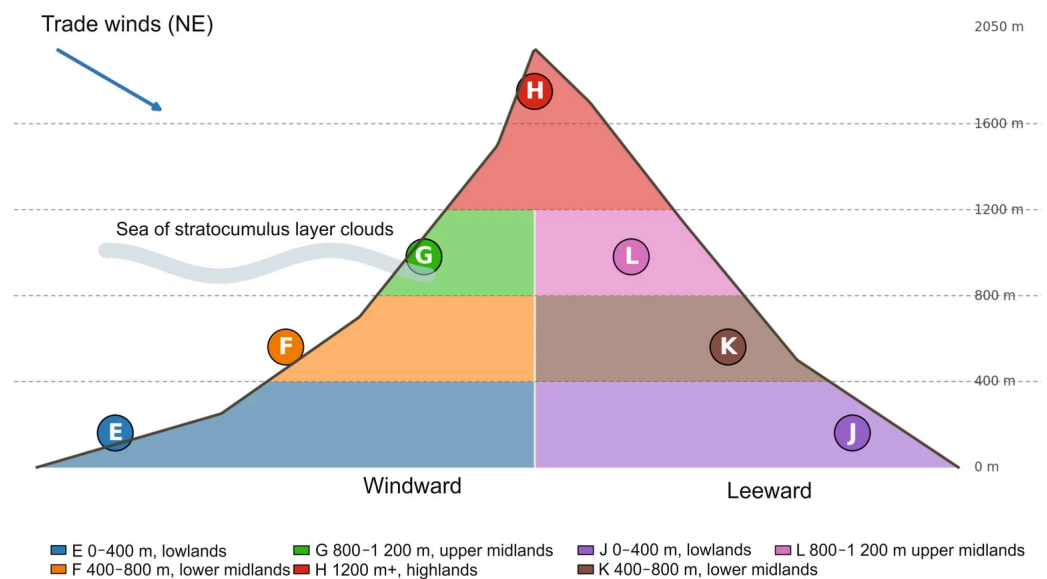


Figure 5. Climatic regionalization of Gran Canaria and spatial units used for regional aggregation. The diagram shows the seven climatic zones and the three regional groupings: windward lowlands and mid-slopes (F, E), upper windward slopes and summit area (high mountains; G, H), and leeward lowlands (J). Hatching identifies the leeward mid-slopes (K) and upper leeward slopes (L), which were excluded from the five-zone aggregate but retained in the climatic-zone trend analysis. Areas used for weighting are indicated for each included zone. Source: adapted from Luque et al. [24].

The seven climatic zones were used for zone-level trend analysis. Three regional series representing non-overlapping spatial units were constructed: (i) windward lowlands and mid-slopes, (ii) upper windward slopes and the summit area, and (iii) leeward lowlands. These three series were combined into an aggregate covering the five constituent climatic zones. The five-zone aggregate was used solely to summarize climatic evolution across the included zones and was not treated as an additional independent spatial unit in comparisons among the three regions.

Aggregation weights were calculated from climatic-zone surface areas obtained by delimiting each zone in a geographic information system according to the altitudinal and windward–leeward exposure criteria described above, following the area-weighting approach applied by Luque et al. [24] to regional series in Gran Canaria. The areas used were 285.8 km² for the windward lowlands, 168.8 km² for the windward mid-slopes, 95.8 km² for the upper windward slopes, 132.0 km² for the summit area, and 396.2 km² for the leeward lowlands. Because meteorological stations are unevenly distributed across Gran Canaria, regional series were constructed by weighting climatic-zone values according to their surface areas, rather than directly averaging all available station values. Each zone's weight was calculated as its area divided by the total area of the zones included

in the corresponding regional grouping or aggregate. This procedure made each zone's contribution proportional to its geographical extent rather than its number of stations.

The leeward mid-slopes (291.5 km²) and upper leeward slopes (225.2 km²) were retained in the climatic-zone trend analysis and spatial interpolation but were excluded from the five-zone aggregate because of their limited station coverage. These zones were represented by only one and two stations, respectively, but together they account for 32.4% of the area of the seven climatic zones. Including them in an area-weighted aggregate would therefore have assigned about one third of the total weight to three stations, making the aggregate highly sensitive to the behaviour of individual stations. As a robustness check, a seven-zone aggregate including both zones was also calculated. It yielded a TMAX trend of 0.243 °C per decade ($p = 0.002$), compared with 0.204 °C per decade for the five-zone aggregate, and a non-significant precipitation trend of 5.87 pp per decade ($p = 0.428$), compared with 6.62 pp per decade; the conclusions were therefore unchanged. These excluded zones are distinguished in Figure 5. Consequently, the aggregate represents only the five included zones and should not be interpreted as an island-wide area-weighted mean.

3.3. Construction of Climatic Anomalies and Regional Series

The main indicators were: (i) annual TMAX anomalies, expressed in degrees Celsius; (ii) annual precipitation anomalies, expressed as percentage deviations from the 1991–2020 monthly climatology; (iii) annual precipitation totals, expressed in millimeters; and (iv) the annual frequency of station-month observations with monthly TMAX greater than 30 °C. For the latter indicator, only values exceeding 30 °C were counted, whereas observations equal to 30 °C were not considered exceedances. For each region and year, the frequency was calculated as the number of station-month observations exceeding this threshold relative to the total number of valid station-month TMAX observations available. Thus, each exceedance represents one station-month observation and should not be interpreted as one hot day or one heatwave.

Due to the strong altitudinal and aspect-related gradients present in Gran Canaria, a direct comparison of raw climatic values across the island would be misleading. Hence, an anomaly-based approach was adopted. Separate monthly climatologies were calculated for each calendar month, preserving the seasonal structure of the local climate and expressing each observation relative to the conditions normally expected at the same time of year at the same station. We used absolute anomalies of TMAX because differences expressed in degrees Celsius have a direct physical meaning. Precipitation was analyzed as relative anomalies, since the same difference in millimeters between observed precipitation and its monthly climatological mean can have very different climatic significance in humid elevated areas and arid leeward lowlands [26,30]. The TMAX anomaly was computed for each station, month and year as the difference between the homogenized monthly observation and the corresponding 1991–2020 monthly climatology:

$$A_{i,m,t}^T = T_{i,m,t} - \bar{T}_{i,m}^{ref} \quad (1)$$

where $A_{i,m,t}^T$ is the TMAX anomaly, expressed in degrees Celsius, for station (i), calendar month (m), and year (t), $T_{i,m,t}$ is the homogenized monthly TMAX observation, and $\bar{T}_{i,m}^{ref}$ is the mean TMAX for station (i) and calendar month (m) during the 1991–2020 reference period.

Precipitation anomalies were expressed as percentage differences relative to the corresponding monthly climatological mean for 1991–2020:

$$A_{i,m,t}^P = 100 \left(\frac{P_{i,m,t} - \bar{P}_{i,m}^{ref}}{\bar{P}_{i,m}^{ref}} \right) \quad (2)$$

where $A_{i,m,t}^P$ is the precipitation anomaly, expressed as a percentage, $P_{i,m,t}$ is the homogenised monthly precipitation recorded at station (i) in month (m) and year (t), and $\bar{P}_{i,m}^{ref}$ is the corresponding mean monthly precipitation during the 1991–2020 reference period. The subscripts (i), (m), and (t) denote the meteorological station, calendar month, and year, respectively.

To avoid very small denominators that could produce excessively large percentage differences, station–month combinations with a mean monthly precipitation below 5 mm during the 1991–2020 reference period were excluded from the relative anomaly calculation. Because the threshold was applied to the climatological mean rather than to individual observations, each station–calendar-month combination was either retained or excluded for the entire study period. Of the 408 station–calendar-month combinations (34 stations $\times$ 12 months), 120 (29.4%) fell below the threshold, corresponding to 4200 of 14,280 station–month observations. All exclusions occurred between April and September, and 87 (72.5%) occurred in June–August. Although numerous, these combinations accounted for only 1.8% of mean annual precipitation (6.9% in the leeward lowlands). In these months, climatological means were often close to or below 1 mm, so a few millimetres of rainfall would have produced anomalies of several hundred or even thousands of per cent, reflecting the arithmetic of the denominator rather than a meaningful hydroclimatic change. The effect was strongest in the leeward lowlands, where all four stations were affected and no station retained a valid climatology between April and August; the leeward lowland precipitation series is therefore based on seven calendar months (January–March and September–December). The windward lowlands and the summit area lost June–August at zone level, but the corresponding regional series retained all 12 months through the adjacent zones. Precipitation anomalies should therefore be interpreted as describing mainly the wet season. Sensitivity analyses using thresholds of 2 mm and 10 mm, together with a threshold-free alternative based on annual totals (Table S1), showed that no regional precipitation trend was statistically significant under any specification, although the magnitude and sign of the point estimates varied. First, station anomalies were averaged monthly within each climatic zone. For each month, an area-weighted regional anomaly was obtained, and regional annual anomalies were then calculated as the average of the available monthly values within each year:

$$A_{r,t} = \frac{1}{M_{r,t}} \sum_{m=1}^{M_{r,t}} \left(\frac{\sum_{s \in r} w_s A_{s,m,t}}{\sum_{s \in r} w_s} \right), \quad (3)$$

where $A_{r,t}$ is the annual climatic anomaly for region (r) in year (t), $A_{s,m,t}$ is the anomaly observed in climatic zone (s) during calendar month (m) of year (t), w_s is the territorial area, expressed in square kilometres, of climatic zone (s), and $M_{r,t}$ is the number of valid monthly regional observations available for region (r) in year (t). The notation $(s \setminus r)$ indicates that climatic zone (s) forms part of region (r). $M_{r,t}$ equals 12 for all regional TMAX series and for the windward, upper windward/summit and five-zone precipitation series, and 7 for the leeward lowland precipitation series.

Because the homogenized series were complete, all 35 annual values (1991–2025) were available for every regional series, and no region–year combination was excluded for missing data for either TMAX or precipitation. For the same reason, annual precipitation totals were calculated from all 12 monthly values for every station–year, and no incomplete annual sums were used.

3.4. Trend, Variability and Association Analysis

We combined parametric and non-parametric methods to estimate the direction and rate of climatic trends, assess their statistical significance, and examine whether the results were consistent across methods. First, ordinary least squares (OLS) regression was used to estimate the linear rate of change over time:

$$y_t = \beta_0 + \beta_1 t + \varepsilon_t, \quad b_{decade} = 10\hat{\beta}_1 \quad (4)$$

where y_t is the annual climatic variable analyzed in year t , t denotes time expressed in years, β_0 is the intercept, β_1 is the linear trend coefficient representing change per year, and ε_t is the error term. The estimated slope, $\hat{\beta}_1$, was multiplied by ten to obtain the decadal rate of change, b_{decade} , expressed in °C per decade for TMAX and percentage points per decade for precipitation anomalies.

Climatic series, however, may contain non-normal distributions, influential years and monotonic changes that are not perfectly linear. Therefore, we supplemented OLS with the Mann–Kendall test and Sen’s median slope, which are commonly used in hydroclimatic studies as they are based on the ordering of observations and less influenced by isolated extremes [31–34]. Where OLS, Mann–Kendall, and Sen’s slope all agreed, this was taken as stronger evidence for a persistent temporal signal. Disagreement was not resolved by automatically privileging one test or the other but instead taken as evidence of sensitivity to model assumptions or limited statistical power. The seasonal extension of the Mann–Kendall test was not required as the data were analyzed annually.

We explicitly considered serial persistence since positive autocorrelation reduces the effective number of independent observations and can overstate the statistical significance of conventional trend tests [35]. Therefore, lag-one residual autocorrelation was adjusted for effective sample size and the significance of the linear trend at individual stations and climatic zone levels as recommended by [36]. Significant p -values were interpreted in combination with magnitude of the trend and spatial coherence.

To characterize interannual precipitation variability, the coefficient of variation was used to compare the relative dispersion of rainfall between regions with significantly different mean totals. The linear association between the annual TMAX and precipitation anomalies was estimated by using Pearson’s correlation coefficient. Spearman’s rank correlation was used to test the presence of a more general monotonic relationship. By estimating both coefficients, we were able to distinguish between relationships that were consistent in direction but not strictly linear. These correlations are simply contemporaneous covariation; they do not establish a causal effect of temperature on precipitation and cannot alone demonstrate drought, torrential rainfall or associated impacts.

3.5. Frequency of Monthly TMAX Observations Above 30 °C

An absolute threshold of 30 °C was adopted as an indication of very warm monthly conditions. The threshold is directly interpretable and allows comparing the frequency of very high monthly TMAX values in space and time. However, existing climate-extreme frameworks are typically based on daily data, percentile-based thresholds and persistence criteria [30,37,38]. Thus, the indicator used here should be considered a screening measure on a monthly basis, instead of a formal heatwave index. The descriptive indicator

was calculated as the percentage of available station-month observations with monthly TMAX > 30 °C for each region and year. We used a negative binomial regression to model the corresponding count, including the natural logarithm of the number of available station-month observations as an offset:

$$Y_{r,t} \sim NB(\mu_{r,t}, \alpha), \quad \log(\mu_{r,t}) = \log(N_{r,t}) + \beta_0 + \beta_1 d_t + \gamma_r, \quad (5)$$

where $Y_{r,t}$ is the count of station-month exceedances in region r and year t , $N_{r,t}$ is the number of available station-month observations, and d_t is time measured in decades from 1991. The term γ_r represents region-specific fixed effects that account for differences in baseline exceedance rates among the three non-overlapping regions in the combined model. The offset $\log(N_{r,t})$, whose coefficient is fixed at one, accounts for differences in observational coverage. A negative binomial specification was adopted due to the exceedance counts being more variable than expected under a Poisson model. Particularly warm monthly observations tend to cluster in particularly hot years or locations [39–41]. Such overdispersion is not unreasonable. The temporal coefficient was exponentiated and expressed as an incidence rate ratio (IRR); an IRR > 1 indicates a higher than expected rate of exceedance per decade.

3.6. Territorial Stress Index

The Territorial Stress Index (TSI) was developed as an exploratory composite indicator which summarizes the relative intensity of observed thermal and pluviometric change. The construction of composite indicators requires transparent choices regarding normalization, direction, and weighting [42]. Composite indicators are useful when a single variable is not enough to capture a multidimensional process. The TSI was therefore not designed to replace the separate results for temperature and precipitation, but rather to provide a compact comparative ranking that could be read in parallel with them. It is a measure of signals of climate change only and does not include hazard occurrence, exposure, vulnerability, coping capacity or observed impacts. The positive trend of TMAX and the magnitude of the absolute value of the precipitation trend for each spatial unit were scaled to the range 0–100:

$$T_j = 100 \frac{\max(b_j^T, 0) - \min_k \{\max(b_k^T, 0)\}}{\max_k \{\max(b_k^T, 0)\} - \min_k \{\max(b_k^T, 0)\}}, \quad H_j = 100 \frac{|b_j^P| - \min_k |b_k^P|}{\max_k |b_k^P| - \min_k |b_k^P|}, \quad (6)$$

where T_j is the normalized thermal component for spatial unit j (one of the seven climatic zones or, in the regional analysis, one of the three regional groupings or the five-zone aggregate defined in Section 3.2), H_j is its normalized precipitation-change component, b_j^T is the estimated TMAX trend in spatial unit j , expressed in degrees Celsius per decade, and b_j^P is the corresponding precipitation trend, expressed in percentage points per decade. The subscript k refers to all spatial units included in the relevant normalization set. Negative TMAX trends were assigned a value of zero in the thermal component because T_j was specifically designed to represent warming-related pressure.

The two components were combined as follows:

$$TSI_j = 0.60T_j + 0.40H_j \quad (7)$$

The 60:40 weighting increases the importance of the more robust and spatially generalized thermal signal while maintaining hydroclimatic change as a strong component. The weights are analytical choices rather than empirically calibrated risk coefficients. Min–max normalization also means that the TSI is relative to the spatial units included in this study. A value of zero identifies the minimum combined trend magnitude in the comparison set, and not a lack of climatic or territorial pressure. For the precipitation component, we used the magnitude of the absolute trend, and the sign of the precipitation trend was reported separately to distinguish between warming–drying and warming–wetting configurations. Thus, a high TSI is a strong combined climatic signal, and not a validated high-risk classification. The sensitivity of the TSI to alternative weights was not assessed. Consequently, its values and rankings are conditional on the 60:40 weighting and cannot be assumed to remain stable under other combinations. The index should therefore be interpreted as an exploratory synthesis of climatic trends. Its use to prioritize areas for planning requires an assessment of ranking stability, while application to other periods, islands, or sets of spatial units requires recalculation and evaluation of the weighting scheme [42].

3.7. Spatial Interpolation

Station trends were represented spatially using inverse-distance weighting (IDW):

$$\hat{z}(s_0) = \frac{\sum_{i=1}^n d(s_0, s_i)^{-p} z(s_i)}{\sum_{i=1}^n d(s_0, s_i)^{-p}}, \quad p = 2. \quad (8)$$

where $\hat{z}(s_0)$ is the interpolated trend at an unsampled location; $s_0, z(i)$ is the trend estimated at meteorological station i ; $d(s_0, s_i)$ is the distance between the prediction location and station i ; n is the number of stations included; and p is the distance-decay parameter, set to 2.

The inverse distance weighting gives progressively more weight to closer stations and is a transparent continuous representation of irregularly spaced point observations [43]. It was selected for exploratory visualization rather than spatial prediction, because it makes fewer assumptions about the distribution than geostatistical methods, and can be applied consistently to TMAX and precipitation trends. However, IDW does not take into account the uncertainty, the topographic barriers, the elevation-dependent lapse rates, and the physical effects of the windward exposure and the rain shadow.

The steep relief and the sharp climatic gradients of Gran Canaria led us to interpret the maps only as spatial summaries of station-level estimates and not as hazard maps or as validated predictions for unmonitored locations.

The uneven distribution of stations further limits the spatial representativeness of these surfaces, particularly in sparsely monitored areas; the quantitative trend estimates and statistical tests were derived from station and climatic-zone series, not from the interpolated values.

The overall methodological workflow followed in this study, from meteorological data processing to the calculation and spatial interpretation of the Territorial Stress Index (TSI), is summarized in Figure 6.

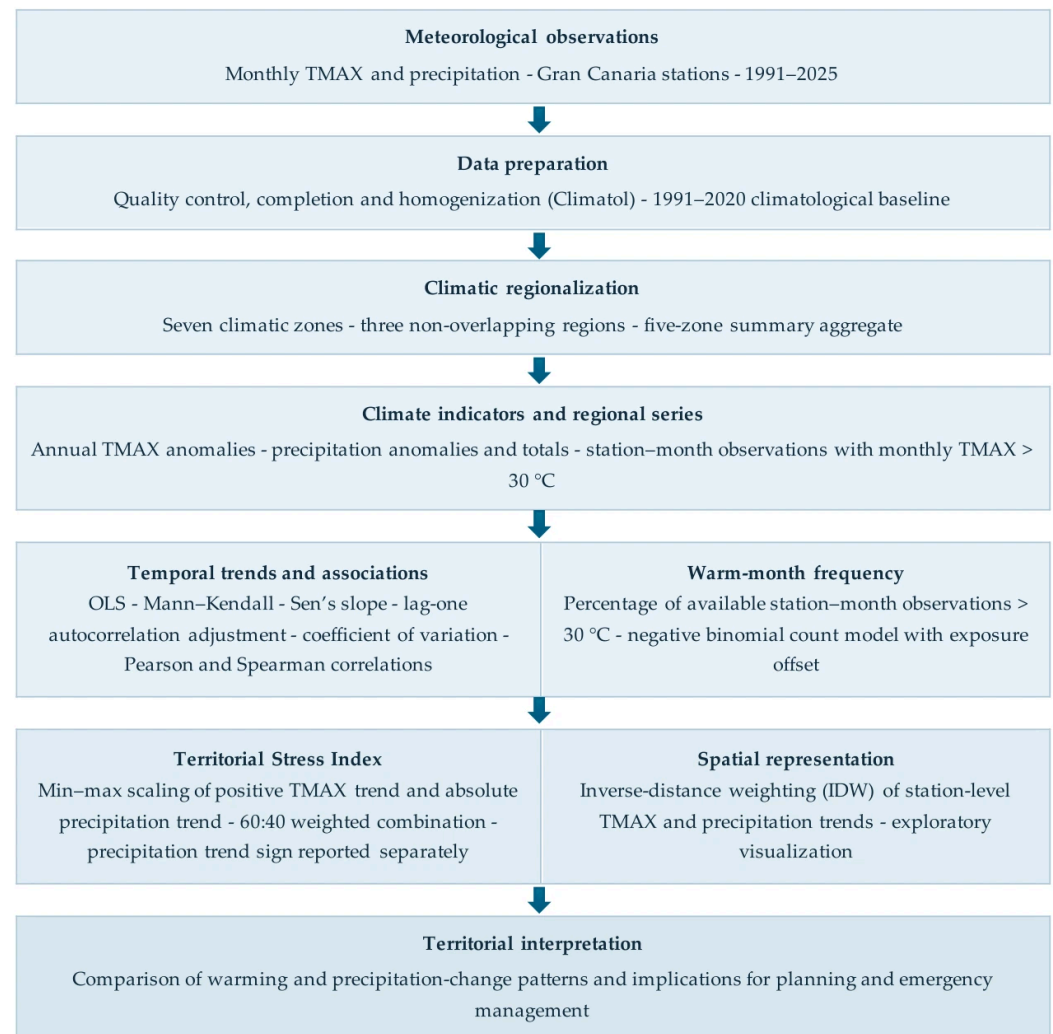


Figure 6. Conceptual flowchart of the data processing and methodological framework applied in this study.

4. Results

4.1. Regional Warming and the Monthly 30 °C Threshold

All three regional TMAX series, together with the five-zone aggregate, showed positive and statistically significant trends over the period 1991–2025 (Table 1). The largest OLS increase occurred in the upper windward slopes and summit area, 0.252 °C per decade and windward lowlands and mid-slopes, 0.228 °C per decade. The five-zone aggregate showed an increase of 0.204 °C per decade, while the smallest trend, but still statistically significant, was in the leeward lowlands, at 0.149 °C per decade. The Mann–Kendall test and Sen’s slope estimator showed the same direction of change for the three regional series and the five-zone aggregate. The mean TMAX anomalies for 2021–2025 were positive in all zones analyzed, with the greatest anomalies occurring in the upper windward slopes and summit area and in the windward lowlands and mid-slopes. The warming signal was thus spatially widespread but of different magnitude in different climatic regions.

The frequency of monthly TMAX observations above 30 °C also increased in the windward lowlands and mid-slopes, the upper windward slopes and summit area, and the five-zone aggregate (Figure 7). Separate negative binomial models showed an increase of 75.0% per decade in the expected exceedance rate in the windward lowlands and mid-slopes, 25.9% in the upper windward slopes and summit area, and 42.1% in the five-zone aggregate. The combined model for the three non-overlapping areas yielded an IRR of

1.442 (95% CI 1.226–1.697; $p < 0.001$), which translates to an average increase of 44.2% per decade after adjusting for persistent differences across regions and the number of observations available. These results suggest that the recent thermal signal is expressed not only in annual anomalies but also in an increasing number of months with very high monthly maxima. However, the exceedances are not to be interpreted as counts of hot days or heatwaves.

Table 1. Regional TMAX trends and monthly observations above 30 °C, 1991–2025.

Region	TMAX Slope	OLS p	Sen Slope	Threshold Slope	Negative Binomial IRR (95% CI)
Windward lowlands and mid-slopes	0.228	0.003 *	0.194	0.788	1.750 (1.320–2.320)
Upper windward slopes and summit area	0.252	0.005 *	0.213	0.700	1.259 (1.035–1.531)
Leeward lowlands	0.149	0.018 *	0.141	0.088	Not interpreted ¹
Five-zone aggregate	0.204	0.004 *	0.166	0.650	1.421 (1.150–1.757)

Note: * Statistically significant at $p < 0.05$. ¹ Only one exceedance was observed across the leeward series, making the separate count model unstable.

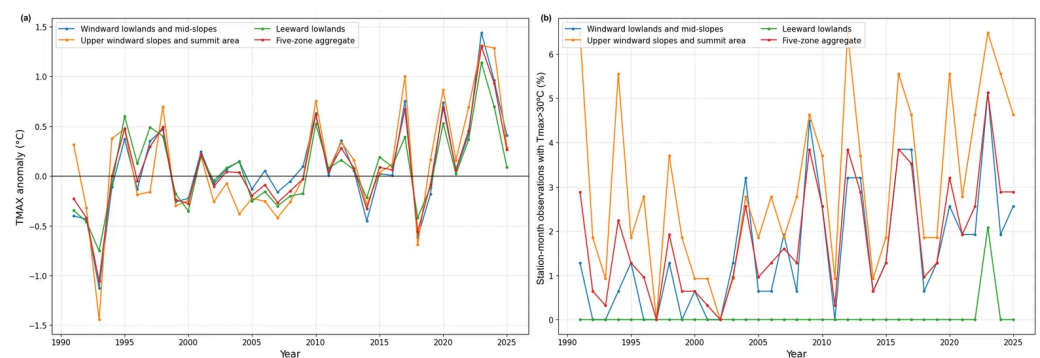


Figure 7. Regional TMAX evolution, 1991–2025: (a) annual TMAX anomalies relative to the 1991–2020 climatological reference period (°C); (b) annual frequency of station-month observations with monthly TMAX > 30 °C (%). The five-zone aggregate combines the three analytical regions but excludes the leeward mid-slopes and upper leeward slopes. The >30 °C threshold is a monthly indicator and should not be interpreted as a measure of hot days or as an official heatwave definition.

4.2. Precipitation Variability and Its Relationship with TMAX

None of the three precipitation series representing the regional groupings defined in Section 3.2 (windward lowlands and mid-slopes, upper windward slopes and summit area, and leeward lowlands), nor the five-zone aggregate, showed a statistically significant monotonic trend (Table 2). OLS slopes were positive for both windward regional series and the five-zone aggregate, whereas the leeward lowlands showed a slightly negative slope close to zero. The confidence intervals were wide and included zero, leaving the direction of change over 1991–2025 inconclusive. Thus, the main precipitation result was strong interannual and spatial variability rather than a uniform increase or decrease, consistent with the complex precipitation geography of the Canary Islands [17].

The leeward lowlands had the lowest mean annual precipitation (90.3 mm) and the highest coefficient of variation (45.7%). This low mean is consistent with the dry conditions of the island's low-elevation leeward sector, which is sheltered from the prevailing north-easterly trade winds by the central relief and receives less precipitation than the windward slopes. The high coefficient of variation indicates substantial interannual variability. The upper windward slopes and summit area recorded the highest mean annual precipitation,

also with considerable interannual variability ($CV = 31.6\%$). TMAX and precipitation anomalies were negatively correlated in most regions, but the relationship was statistically significant only in the upper windward slopes and summit area (Spearman $\rho = -0.367$; $p = 0.030$). The correlation in the windward lowlands and mid-slopes did not reach the conventional 0.05 significance level ($\rho = -0.315$; $p = 0.066$). These results do not indicate a consistent temperature–precipitation association across the analyzed regions; the strength of this relationship varies with the climatic setting.

Table 2. Regional precipitation trends, variability and association with TMAX.

Region	PRCP Slope	OLS p	Mean Annual PRCP (mm)	CV (%)	Spearman ρ with TMAX	Spearman p
Windward lowlands and mid-slopes	8.564	0.159	286.8	24.8	−0.315	0.066
Upper windward slopes and summit area	6.158	0.344	493.5	31.6	−0.367	0.030 *
Leeward lowlands	−0.668	0.962	90.3	45.7	−0.060	0.732
Five-zone aggregate	6.620	0.342	321.5	26.9	−0.271	0.115

Note: * Statistically significant at $p < 0.05$.

The 2022 strong positive precipitation anomaly, particularly in the leeward lowlands, illustrates why short recent averages are likely to be strongly influenced by individual wet years (Figure 8a). Moreover, an increase in annual precipitation does not necessarily imply an increase in heavy precipitation. To establish that relationship, daily indices would be needed, such as maximum one-day or five-day precipitation, very wet day totals and rainfall intensity [35].

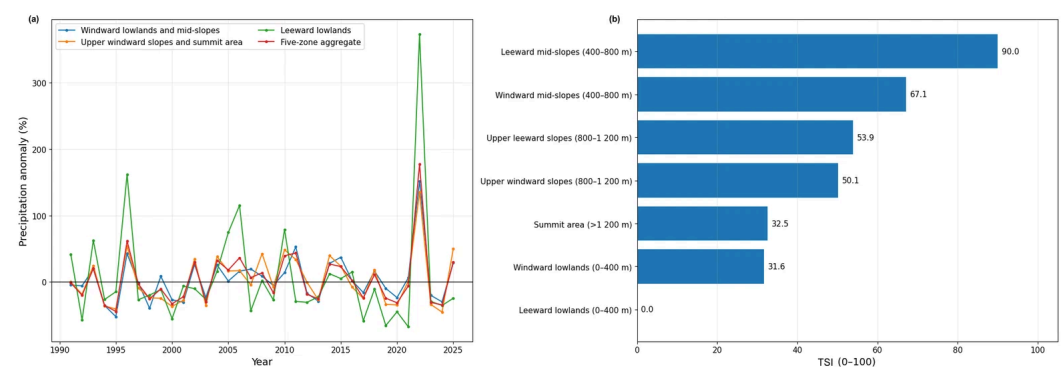


Figure 8. Hydroclimatic variability and territorial stress: (a) annual regional precipitation anomalies (%), with the horizontal black line at 0% indicating no deviation from the corresponding reference mean; positive values indicate wetter-than-average years and negative values indicate drier-than-average years; (b) relative TSI ranking by climatic zone.

4.3. Spatial Differentiation and the Territorial Stress Index

The analysis of climatic zones showed stronger spatial differences than the regional aggregates (Table 3). For TMAX, positive trends were found in all seven zones, from 0.149°C per decade in the leeward lowlands to 0.408°C per decade on the leeward mid-slopes. Correction for residual autocorrelation did not alter the significance of the trends in the leeward mid-slopes, in the summit area, on the windward mid-slopes, on the upper windward slopes and in the windward lowlands. The precipitation behavior showed a less spatially coherent pattern: only the windward mid-slopes were found to have a statistically significant increase (8.83 percentage points per decade), while the negative

slopes estimated for the leeward mid-slopes, the summit area and the leeward lowlands were not statistically significant.

Table 3. Territorial Stress Index and climatic configuration by climatic zone.

Rank	Climatic Zone	TMAX Trend (°C Decade ^{−1})	PRCP Trend (pp Decade ^{−1})	TSI	Climatic Configuration
1	Leeward mid-slopes (400–800 m)	0.408	−6.785	90.0	Warming–drying
2	Windward mid-slopes (400–800 m)	0.266	8.829	67.1	Warming–wetting
3	Upper leeward slopes (800–1200 m)	0.217	8.424	53.9	Warming–wetting
4	Upper windward slopes (800–1200 m)	0.207	8.140	50.1	Warming–wetting
5	Summit area (>1200 m)	0.284	−0.900	32.5	Warming–drying
6	Windward lowlands (0–400 m)	0.206	4.421	31.6	Warming–wetting
7	Leeward lowlands (0–400 m)	0.149	−0.668	0.0	Warming–drying

The IDW surfaces (Figure 9) permit a spatially differentiated interpretation. The strongest increases in TMAX were generally restricted to interior and higher terrain, with several coastal stations showing gentler slopes. The precipitation surface showed neighboring positive and negative values, indicating that the island-wide averages conceal fine-scale hydroclimatic contrasts. The interpolation is exploratory but consistent with the strong climatic gradients created by relief, altitude and exposure to the trade winds in Gran Canaria [17,24].

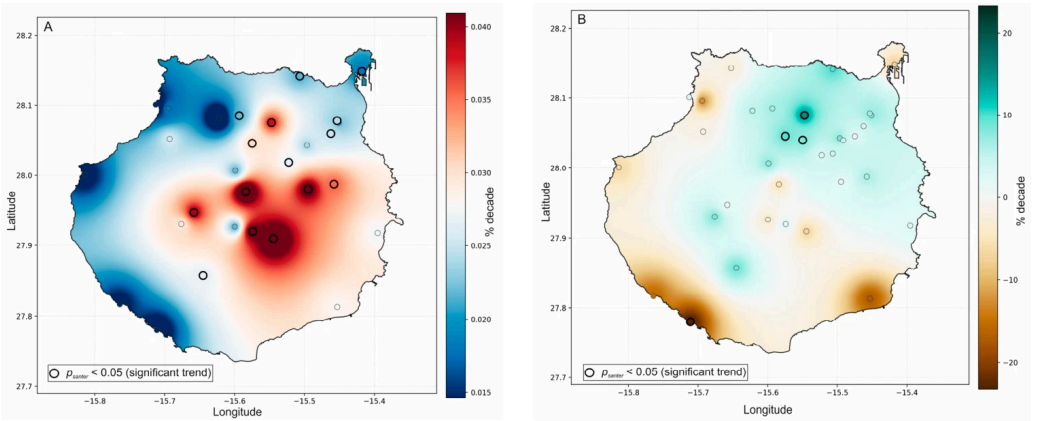


Figure 9. IDW interpolation of station-level trends for the period 1991–2025: (A) annual TMAX trends (°C year^{−1}) and (B) annual precipitation trends (% per decade). Thick station outlines identify trends that remained statistically significant after the Santer autocorrelation adjustment ($p < 0.05$).

The seven climatic zones were normalized individually. At this spatial scale, the leeward mid-slopes ranked first with a TSI of 90.0 and a warming–drying configuration. They were followed by windward mid-slopes (67.1), upper leeward slopes (53.9) and upper windward slopes (50.1) all with warming–wetting configurations. Intermediate values were observed in the summit region and windward lowlands, while leeward lowlands exhibited the relative minimum. The regional and climatic-zone indices are calculated on different sets of normalization, and their numerical values are not directly comparable. The direction of the precipitation trend was robust to the choice of threshold in the leeward mid-slopes (drying) and in the windward mid-slopes and upper windward slopes (wetting), but not in the windward lowlands, summit area, leeward lowlands and upper leeward slopes, where the sign changed between the 2 mm and 10 mm thresholds (Table S2). The warming–drying and warming–wetting labels of these four zones should therefore be interpreted with caution.

5. Discussion

5.1. A Spatially Uneven Climate Change in Gran Canaria

The results obtained show that recent climate change in Gran Canaria cannot be interpreted as a homogeneous process across the entire territory. The maximum temperature shows a generalized warming trend, with positive trends in all the analyzed climatic zones, while precipitation shows no statistically significant trend at the island-wide scale, although substantial spatial variability is observed in the magnitude and direction of the estimated changes across climatic zones. This spatial differentiation is consistent with previous studies in the Canary Islands highlighting the importance of high-resolution climate information to capture differences in temperature and precipitation associated with elevation and exposure to the prevailing north-easterly trade winds, particularly the contrasts between windward and leeward slopes [22].

At a broader scale, the generalized warming observed in Gran Canaria is consistent with the climatic evolution reported for small islands worldwide. The IPCC indicates that most small-island regions have warmed over the instrumental record, whereas precipitation trends show substantially greater regional variability and are frequently mixed or statistically non-significant [4]. A similar contrast between a robust thermal signal and a less spatially coherent precipitation response is observed at the national scale. In Spain, long-term observations show a clear warming trend, while no statistically significant trend in mean annual precipitation has been detected for the country as a whole since 1961, despite significant decreases in some regions [44]. In this broader context, the results obtained for Gran Canaria reproduce the general contrast between a consistent warming signal and a more heterogeneous precipitation response, while additionally revealing that substantial differences can occur even within a single island.

The consistency of the thermal signal is observed both in the trends of TMAX and in the increase in the relative frequency of monthly observations above 30 °C. The combined model shows a significant increase in the expected rate of these observations, indicating that the detected warming is not limited to a shift in mean values, but is also accompanied by a greater recurrence of particularly warm monthly conditions. However, this indicator should be interpreted exclusively as a measure of monthly thermal conditions and not as evidence of an increase in heatwaves, whose identification would require daily data and specific criteria of duration and intensity [37]. Precipitation offers a different picture. The absence of a uniform and statistically significant regional trend prevents supporting a general trajectory of aridification for Gran Canaria as a whole. On the contrary, the positive and negative trends observed between neighboring areas show that the rainfall behavior maintains a high spatial complexity. This circumstance is especially relevant on an island characterized by strong altitudinal and exposure gradients, where island averages can conceal divergent climatic processes over relatively short distances.

The analysis of the seven climatic zones reinforces this interpretation. Although all show positive trends in TMAX, their magnitude varies considerably, reaching the highest values in certain sectors of the interior and the mid-slopes. Precipitation, on the other hand, combines positive and negative trends, and only shows a statistically significant increase in the windward mid-slopes. The spatial results obtained through IDW confirm that the most relevant climatic signals are not evenly distributed across the island. Therefore, the relevant issue for territorial planning is not only to determine whether Gran Canaria is warming, but also where the change is occurring with greater intensity and how precipitation is behaving at the same time. This differentiation constitutes the foundation for interpreting the results from a territorial stress perspective.

5.2. From Climate Stress to Territorial Emergency Management

The TSI allows synthesizing this differentiation without assuming that all areas subject to intense climate changes evolve in the same direction. The results identify the leeward mid-slopes as the unit with the highest index value (TSI = 90.0), also characterized by a warming–drying configuration. In contrast, other areas with high TSI values, such as the windward mid-slopes or certain upper sectors, exhibit warming–wetting configurations. The value of the index should therefore be interpreted together with the direction of the rainfall trend and not as a linear scale of greater or lesser risk.

This distinction is particularly relevant from the perspective of emergency management. In warming–drying configurations, the combination of sustained temperature increases and reduced precipitation can contribute to the generation of conditions compatible with higher evaporative demand, water stress, and reduced moisture availability in vegetation and soil. These processes are part of the environmental conditions that can favor fuel availability and dryness and, consequently, contribute to more favorable contexts for the occurrence and spread of wildfires [10,11]. However, the results obtained do not directly allow us to establish that areas with a higher TSI have a greater probability of fire, as the fire hazard also depends on short-term meteorological factors, fuel characteristics and continuity, topography, land use, ignitions, and management actions.

This distinction is fundamental. The TSI is neither a fire hazard index nor a disaster risk index. Its usefulness lies in the identification of areas where background climatic conditions are changing with different intensity and direction. From the perspective of civil protection, this information can serve as a complementary layer to guide subsequent processes of risk assessment, preventive planning, and operational preparation. The result does not determine where the next emergency will occur, but it does identify where certain climatic components of the territory are undergoing transformations that should be considered in planning.

This approach also raises an important question about the scale at which the risk is managed. The climatic units used in this study do not necessarily coincide with municipal administrative boundaries. The same municipality can extend from coastal to mid-slope areas or summit zones and therefore contain territories subject to different climatic configurations. Consequently, it would not be methodologically correct to automatically assign a single TSI value to each municipality based on the analyzed climatic zones. The value of 90.0 corresponding to the windward mid-slopes characterizes that climatic unit and not the entirety of the municipalities over which it may extend.

This lack of correspondence between climatic and administrative boundaries, however, has a direct application for emergency management. Municipal civil protection planning, forest fire prevention, or the territorial distribution of certain resources should not necessarily assume homogeneous environmental conditions within each municipality. The future overlap of climatic zones and the TSI with municipal boundaries would allow the identification of which sectors of each municipality are included in more intense warming–drying configurations and which present different climatic trajectories. In this way, the TSI could be used as complementary climatic information within higher-resolution territorial assessments.

The situation is different in warming–wetting configurations. A high TSI in these areas does not imply the same type of territorial pressure as in the warming–drying configurations. The simultaneous increase in temperature and precipitation could be related to different processes, but the monthly data used in this study do not allow determination of whether the increase in rainfall is due to a higher frequency of moderate precipitation or changes in intense episodes. Therefore, it would not be possible to infer from these

results an increase in the risk of flooding or other hydro-geomorphological processes. That hypothesis would require an analysis of daily or sub-daily precipitation and its extremes.

The main implication for emergency management is, therefore, that the same thermal change does not necessarily generate the same territorial risk conditions throughout the island. The direction and magnitude of rainfall changes, combined with the environmental and social characteristics of each territory, determine different contexts that require equally differentiated adaptation strategies.

5.3. Scope of the TSI, Limitations, and Application to Risk Planning

The TSI summarizes the relative intensity of climatic changes and should be interpreted within the broader sequence linking climatic stressors, potential changes in hazards, exposure, vulnerability, and impacts (Figure 10) [8,14,15]. The present analysis addresses climatic trends but does not directly assess hazard occurrence, exposed populations and assets, vulnerability, response capacity, or observed impacts. A high TSI value therefore does not establish a high disaster risk level or demonstrate effects on human health. Its contribution to emergency planning is to identify spatial contrasts in climatic pressures that require further assessment using hazard-specific and socioeconomic data.

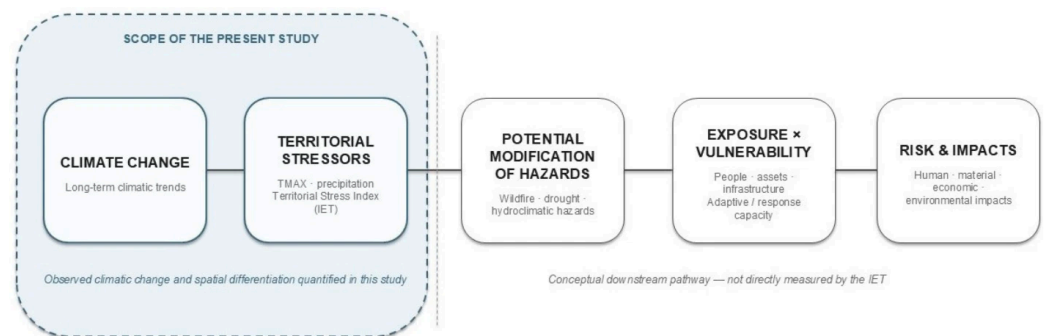


Figure 10. Conceptual sequence linking climate change, territorial stressors, potential hazard modification, exposure and vulnerability, and risk and impacts.

This study provides evidence primarily on the first two components of this sequence. This limitation is, at the same time, a clear pathway to develop the indicator. Overlapping the TSI with information on historical fires, fuel models, urban-forest interface, population exposure, critical infrastructure, and operational capacity would enable empirical verification of whether areas subject to greater climate stress also present more problematic configurations from the perspective of emergency management.

Administrative territorialization constitutes a second necessary development. Spatial intersection between the seven climatic zones and the 21 municipalities of Gran Canaria would facilitate a determination of the proportion of each municipality that corresponds to each climatic configuration, avoiding simplified assignments on the sole basis of forming part of a municipality. Based on such information, surface-weighted municipal indicators could be explored, with the clarification that these would constitute a new methodological development and not a direct transfer of the zonal TSI. There are also limitations related to the temporal resolution of the data. Monthly series allow the identification of background climate changes, but do not adequately characterize short-duration extreme phenomena, such as heatwaves, torrential rainfall episodes, or specific weather conditions associated with large wildfires. The future incorporation of daily series would facilitate a correlation of the structural climatic evolution identified in this study with indicators that are operationally closer to the hazards managed by civil protection services.

Despite these limitations, the results show the potential of incorporating intra-island climatic differentiation into emergency planning. In island territories with a strong to-

pographic gradient, the exclusive use of aggregated climate trends can obscure sectors subject to significantly different trajectories. The identification of these differences does not replace specific risk assessment tools but can provide a localized climatic basis on which to subsequently integrate hazard, exposure, vulnerability, and response capacity.

6. Conclusions

The results show that recent climate change in Gran Canaria does not manifest itself homogeneously across the territory. Maximum temperature exhibits a generalized and statistically significant warming trend, although its magnitude varies considerably among climatic zones, whereas precipitation shows greater spatial heterogeneity and no statistically significant trend at the island-wide scale. The Territorial Stress Index (TSI) synthesizes these spatial differences and identifies contrasting climatic trajectories. The highest relative TSI value (90.0) occurs in the leeward mid-slopes, where pronounced warming coincides with decreasing precipitation, while other areas show warming–wetting configurations. These findings demonstrate that island-wide averages can conceal substantially different climatic trajectories within a relatively small and topographically complex territory.

The results should nevertheless be interpreted within the limitations of the study. The TSI is an exploratory indicator of climatic stress and not a disaster risk index, as it does not directly incorporate hazard occurrence, exposure, vulnerability, response capacity, or observed impacts. Furthermore, the use of monthly data allows the identification of background climatic trends but does not adequately characterize short-duration extremes such as heatwaves, torrential rainfall events, or specific meteorological conditions associated with wildfires. Future research should therefore incorporate daily and sub-daily data and integrate the TSI with hazard-specific and socioeconomic information, including historical fires, fuel characteristics, wildland–urban interfaces, population and infrastructure exposure, and operational response capacity. Spatial intersection of climatic zones with municipal boundaries would also facilitate the development of territorially more detailed applications for planning and emergency management.

From an adaptation perspective, the marked intra-island differentiation identified in this study supports the use of spatially differentiated strategies rather than uniform island-wide approaches. The results can contribute to prioritizing climate monitoring, water-resource planning, wildfire prevention, land-use planning, protection of critical infrastructure, and emergency preparedness according to the climatic trajectory of each territory. Mitigation measures should complement these adaptation actions through continued reductions in greenhouse-gas emissions, improvements in energy efficiency, and the expansion of low-carbon and renewable-energy systems. Overall, the results highlight the value of incorporating fine-scale climatic information into climate adaptation, mitigation, territorial planning, and emergency-management strategies in Gran Canaria.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cli14110230/s1>, Table S1: Sensitivity of regional precipitation trends to the minimum climatological threshold used in the calculation of relative anomalies. Values are OLS trends of annual precipitation anomalies (percentage points per decade, 1991–2025), with OLS *p*-values in parentheses; Table S2: Sensitivity of climatic-zone precipitation trends to the minimum climatological threshold used in the calculation of relative anomalies. Values are OLS trends of annual precipitation anomalies (percentage points per decade, 1991–2025), with OLS *p*-values in parentheses.

Author Contributions: Conceptualization, F.M.M., A.I. and P.M.S.; methodology, F.M.M., A.I., P.M.S., C.V.R. and J.D.C.; validation, F.M.M. and A.I.; formal analysis, F.M.M., P.M.S. and W.O.N.; investigation, F.M.M.; resources, F.M.M. and P.M.S.; data curation, F.M.M., A.I., W.O.N., C.V.R. and J.D.C.; writing—original draft preparation, F.M.M. and A.I.; writing—review and editing, F.M.M., A.I., P.M.S., C.V.R. and J.D.C.; visualization, F.M.M., P.M.S. and W.O.N.; supervision, P.M.S.; project

administration, F.M.M. and P.M.S.; funding acquisition, P.M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the European Commission through the projects “Development and Monitoring of Coordinated Actions in the Macaronesia Region on Risks and Threats Related to Climate Change” (PLANCLIMAC2; Reference: 1/MAC/2/2.4/0006) and “Innovative and Strategic Renewable Energy Sources to Drive the Transition to Climate Neutrality in Macaronesia” (RESMAC; Reference: 1/MAC/2/2.2/0011).

Data Availability Statement: The meteorological data supporting the findings of this study were obtained from the Spanish State Meteorological Agency [45]. The study uses homogenized monthly series of maximum temperature and precipitation for Gran Canaria covering the period 1991–2025. Additional spatial and territorial data were obtained from the official sources referenced in the manuscript. All data sources used in this study are identified and cited within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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