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Analysis of Drivers of Temperature and Precipitation Regime Variability on Three Small Islands in the Adriatic Sea and Implications for Drought

Ognjen Bonacci [1], Ana Žaknić-Ćatović [2,*] and Tanja Roje-Bonacci [1]

[1] Faculty of Civil Engineering, Architecture and Geodesy, Split University, Matice Hrvatske 15, 21000 Split, Croatia; obonacci@gradst.hr (O.B.); bonacci@gradst.hr (T.R.-B.)
[2] Department of Physical and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Scarborough, Toronto, ON M1C 1A4, Canada
* Correspondence: ana.zaknic.catovic@utoronto.ca

Abstract

This study analyzes changes in temperature, precipitation, and drought conditions on three small islands in the southern Adriatic (Vis, Lastovo, and Mljet) over the period 1981–2024, to identify the spatial and seasonal heterogeneity of the climate signal and its relationship with drought occurrence. The analysis reveals a statistically significant and consistent increase in mean annual air temperature at all analyzed stations, with warming being strongly seasonally asymmetric and most pronounced during the summer months. In contrast, precipitation trends are weak, spatially heterogeneous, and statistically insignificant in most cases, with a locally pronounced increase in precipitation in the interior and more orographically complex areas of Mljet. Drought conditions were assessed using the Standardized Precipitation Index (SPI) and the New Drought Index (NDI). The annual SPI exhibits strong interannual variability without a clear long-term trend, and in some cases an apparent increase driven by episodic extremely wet years. In contrast, the NDI clearly detects a systematic increase in aridity, particularly during the warm part of the year, reflecting the combined effect of rising temperatures and unfavourable precipitation distribution. June emerges as a key transitional month with a regionally coherent and statistically significant drying signal, whereas October shows weak and inconsistent trends due to the dominance of episodic precipitation extremes. The results confirm that drought assessment on small Mediterranean islands based solely on precipitation may be misleading, and that integrated indices incorporating the energy aspect of climate provide a more realistic representation of changes in aridity.

Keywords: air temperature; precipitation; climate variability; new drought index (NDI); standardized precipitation index (SPI); small islands (Adriatic Sea)

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Academic Editor: Jens Hesselbjerg Christensen

Received: 17 March 2026
Revised: 11 May 2026
Accepted: 12 May 2026
Published: 16 May 2026

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1. Introduction

The Mediterranean region is widely recognized as one of the global climate change hotspots, characterized by pronounced warming trends, increasing hydroclimatic variability, and growing pressure on freshwater resources [1–6]. Climate change impacts are particularly important on small Mediterranean islands, where freshwater availability depends strongly on precipitation variability and limited groundwater recharge.

Several studies have analyzed recent changes in temperature and precipitation in different parts of the Mediterranean region. Most studies consistently report statistically

significant warming trends, whereas precipitation trends are spatially heterogeneous, seasonally variable, and frequently statistically insignificant.

Homar et al. [7] identified significant warming and weak declining precipitation trends in the Balearic Islands. Similar conclusions were reported for Adriatic and Tyrrhenian Islands, where warming trends are robust but precipitation changes remain weak or spatially inconsistent [8,9]. However, precipitation trends in certain Mediterranean coastal and island regions are not uniformly negative. Sakalis [10], in an analysis of trends in the eastern Mediterranean Basin, reported an increase in annual precipitation during the period 1990–2021. However, these trends are not consistently statistically significant, indicating that precipitation trends across the Mediterranean are heterogeneous rather than regionally uniform. Other studies indicate that Mediterranean precipitation changes are increasingly expressed through seasonal redistribution and variability rather than through systematic decreases in annual totals [10–12].

Several studies further suggest that northern Mediterranean regions may experience neutral or locally positive precipitation trends, including increases in precipitation extremes, whereas southern and eastern Mediterranean regions are generally more affected by drying and aridification [11]. These contrasting responses are associated with differences in atmospheric circulation, cyclonic activity, orographic forcing, and the expanding influence of subtropical anticyclones.

Mediterranean islands represent environmentally vulnerable systems characterized by pronounced geographic, geological, climatic and ecological diversity, including exceptionally high levels of biodiversity and endemism [13,14]. Freshwater resources on small Mediterranean islands are generally limited and strongly dependent on precipitation-driven groundwater recharge [15]. Increasing climatic pressures and growing anthropogenic stress further enhance the vulnerability of water resources throughout the Mediterranean region [16].

The Croatian Adriatic coast includes numerous islands and islets [17], many of which are characterized by limited freshwater resources and vulnerable hydrogeological settings. Only a few islands exhibit hydrological or hydrogeological conditions sufficient to sustain reliable local water supplies [18].

Climate change is expected to exert substantial impacts on Croatia's coastal region throughout the 21st century [19]. Regional climate model projections for the Croatian Adriatic under the IPCC SRES A1B indicate a potential increase in mean air temperature of up to 5.5 °C, toward the end of the 21st century, accompanied by a slight reduction in precipitation totals, and an increasing frequency of extreme events such as flash floods and droughts [20]. These projected changes pose a particularly serious risk to populations on small and remote islands, where settlements are highly dispersed and dependent on local freshwater resources.

Although warming in the Mediterranean is unequivocal and statistically robust, precipitation changes remain regionally heterogeneous, seasonally asymmetric, and often statistically weak, especially on small islands. This combination of a strong and certain temperature increase, coupled with uncertain yet hydrologically unfavourable precipitation redistribution, represents a critical risk to hydrological stability, freshwater availability, environmental sustainability, and the socio-economic resilience of Mediterranean island archipelagos. Across many Mediterranean regions, increasing temperatures combined with seasonal redistribution of precipitation may contribute to less favourable hydroclimatic conditions, including reduced infiltration efficiency and increasing pressure on groundwater resources [21]. Examples of recent climate-driven changes on small islands in the Croatian Adriatic have been documented by Bonacci et al. [22–24] and Bonacci and Vrsalović [25].

The main objective of this study is to analyze long-term variability and trends in air temperature and precipitation across three Adriatic islands and to assess drought evolution using two complementary indicators: the Standardized Precipitation Index (SPI) and the New Drought Index (NDI). The combined use of SPI and NDI enables a comparative assessment of drought conditions derived from precipitation-only variability versus those additionally influenced by temperature effects on evaporation and moisture availability. The study further examines spatial and seasonal differences in climate variability across three relatively proximate small islands in the southern Adriatic Sea (Croatia), namely Vis, Lastovo, and Mljet (Figure 1).



Figure 1. Study area map showing the location of Vis, Lastovo, and Mljet islands within the Adriatic Sea (Mediterranean Basin, Europe). Analyzed meteorological stations are indicated as: 1-Komiža, 2-Lastovo, 3-Goveđari, 4-Babino Polje, and 5-Maranovići).

2. Materials and Methods

2.1. Study Area

Table 1 presents the basic information for the five meteorological stations located on the three islands shown in Figure 1, whose data were analyzed in this study. While Vis and Lastovo each host a single station, Mljet contains three stations.

The analyzed meteorological stations are located on three relatively proximate islands in the Adriatic Sea, with the maximum distance between stations being approximately 134 km, indicating the small spatial scale of the study area.

Vis is the most remote inhabited Central Adriatic island with an area of 89.72 km^2 and a maximum elevation of 587 m a.s.l. [17]. According to the Köppen–Geiger climate classification [26], Vis and the Vis archipelago belong to the Csa Mediterranean climate type [27]. The island is composed predominantly of karstified Cretaceous limestones and dolomites and relies entirely on a local karst aquifer for freshwater supply [28]. Seasonal

groundwater-level fluctuations are pronounced, while increasing air temperatures, sea-level rise, aquifer salinization, and enhanced evapotranspiration may intensify future freshwater vulnerability [29].

Table 1. Basic information on the five stations whose data were analyzed in this study.

Island	Station	H (m a.s.l.)	Geographical Coordinates	
Vis	Komiža	20	43° 02′ 55″ N	16° 05′ 14″ E
Lastovo	Lastovo	186	42° 46′ 06″ N	16° 54′ 00″ E
Mljet	Goveđari	30	42° 46′ 30″ N	17° 21′ 46″ E
	Babino Polje	120	42° 44′ 05″ N	17° 33′ 13″ E
	Maranovići	115	42° 42′ 53″ N	17° 40′ 03″ E

Lastovo is a small carbonate island in the central part of the southern Adriatic with an area of 40.82 km^2 and a maximum elevation of 417 m a.s.l. [17]. The island is surrounded by numerous smaller islets and reefs, and is characterized by a Csa Mediterranean climate type [27] and predominantly carbonate geological composition.

Mljet is a small Adriatic island covering 98.02 km^2 with its highest peak reaching 514 m a.s.l. [17]. The island is predominantly composed of Mesozoic carbonate deposits [30]. According to the Köppen–Geiger classification [26], Mljet has a Csa Mediterranean climate with hot, dry summers and mild, wet winters. The island is characterized by pronounced geomorphological variability with alternating ridges and depressions. The western part of the island, including the Goveđari climatological station, forms part of Mljet National Park [31], while the Babino Polje and Maranovići rain gauge stations are located within the central and eastern sectors, respectively.

Although the analysis is based on a limited number of meteorological stations, the selected stations are considered representative of the principal and physiographic characteristics of the analyzed islands. Nevertheless, local microclimatic variability may not be fully captured.

2.2. Data Used

Table 1 presents the main characteristics of the five analyzed stations in this study. Three of them (Komiža, Lastovo, and Goveđari) are climatological stations providing both temperature and precipitation measurements, whereas Babino Polje and Maranovići are precipitation-only stations. The analysis covers the period 1981–2024. All meteorological data used in this study are official records from the Croatian Meteorological and Hydrological Service (DHMZ), Zagreb.

Data completeness was high across all analyzed stations during the period 1981–2024, and no gap-filling procedures were required. Prior to analysis, the datasets were visually inspected for potential inconsistencies and obvious inhomogeneities. While formal homogenization testing was beyond the scope of this study, no major discontinuities affecting long-term trend interpretation were identified.

2.3. Methods

Linear regression analysis was applied to determine linear trends in time series of mean annual air temperature (T) and total annual precipitation (P). The regression equation is expressed as:

$$Y = (A \times X) + B \quad (1)$$

where Y represents the dependent variable (precipitation P or air temperature T), and X denotes the independent variable, which in trend analysis corresponds to time (year

t). The coefficients A and B are linear regression parameters, estimated using the least-squares method, which minimizes the sum of squared deviations between observed values and the regression line. The coefficient A represents the slope of the regression line. A negative value of A indicates a declining trend, whereas a positive value indicates an increasing trend.

The Pearson correlation coefficient (R) was used to quantify the strength and direction of linear relationships between variables, indicating the degree to which changes in one variable correspond to changes in another under a direct or inverse relationship. For each case analyzed in this study, values of the Pearson correlation coefficient (R) and the coefficient of determination (R^2) were calculated.

The statistical significance of monotonic increasing or decreasing trends in the analyzed climatological time series was assessed using the nonparametric Mann–Kendall (M-K) test [32,33]. The null hypothesis assumes no statistically significant monotonic trend exists in the analyzed series, whereas the alternative hypothesis assumes the presence of a statistically significant trend. The alternative hypothesis was accepted when the M-K test $p < 0.05$.

To characterize linear trends in the analyzed time series, both the parametric regression slope (A), estimated using the least-squares method, and the nonparametric Sen's slope (S) [34] were calculated. It should be noted that the regression parameter A from Equation (1) is highly sensitive to assumptions of normality and the absence of extreme values, which are often present in climatic time series, particularly in the recent period as a result of climate change. Sen's slope estimates the trend as the median of all pairwise slopes between observations, and it is therefore substantially more robust to outliers, nonlinearity, and changes in variance. Consequently, Sen's slope provides a more stable and physically representative estimate of long-term monotonic trends in real-world time series, whereas the regression slope A is more appropriate under idealized conditions in which statistical assumptions are satisfied. In dimensional terms, both trend indicators are expressed in °C/year for mean annual temperature series and in mm/year for annual precipitation series, while trend robustness was evaluated through comparison of parametric and nonparametric estimators together with Mann–Kendall significance testing.

Using mean annual air temperature (T) and annual precipitation (P) data from the climatological stations Komiža (Vis Island), Lastovo (Lastovo Island), and Goveđari (Mljet Island) for the period 1981–2024, values of the New Drought Index (NDI) [35] were calculated. The NDI is a measure of drought intensity, which has been increasingly applied in various regional studies since its introduction in 2023 and has proven to be a reliable drought indicator [36–39]. Weaver et al. [40] applied it to reassess drought conditions in Missouri (USA) for the period 2018–2024.

Although the NDI is based solely on standardized precipitation and temperature anomalies, it reflects hydrological conditions indirectly through the combined influence of moisture supply and temperature-related effects on evaporation and moisture availability.

The NDI is defined as:

$$NDI_i = [(P_i - P_{av})/SD_P] - [(T_i - T_{av})/SD_T] \quad (2)$$

where P_i is precipitation in year i, P_{av} is the average precipitation of the analyzed series, SD_P is the standard deviation of precipitation, T_i is the mean annual air temperature in year i, T_{av} is the average annual temperature of the analyzed series, and SD_T is the standard deviation of mean annual temperature. The index combines standardized precipitation and temperature anomalies within a unified framework, allowing assessment of how temperature variability modifies drought signals beyond precipitation-only conditions. It

assigns equal mathematical weighting to both standardized components, although their physical hydrological influence may vary spatially and seasonally.

Drought monitoring and early warning systems commonly use the Standardized Precipitation Index (SPI) as a quantitative indicator of meteorological drought [41,42]. In this study, the SPI was calculated for all five precipitation stations. It is defined as:

$$SPI_i = (P_i - P_{av})/SD_P \quad (3)$$

where P_i is precipitation in year i, P_{av} is the average precipitation of the analyzed series, and SD_P is the standard deviation of precipitation.

In this study, SPI was computed using a standardized anomaly approach based on mean and standard deviation, capturing interannual precipitation variability and allowing direct comparison with the NDI. This formulation does not include fitting a theoretical probability distribution as in the original SPI procedure.

Drought intensity categories are identical for both indices: mild drought (0 to −1.0), moderate drought (−1.0 to −1.5), severe drought (−1.5 to −2.0), and extreme drought (below −2.0).

Both drought indices (SPI and NDI) and trend analyses were computed on an annual time scale to ensure consistency across variables.

The Standardized Precipitation Evapotranspiration Index (SPEI) was not applied in this study as the objective was to directly compare a precipitation-only index (SPI) with a combined precipitation–temperature anomaly-based index (NDI) within a consistent methodological framework.

3. Results and Discussion

3.1. Analysis of Temperature at the Annual Scale

Figure 2 presents the time series of mean annual air temperatures recorded at the Komiža, Lastovo, and Goveđari stations during the period 1981–2024. Over the analyzed period, Lastovo exhibits the lowest average annual temperature (16.28 °C), while the highest average temperature is observed at Komiža (17.14 °C). The Goveđari station records an intermediate average annual temperature of 16.94 °C.

Table 2 summarizes the trend probabilities (p) derived from the Mann–Kendall test, the Sen slope estimates (S), and linear regression slopes (A) for the mean annual temperature series. A statistically significant warming trend is detected at all three stations ($p < 0.05$), and both trend estimators show strong agreement across all datasets.

Table 2. Trend estimates for mean annual temperature at three stations (1981–2024). Values represent trend probabilities (p) from the Mann–Kendall test, Sen slopes (S), and linear regression slopes (A).

Station	p	S (°C/Year)	A (°C/Year)
Komiža	**2.5×10^{-9}**	0.0455	0.0458
Lastovo	**2.9×10^{-6}**	0.0293	0.0294
Goveđari	**9.3×10^{-10}**	0.0457	0.0447

Note: Red bold values indicate statistically significant increasing trends according to the Mann–Kendall test ($p < 0.05$).

Differences in mean annual temperatures among Komiža, Lastovo, and Goveđari (Mljet Island) are primarily driven by geographic latitude, exposure to the open sea, and local physiographic characteristics.

Komiža records the highest mean temperature due to its position on the western coast of Vis Island, directly exposed to the open Adriatic Sea. This strong maritime influ-

ence moderates winter cooling and enhances the moderating thermal influence of the sea throughout the year.

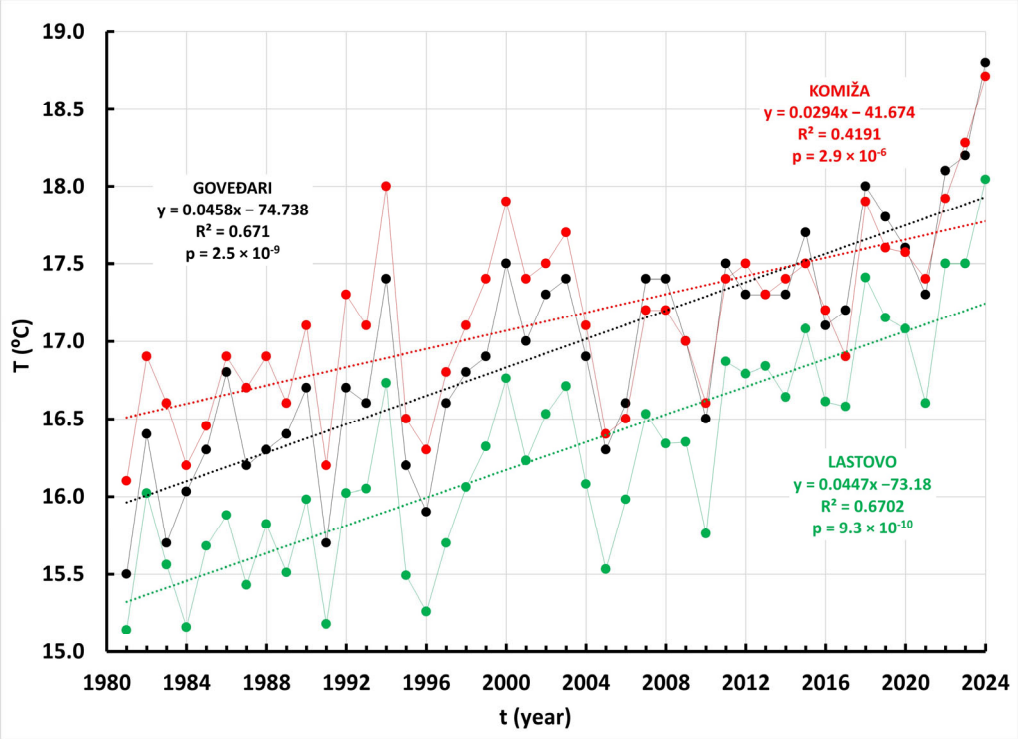


Figure 2. Mean annual air temperature time series at Komiža, Lastovo, and Goveđari (1981–2024).

Lastovo exhibits the lowest mean annual temperature despite its more southerly position. This is partly attributable to its higher elevation relative to other stations, as well as stronger exposure to open-sea conditions, which enhances nocturnal and winter cooling in the absence of significant topographic shielding.

Goveđari on Mljet records intermediate temperature values, reflecting a more balanced influence of maritime exposure and local topographic conditions in the southern Adriatic environment.

Although the temperature differences are small, they are spatially and physically consistent, reflecting the combined effect of elevation, maritime influence, and regional atmospheric circulation patterns.

3.2. Analysis of Precipitation at the Annual Scale

Figure 3 presents the time series of annual precipitation totals recorded at Komiža, Lastovo, Goveđari, Babino Polje, and Maranovići stations during 1981–2024. Annual precipitation varies substantially across the five stations. Average precipitation values for the 1981–2024 study period are as follows: (1) Komiža 724.7 mm; (2) Lastovo 630.8 mm; (3) Goveđari 830.9 mm; (4) Babino Polje 990.0 mm; (5) Maranovići 1031.4 mm.

At Lastovo, a statistically insignificant decreasing trend is observed, whereas Komiža and Goveđari exhibit statistically insignificant increasing trends. In contrast, the two remaining stations on Mljet island (Babino Polje and Maranovići) show a statistically significant increasing precipitation trend ($p < 0.05$). Table 3 summarizes the Mann–Kendall trend probabilities (p), Sen slope estimates (S), and linear regression slopes (A). For the annual precipitation series, the S and A values differ slightly more than in the temperature analysis, although the discrepancy remains minor.

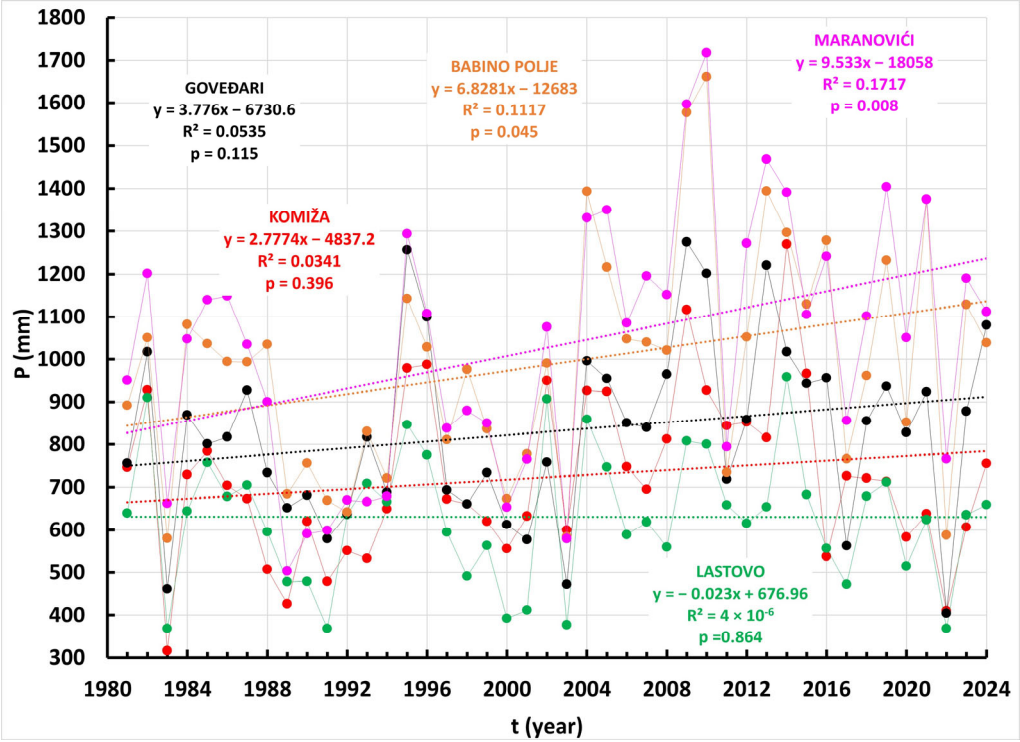


Figure 3. Annual precipitation time series at Komiža, Lastovo, Goveđari, Babino Polje, and Maranovići (1981–2024).

Table 3. Trend probabilities (*p*), Sen slopes (*S*), and regression slopes (*A*) for annual precipitation series (1981–2024).

Station	*p*	*S* (mm/Year)	*A* (mm/Year)
Komiža	0.396	2.31	2.78
Lastovo	0.864	−0.24	−0.023
Goveđari	0.115	4.24	3.78
Babino Polje	**0.0452**	6.21	6.82
Maranovići	**0.0085**	9.52	9.53

Note: Red bold values indicate statistically significant increasing trends according to the Mann–Kendall test ($p < 0.05$).

Differences in mean annual precipitation among Lastovo, Vis, and Mljet result from a combination of regional atmospheric circulation, distance from the mainland, and orographic effects, with Mljet exhibiting a clear advantage in precipitation accumulation.

Lastovo records the lowest precipitation totals due to its greater distance from the mainland and its location within a strongly maritime regime characterized with limited influence from cyclones forming or intensifying over the continental Adriatic region. Air masses approaching Lastovo from the south and west are often thermodynamically stabilized and moisture-depleted, while the absence of pronounced relief further suppresses condensation processes.

Vis receives slightly higher precipitation than Lastovo owing to its closer proximity to the central Adriatic and more frequent exposure to secondary cyclonic systems. Although Vis also experiences a strongly maritime climate, intermittent orographic influences and increased exposure to frontal systems result in moderately higher annual precipitation totals.

Mljet experiences substantially higher precipitation due to the combined effects of its proximity to the mainland, orography, and dynamic atmospheric circulation. The island lies

along the southern Dalmatian coast and is strongly influenced by moist south-westerly and southerly airflows, which undergo forced ascent over Mljet's elevated terrain, enhancing condensation and precipitation production. In addition, Mljet frequently lies within a convergence zone between maritime and continental air masses, favouring longer lasting and more intense precipitation events.

The precipitation gradient from Lastovo through Vis to Mljet reflects a transition from a purely maritime regime toward an orographically enhanced coastal regime, explaining Mljet's dominant precipitation totals within the analyzed island group.

3.3. Analysis of Monthly Temperature Variability

Figure 4 shows mean monthly air temperatures recorded at the Lastovo, Komiža, and Goveđari stations during the period 1981–2024. At all stations, a pronounced temperature minimum occurs during the winter months (January–February), while maximum values are observed in summer, with peak temperatures in July and August. Komiža consistently records the highest temperatures throughout the year, particularly during winter and autumn, indicating a stronger maritime influence and milder winter conditions. Lastovo exhibits the lowest monthly temperatures, especially in winter and during transitional seasons, whereas Goveđari generally shows intermediate values.

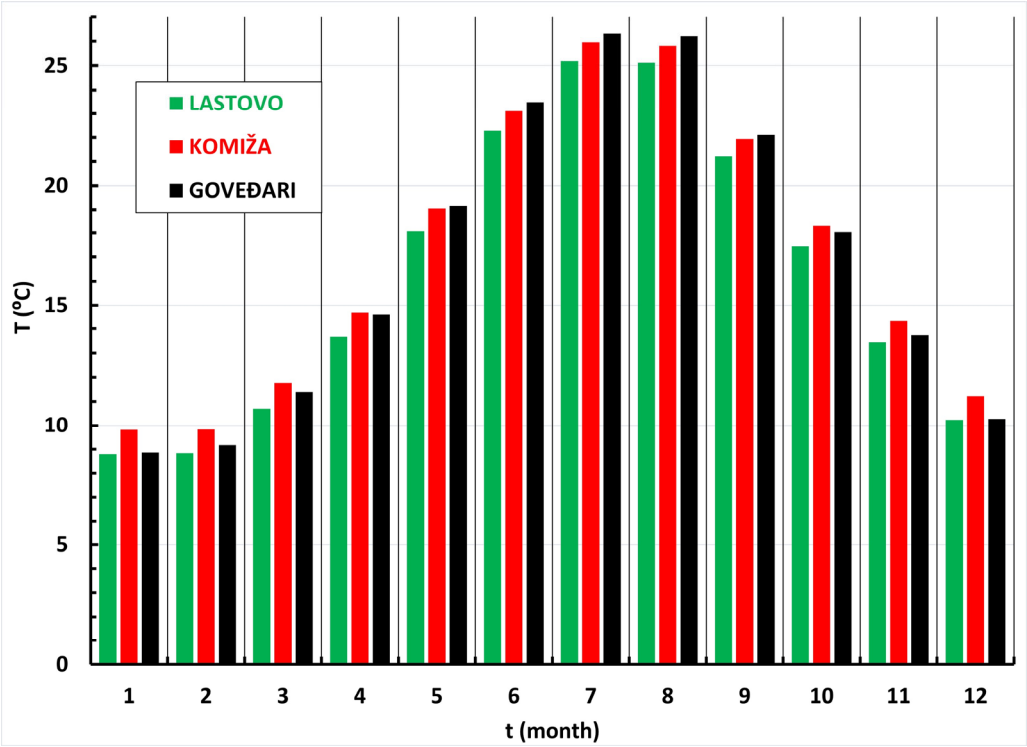


Figure 4. Mean monthly temperatures for the period 1981–2024 recorded at the Lastovo, Komiža, and Goveđari stations.

Inter-station differences are least pronounced in summer, when regional-scale solar forcing and stable atmospheric conditions dominate. In contrast, differences become more evident during winter and transitional months, reflecting local variations in marine exposure, geographic position, and orography. Figure 4 shows subtle yet consistent climatic differences among the analyzed islands.

Table 4 presents Mann–Kendall trend probabilities (p) calculated for monthly mean temperature series at Komiža, Lastovo and Goveđari stations. The results indicate that statistically significant warming is primarily concentrated in the warmer part of the year.

At all stations, the summer months (June-August) stand out clearly, with very low p-values ($p \ll 0.05$), indicating a robust and consistent warming trend. Statistically significant trends are also detected in February and November. In contrast, during the spring months (March–May), warming trends are more pronounced at Lastovo and Goveđari than at Komiža.

Table 4. Mann–Kendall trend probabilities (p) for monthly mean temperature series at three stations during 1981–2024.

Month	Komiža	Lastovo	Goveđari
January	0.384	0.052	0.121
February	**5.0×10^{-3}**	**1.8×10^{-3}**	**3.7×10^{-3}**
March	0.168	**0.022**	0.054
April	0.195	**4.5×10^{-4}**	**1.5×10^{-3}**
May	0.517	**0.047**	**0.030**
June	**6.4×10^{-5}**	**3.5×10^{-6}**	**6.6×10^{-6}**
July	**1.2×10^{-3}**	**1.0×10^{-4}**	**7.2×10^{-5}**
August	**1.9×10^{-3}**	**1.0×10^{-4}**	**7.6×10^{-5}**
September	0.336	**0.040**	**0.019**
October	0.903	0.107	0.153
November	**0.015**	**2.1×10^{-4}**	**4.0×10^{-4}**
December	0.202	**6.6×10^{-3}**	**0.011**

Note: Red bold values indicate statistically significant increasing trends according to the Mann–Kendall test ($p < 0.05$).

Conversely, winter months (January and December) and October generally do not exhibit statistically significant trends, particularly at Komiža, suggesting greater interannual variability and a weaker long-term signal during these periods.

Overall, the results confirm that warming at the analyzed stations is seasonally asymmetric, with a dominant contribution from summer and late spring months.

Table 5 presents the magnitude of monthly mean temperature trends expressed as Sen slopes (S) and linear regression slopes (A), respectively. Values obtained using the two methods are very similar across all months and stations, confirming the robustness of the trend estimates and the consistency between non-parametric and parametric approaches.

The largest positive slopes occur during the summer months (June–August) at all stations, with values generally ranging between 0.05 and 0.075 °C/yr, indicating particularly strong summer warming. Lastovo and Goveđari stand out with systematically higher slopes than Komiža, suggesting a greater rate of temperature increase in the southern Adriatic.

Significant positive slopes are also observed in February and November, indicating an extension of warming from summer into late winter and autumn. In contrast, October shows very small or negligible slopes, especially at Komiža, consistent with the absence of statistically significant trends identified by the Mann–Kendall test.

During winter and transitional months (January, March, April, and September), slopes are generally positive but smaller and spatially more heterogeneous, reflecting greater interannual variability and a weaker long-term signal.

Table 5. Sen's slope (*S*) and regression slope (*A*) values for mean monthly air temperature trends at three analyzed stations during 1981–2024.

Month	Komiža	Lastovo	Goveđari
January	0.018 (0.017)	0.029 (0.026)	0.029 (0.022)
February	0.056 (0.052)	0.066 (0.060)	0.062 (0.059)
March	0.024 (0.023)	0.034 (0.039)	0.034 (0.035)
April	0.012 (0.017)	0.037 (0.044)	0.040 (0.041)
May	0.009(0.012)	0.025 (0.032)	0.033 (0.037)
June	0.061 (0.056)	0.075 (0.073)	0.072 (0.071)
July	0.044 (0.043)	0.063 (0.058)	0.059 (0.057)
August	0.052 (0.047)	0.064 (0.063)	0.067 (0.062)
September	0.012 (0.014)	0.031 (0.027)	0.036 (0.033)
October	0.000 (0.001)	0.024 (0.025)	0.022 (0.025)
November	0.043 (0.045)	0.058 (0.058)	0.058 (0.062)
December	0.020 (0.021)	0.040 (0.039)	0.040 (0.040)

Note: Values outside parentheses represent Sen's slope estimates, while values in parentheses represent linear regression slopes (°C/year).

Taken together, these results confirm that warming is seasonally uneven, with a dominant contribution from summer months and secondary intensification during late winter and autumn.

3.4. Analysis of Monthly Precipitation Variability

Figure 5 presents the average monthly precipitation totals recorded at the Lastovo, Komiža, Goveđari, Babino Polje, and Maranovići stations during the period 1981–2024. All stations exhibit a pronounced precipitation minimum during the summer months, with the driest conditions occurring in July, while precipitation maxima occur in late autumn and winter, particularly in October and November. This seasonal distribution reflects the dominance of stable anticyclonic conditions in summer and enhanced cyclonic activity and frontal systems during the colder part of the year.

The Babino Polje and Maranovići stations, located in the interior and eastern part of Mljet Island, record the highest precipitation amounts throughout the year, indicating a strong orographic effect and greater exposure to moisture-laden air masses. Goveđari exhibits intermediate precipitation values, whereas the coastal stations Komiža and Lastovo are drier, especially during summer, due to stronger maritime influence and weaker orographic forcing. The overall picture confirms a clear spatial and seasonal differentiation of the precipitation regime in the southern Adriatic, with interior and orographically complex island portions being significantly wetter than coastal locations.

Table 6 summarizes monthly precipitation trends at five analyzed stations during the period 1981–2024. Values outside parentheses represent Sen's slope estimates, while values in parentheses indicate least-squares regression slopes. Statistically significant trends according to the Mann–Kendall test ($p < 0.05$) are highlighted in red bold font. Unlike temperature, precipitation does not exhibit systematic or spatially consistent statistically significant trends across most months and stations.

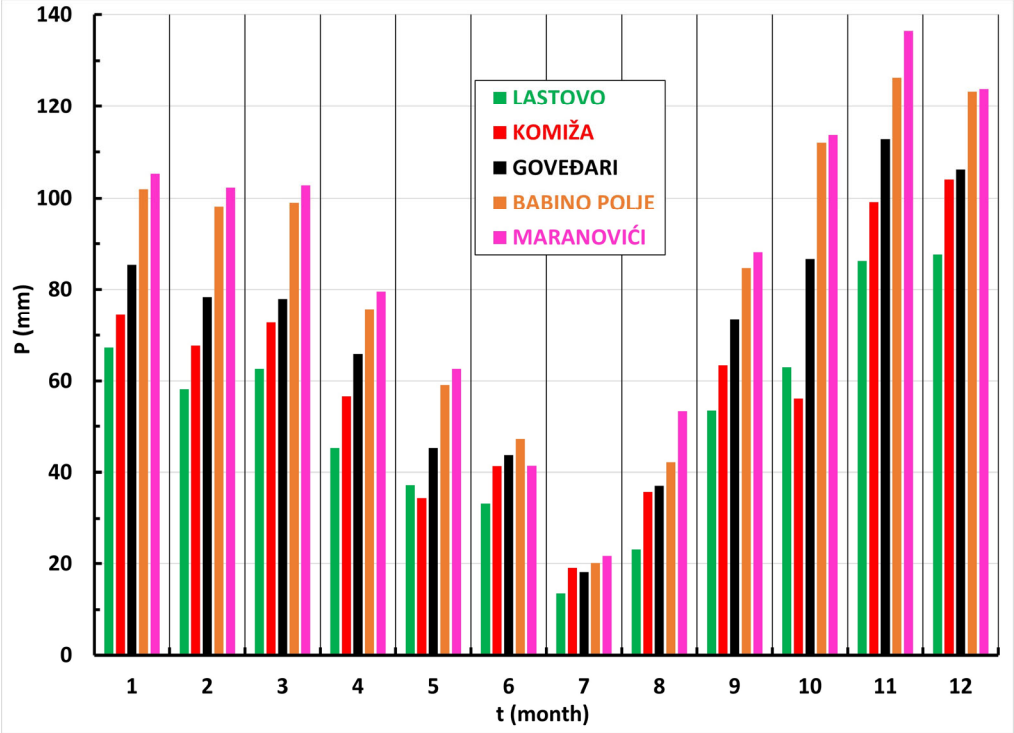


Figure 5. Mean monthly precipitation recorded at the Lastovo, Komiža, Goveđari, Babino Polje, and Maranovići stations during the period 1981–2024.

Table 6. Monthly precipitation trends at five stations during 1981–2024. Values outside parentheses represent Sen's slope (mm/yr), while values in parentheses indicate least-squares regression slopes.

Month	Komiža	Lastovo	Goveđari	Babino Polje	Maranovići
January	0.38 (0.37)	0.62 (0.65)	**1.45 (1.35)**	**2.17 (1.97)**	**2.05 (1.94)**
February	−0.34 (−0.27)	−0.37 (−0.35)	0.15 (0.13)	0.61 (0.81)	1.04 (1.00)
March	0.55 (0.52)	−0.03 (−0.13)	−0.01 (0.15)	0.23 (0.12)	0.18 (0.04)
April	0.22 (0.08)	−0.20 (−0.09)	0.20 (0.16)	0.07 (0.17)	0.69 (0.76)
May	0.36 (0.57)	0.02 (0.15)	0.05 (0.13)	0.23 (0.50)	0.81 (0.95)
June	−0.03 (0.07)	−0.08 (0.08)	−0.15 (0.26)	−0.12 (0.54)	0.07 (0.23)
July	0.05 (−0.01)	0.03 (0.17)	0.00 (0.08)	0.07 (0.21)	0.20 (0.29)
August	0.04 (0.14)	0.03 (0.04)	0.00 (0.24)	−0.11 (0.13)	0.07 (0.38)
September	0.19 (0.67)	−0.15 (−0.39)	0.51 (1.04)	0.46 (0.93)	1.42 (1.72)
October	−0.49 (−0.17)	−0.33 (−0.74)	−0.67 (−0.61)	−0.28 (0.12)	−0.23 (0.33)
November	0.56 (0.68)	0.10 (0.21)	0.88 (0.84)	0.85 (0.90)	1.02 (0.99)
December	0.22 (0.13)	0.09 (0.38)	−0.06 (0.01)	0.21 (0.45)	0.68 (0.92)

Note: Red bold values denote statistically significant increasing trends according to the Mann–Kendall test ($p < 0.05$).

Statistically significant increasing trends ($p < 0.05$) occur only sporadically and locally, specifically in January at the Goveđari, Babino Polje, and Maranovići stations. At the remaining stations and during other months, precipitation trends are statistically insignificant.

These results indicate pronounced natural variability in precipitation and a weak long-term signal at the monthly scale. Unlike temperature, precipitation changes are spatially heterogeneous and seasonally inconsistent, making robust statistical trend detection more difficult.

The Sen's slope and least-squares regression methods yield generally comparable results. Positive slopes occur most frequently during winter and autumn months, particularly in January, September, and November, with the largest values observed at Babino Polje and Maranovići. This suggests a potential increase in cold-season precipitation in the interior and orographically enhanced parts of Mljet Island. In contrast, the coastal stations Komiža and Lastovo display substantially smaller slopes, often close to zero.

During the summer months (June–August), slopes are generally small and alternate between positive and negative values without a clear spatial pattern, consistent with the absence of statistically significant trends and indicating the dominance of interannual variability over any long-term signal. October stands out as a month with predominantly negative slopes at most stations. However, these trends are not statistically significant, suggesting a possible weakening of autumn precipitation without robust statistical confirmation.

Overall, the results confirm that precipitation changes cannot be described by a single regional trend but instead exhibit strong local and seasonal dependence. In contrast to temperature, for which the warming signal is spatially coherent and statistically robust, precipitation trends remain weak, heterogeneous, and uncertain.

3.5. Drought Analysis Using SPI

Figure 6 presents annual SPI values calculated at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024. The annual SPI series exhibits pronounced interannual variability, with frequent alternation between dry and wet years, but without a statistically significant long-term trend. Although regression lines at individual stations indicate a slight increase in SPI, this is primarily the result of several exceptionally wet years in the more recent period that elevate the average of the series, rather than a systematic change in the precipitation regime. This interpretation is supported by very low coefficients of determination (R^2) and statistically insignificant p-values. The figure does not include the Babino Polje and Maranovići stations on Mljet Island, where locally significant positive precipitation trends were identified. However, these trends were largely associated with individual months, particularly January precipitation totals, and therefore explain only a minor fraction of the weak annual precipitation increase observed at three stations. Consequently, the identified changes remain spatially and seasonally limited and do not alter the overall absence of a coherent long-term precipitation signal.

In this context, SPI at the annual scale is not a reliable indicator of an actual change in drought conditions on the Adriatic islands, as it accounts exclusively for precipitation amounts and does not reflect increasing evaporative losses. Under warming conditions, droughts may become more frequent and intense despite stable or even increasing precipitation totals, a signal that SPI fails to detect. For these islands, indices that incorporate temperature and energy-related components (e.g., SPEI or NDI) are therefore more appropriate, particularly at seasonal and warm half-year time scales.

Figure 7 presents annual SPI values calculated at three stations on the island of Mljet (Goveđari, Babino Polje, and Maranovići) for the period 1981–2024. The annual SPI series for Mljet again shows strong interannual variability, but with more pronounced differences among stations than in the previous comparison. At Maranovići, a statistically significant positive SPI trend is observed (p = 0.009), while at Babino Polje the trend is weaker but

close to the significance threshold (p = 0.045). No statistically significant trend is detected at Goveđari.

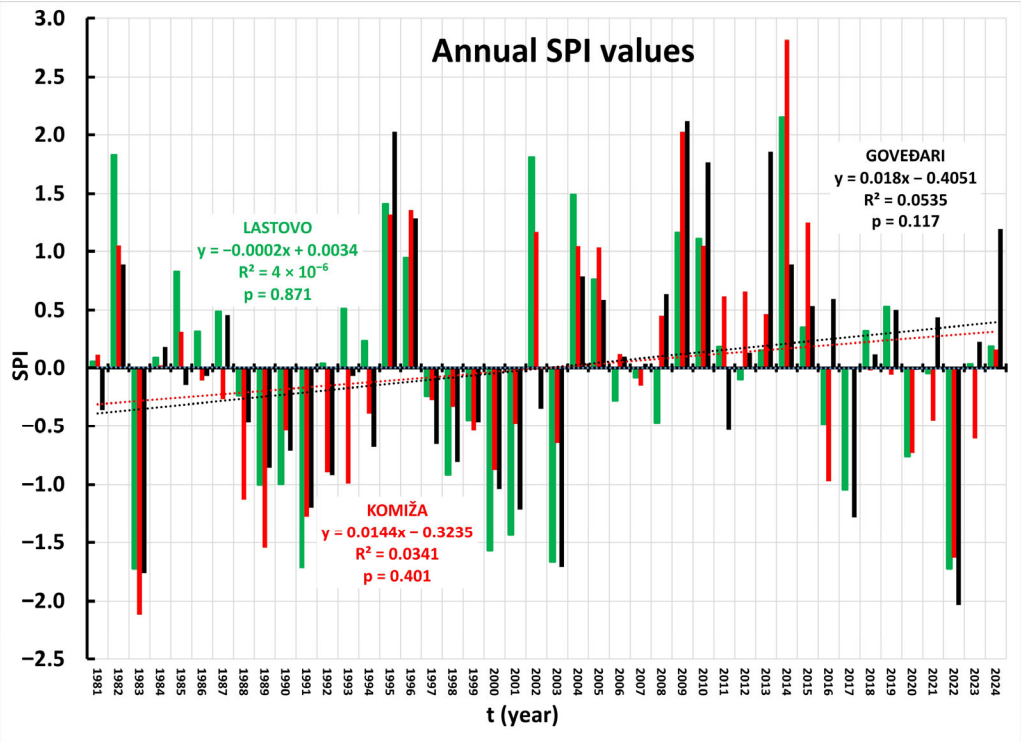


Figure 6. Annual SPI values at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024.

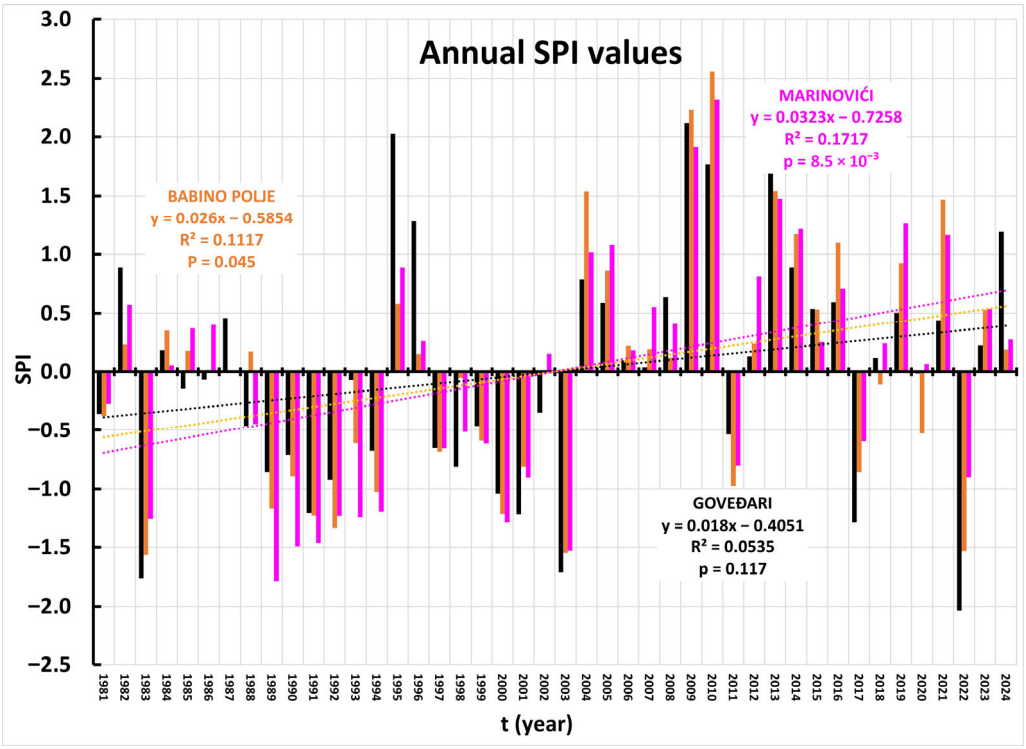


Figure 7. Annual SPI values at three stations on the island of Mljet (Goveđari, Babino Polje, Maranovići) for the period 1981–2024.

It is important to emphasize that a positive SPI trend on Mljet does not imply a reduction in drought severity but rather reflects an increase in annual precipitation or a higher frequency of very wet years, particularly after 2000, which exerts a strong influence on the regression slope. At the same time, the series still contains numerous years with negative SPI values, including pronounced drought episodes, indicating increased variability rather than a stable shift toward wetter climatic conditions.

In the context of Mljet, where drought is perceived and experienced primarily through water availability during the warm part of the year, annual SPI is a limited indicator. It does not account for increased evaporative demand associated with rising air temperatures or for seasonal redistribution of precipitation. Consequently, relatively stable or slightly increasing annual SPI values may coincide with less favourable hydroclimatic conditions during the warm season, underscoring the need for alternative drought indices and analyses at seasonal and semi-annual time scales, particularly for islands such as Mljet.

3.6. Drought Analysis Using NDI

Figure 8 shows the time series of annual NDI values at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024.

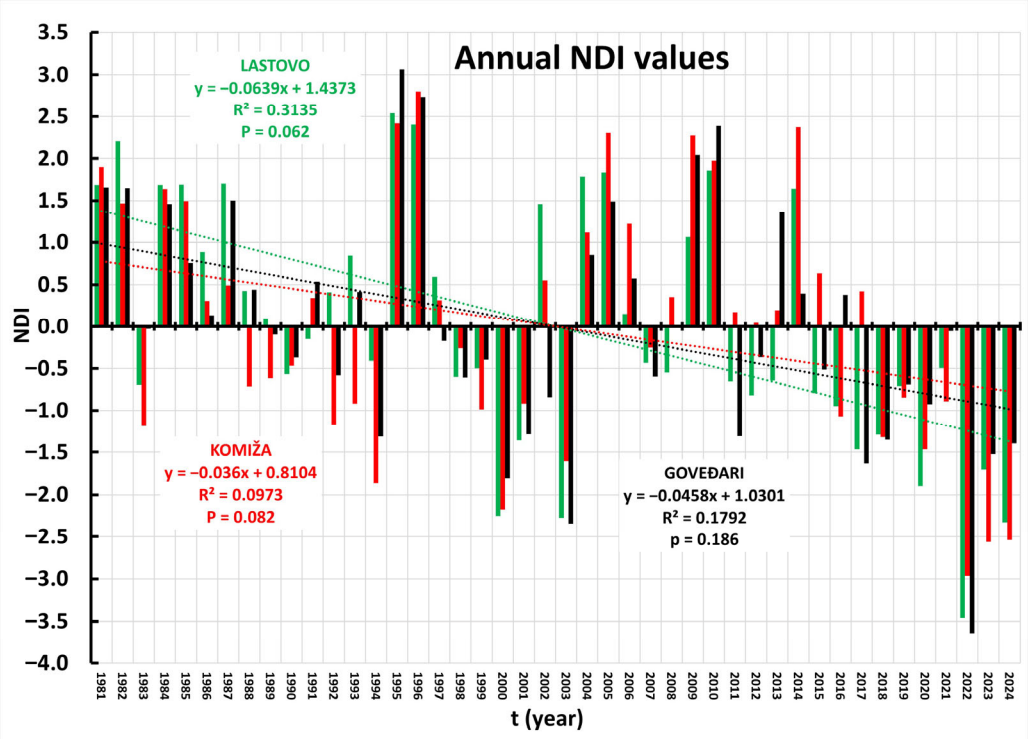


Figure 8. Annual NDI values at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024.

The annual NDI series exhibit a systematic downward tendency at all stations, in contrast to the results obtained by SPI. The trend is most pronounced at Lastovo, where a relatively high coefficient of determination (R^2 = 0.31) indicates moderate explanatory strength of the linear model. Komiža and Goveđari also display negative slopes, although with greater scatter and weaker statistical support. For Lastovo, the trend is close to the conventional significance threshold ($p \approx 0.06$) and therefore should be interpreted as marginally significant rather than strictly conclusive.

Unlike SPI, for which regression lines often show weak or even positive trends due to increasing annual precipitation and occasional extremely wet years, NDI indicates a pro-

gressive deterioration of hydroclimatic conditions over time. This fundamental difference arises from the nature of the indices themselves. SPI responds exclusively to precipitation and is therefore sensitive to precipitation-rich years that can mask drought signals, particularly at the annual scale. In contrast, NDI incorporates the energetic component of climate (temperature and evaporative losses), enabling it to detect increasing drought severity even under stable or rising precipitation totals. The past decade illustrates this contrast particularly clearly. SPI frequently fluctuates around zero or slightly positive values, whereas NDI consistently shifts into negative territory, with pronounced extremes during several recent years.

These results confirm that SPI at the annual scale underestimates the long-term drying trend on the Adriatic islands, whereas NDI captures the underlying climatic signal associated with rising temperatures, evapotranspiration, and increasing drought frequency far more effectively.

Figure 9 presents the NDI time series calculated for June at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024. June exhibits the strongest and most consistent drying signal across the entire dataset. Importantly, the negative June trend persists despite occasional very wet episodes (positive NDI spikes), which do not alter the long-term downward trajectory. Since the early 2000s, negative NDI values have dominated, becoming increasingly frequent and intense in the past decade, clearly indicating a deterioration of hydroclimatic conditions at the very onset of the dry summer season. All three stations show statistically significant negative NDI trends, with p-values ranging from 0.003 to 0.007 and very similar regression slopes (A = −0.04 to −0.05 per year), indicating a regionally coherent climatic signal rather than a local anomaly.

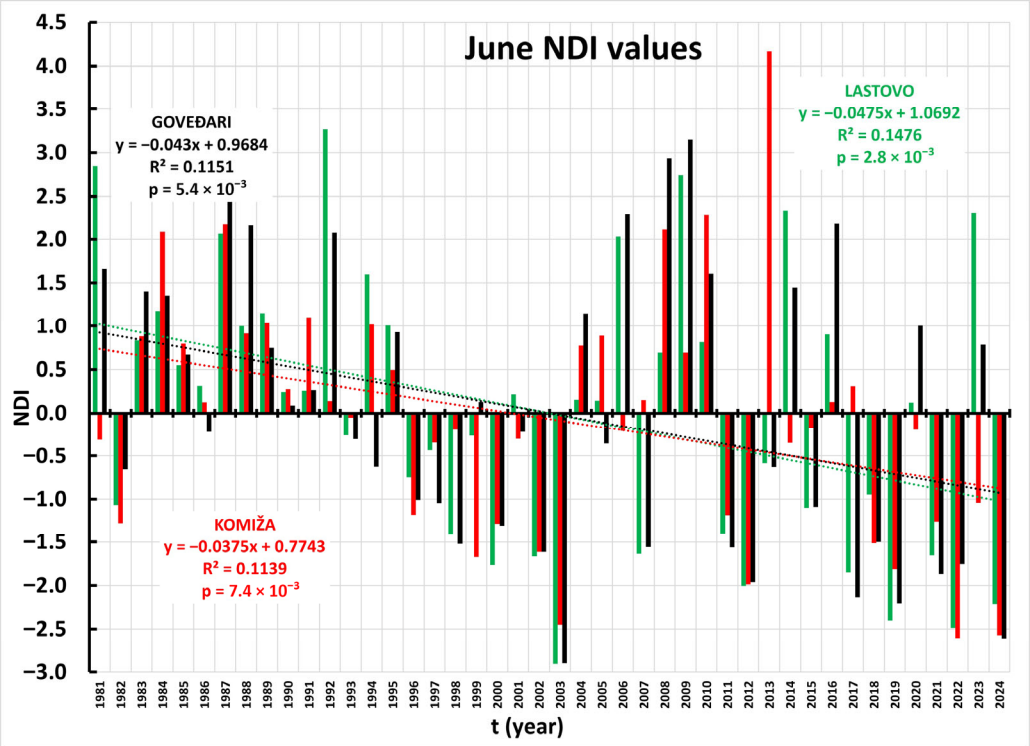


Figure 9. NDI values calculated for the month of June at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024.

From an interpretative perspective, June emerges as a critical transition month. Although precipitation events may still occur and can be intense, rising temperatures and evaporative losses lead to early depletion of available moisture. This explains why NDI

in June captures a signal that SPI cannot reliably detect, making it a key indicator of climate-driven drought on the Adriatic islands.

Figure 10 shows the NDI time series calculated for October at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024. October exhibits a markedly weaker and more heterogeneous signal compared to June, both in terms of long-term trends and statistical robustness. Although all three stations display negative regression slopes, the trends are weak and statistically insignificant ($p \gg 0.1$), with very low R^2 values, particularly at Komiža. This indicates that interannual variability dominates over any long-term climatic signal in October.

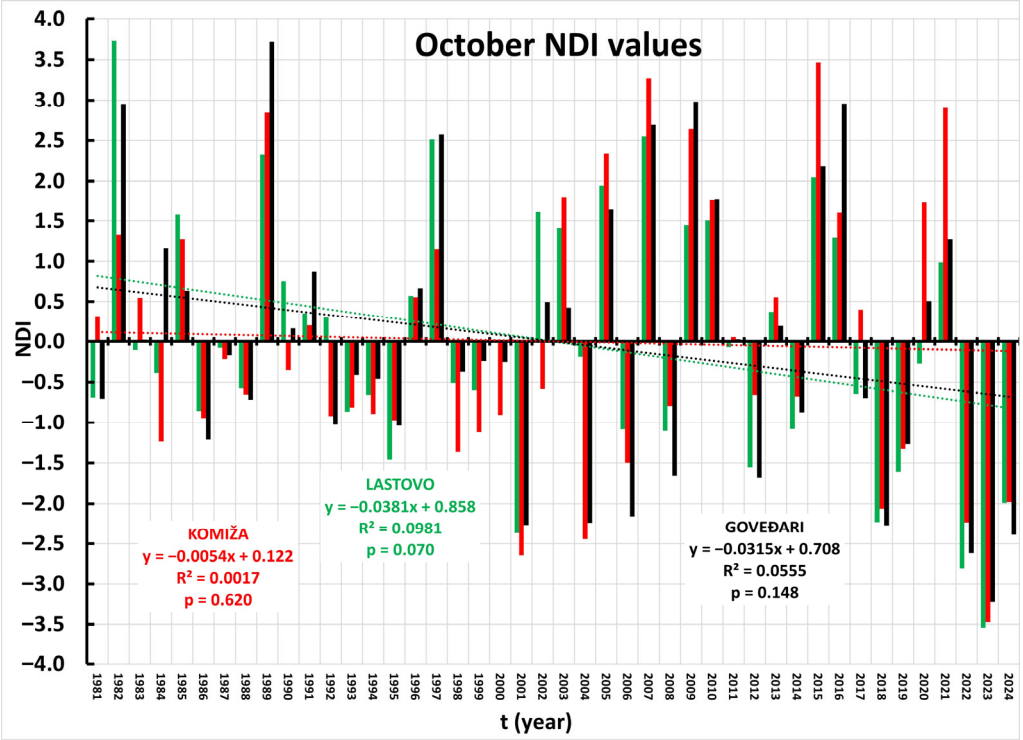


Figure 10. NDI values calculated for October at three stations on the islands of Vis (Komiža), Lastovo, and Mljet (Goveđari) for the period 1981–2024.

Unlike June, October is characterized by a precipitation regime dominated by episodic, often very intense rainfall events, which can occasionally produce strongly positive NDI values. Such events effectively interrupt drought sequences and obscure long-term trends, even under conditions of elevated sea and air temperatures. Consequently, regression slopes remain shallow, and the drying signal lacks spatial coherence among stations.

From an interpretative standpoint, October represents a transitional month with pronounced synoptic variability, during which NDI primarily reflects intermittent precipitation extremes rather than gradual depletion of available moisture. Therefore, unlike early summer, October is not a reliable indicator of long-term drying trends but rather an indicator of changes in the frequency and intensity of extreme precipitation events.

4. Conclusions and Directions for Future Research

This study examined changes in temperature, precipitation, and drought conditions across three small, relatively proximate islands in the southern Adriatic (Vis, Lastovo, and Mljet) from 1981 to 2024, to elucidate the spatial and seasonal heterogeneity of the climatic signal and its implications for drought occurrence. The results demonstrate that climate change on small Mediterranean islands does not manifest uniformly, but rather

through a complex combination of pronounced warming and spatially heterogeneous precipitation variability.

At all analyzed stations, a statistically significant increase in mean annual air temperature was identified, with warming exhibiting pronounced seasonal asymmetry and being strongest during the warm part of the year. The most pronounced and statistically robust trends occur in summer months, particularly June, July, and August, likely enhancing evaporative losses and contributing to increasing pressure on island water resources. In contrast, precipitation changes do not exhibit a consistent regional trend. Annual and monthly precipitation totals generally display weak, spatially heterogeneous, and often statistically insignificant trends, with localized increases observed primarily in the interior and more orographically complex areas of Mljet.

SPI-based drought analysis reveals strong interannual variability. While no statistically significant long-term trend is detected at the annual scale, the temporal distribution of SPI values suggests a reduction in the frequency of strongly negative anomalies in the second half of the record compared to the first half. However, this apparent shift is not sufficient to indicate a robust change in drought occurrence, as it is strongly influenced by internal variability and episodic wet years. In some cases, even positive SPI trends are detected, driven by several exceptionally wet years in the recent period rather than by a genuine reduction in drought conditions. This highlights the sensitivity of SPI to precipitation variability and extreme wet events when assessed at the annual scale.

By contrast, NDI consistently detects a systematic increase in drought severity across all analyzed islands, particularly at the annual scale and during summer months. Negative NDI trends reflect the combined effect of rising temperatures and insufficient or unfavorably distributed precipitation and are consistent with observed deterioration of hydroclimatic conditions. June emerges as a key transitional month, during which a statistically significant and regionally coherent drying signal is evident despite occasional rainfall. Conversely, October exhibits a weak and inconsistent signal, indicating the dominant influence of episodic precipitation extremes and enhanced synoptic variability during the autumn season.

These findings confirm that drought on small Adriatic islands, and likely across much of the Mediterranean, cannot be reliably assessed using precipitation-based indicators alone, but requires an integrated approach that explicitly incorporates the energetic component of the climate system. In this respect, NDI proves to be a substantially more appropriate index for evaluating climate-driven drought in Mediterranean island environments.

Future research should therefore focus on: (1) drought analyses at shorter temporal scales (seasonal and semi-annual), with particular emphasis on the warm half-year; (2) linking NDI with hydrological and hydrogeological indicators, including groundwater levels, spring discharge, and aquifer salinization; (3) detailed assessment of compound extreme events (combined droughts and intense precipitation) and their role in altering effective water availability; and (4) expanding the analysis to a larger number of island stations to test the spatial robustness of the identified patterns.

Although the results clearly indicate a deterioration of hydroclimatic conditions, it should be emphasized that the length of the analyzed period remains relatively short for detecting nonlinear climate dynamics and potential regime shifts. Moreover, while NDI represents a methodological improvement over SPI, it remains an index-based metric that simplifies the complex processes governing real island hydrological systems. Consequently, the conclusions should be interpreted as a robust signal of emerging trends rather than a comprehensive representation of all components of island water balance. These limitations further highlight the need for future studies to integrate climatological, hydrological, and socioeconomic perspectives.

Author Contributions: Conceptualization, O.B.; methodology, O.B. and T.R.-B.; software, O.B. and A.Ž.-Ć.; validation, A.Ž.-Ć. and T.R.-B.; formal analysis, O.B. and T.R.-B.; investigation, O.B. and A.Ž.-Ć.; data curation, O.B. and A.Ž.-Ć.; writing—original draft preparation, O.B.; writing—review and editing, A.Ž.-Ć.; visualization, O.B. and A.Ž.-Ć.; supervision, T.R.-B.; project administration, T.R.-B. 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 original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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