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# Spatial and Temporal Analysis of Extreme Wind Events in Türkiye

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## Abstract

This study investigated the spatial distribution, occurrence frequency, and long-term trends of extreme wind conditions in Türkiye using daily maximum wind speed records from 79 meteorological stations covering 1975-2023. For each station and calendar month, annual P90 wind speeds were calculated, and their mean over valid years was used as the long-term P90 threshold. Days on which daily maximum wind speed equalled or exceeded this threshold were counted, and seasonal exceedance frequencies were standardized to 90 valid days. Trends were assessed using the Mann-Kendall test, Sen's slope, and BH-FDR correction. P95 was used to evaluate sensitivity to percentile selection, and four homogeneity tests were applied to the seasonal P90 and P95 wind speed series. In winter, high wind speeds were concentrated mainly in northwestern Türkiye and at coastal stations exposed to maritime influences; in summer, localized high-speed areas occurred in both coastal and inland regions. Stations with the highest wind speeds did not always have the highest exceedance frequencies. P90 exceedance frequencies decreased significantly at 50 of 77 stations and increased significantly at 2 stations in winter; the corresponding numbers for summer were 42 and 13 of 79 stations. P90 and P95 trend classifications agreed at 96.1% of stations in winter and 93.7% in summer, with no reversal between significant increases and decreases. Homogeneity results were treated as supplementary data-quality information, and no homogenization adjustments were applied. The study provides an observational framework integrating local extreme wind speeds, exceedance frequencies, and temporal changes across Türkiye.

## Keywords

Windstorm, Wind Speed, Percentile, Storminess, Türkiye

## 1. Introduction

Variability and long-term changes in the climate system can influence the frequency, intensity and spatial distribution of meteorological hazards such as heatwaves, heavy rainfall, drought and extreme winds. Monitoring these hazards is important in terms of disaster risk reduction, transport and infrastructure safety, coastal management and early warning systems [1] [2]. Wind conditions vary on a regional scale, depending not only on atmospheric circulation but also on the land-sea distribution, elevation, orography and surface characteristics. The fact that surface winds in Türkiye reflect the combined influence of synoptic pressure conditions and physical geographical features demonstrates that the country cannot be regarded as a single, homogeneous wind region [3]. For this reason, in the climatology of extreme winds, it is necessary to examine wind speeds, occurrence frequencies, seasonality and spatial distribution patterns. The percentile approach is widely used to determine relatively high wind speeds in long-term time series. This approach enables stations with different climatological characteristics to be assessed within their own observation distributions. Whilst P90 represents approximately the top 10 per cent of daily observations, more selective percentiles can test the sensitivity of the findings to the chosen threshold. Furthermore, extreme wind speed and the frequency of occurrence of these conditions can be considered as different indicators [4]. In international studies, station observations, reanalysis, and regional climate models have been used in conjunction with the P90-P99, Peak-Over-Threshold, return period, and trend methods [5]-[9]. This diversity in the studies necessitates the clear specification of wind variables, data sources, temporal scales, and definitions of extremes. The regional distribution of extreme winds reflects the interaction between large-scale atmospheric circulation and local geographical conditions. The Mediterranean's location between the mid-latitudes and the subtropical zone, together with its surrounding mountain ranges and sharp land-sea transitions, influences cyclone formation and tracks [10]. The seasonal variability of high-wind conditions in the eastern Mediterranean may be associated with cyclonic systems and strong pressure gradients during winter [2] [10] and with the Etesian circulation during summer [11]. Because coastal exposure, straits, valleys, and topographic barriers can modify the surface effects of this circulation at the local scale, station-based observations are essential for characterizing regional wind climatology. Studies in Türkiye have primarily focused on trends in average wind speeds, energy potential, and wind or storm climatology in specific regions. Studies based on long-term station records have indicated that decreasing trends in average wind speeds are widespread [12]-[14]. In energy-focused studies, probability distributions, power density, artificial neural networks and GIS-based mapping methods have been utilized [15]-[17]. Research on extreme conditions has largely focused on coastal areas, the Black Sea Region, or the winter season; wind-wave relationships, station classification, and synoptic patterns have been examined [18]-[20]. **Table 1** summarizes the data, methods, and research focus of the selected studies.

**Table 1.** Summary of selected studies on extreme winds and storms in terms of data, methodology and research focus.

| Study | Data and methods used | Research focus |
|---|---|---|
| Kunz *et al.* [5] | Station observations for Germany, including REMO and CCLM outputs; POT, GPD and return period analysis. | Extreme wind events and the performance of regional climate models. |
| Vagenas *et al.* [6] | RegCM3 outputs for the Greek seas and 15 coastal stations; P95 and model-observation comparison. | Strong winds over marine areas and model performance. |
| Kruglova and Myslenkov [8] | Model-based wind and wave data for the Caspian Sea; POT and storm sequence analysis. | The number, duration and variation of marine wave storms. |
| Dadaser-Celik and Cengiz [12] | 206 stations in Türkiye, 1975-2006; Mann-Kendall, pre-whitening and Sen's slope. | Annual, seasonal and monthly average wind speed trends. |
| Yilmaz [13] | 111 stations in Türkiye, 1959-2018; analyses of homogeneity and trends. | Average wind patterns, data homogeneity and trends. |
| Şahin [18] | Wind and wave data for the Sakarya River Delta; climatology and storm analysis | Coastal winds, wave conditions and storm characteristics |
| Başar Görgün and Menteş [20] | NEWA and ERA5 data for Türkiye; P98, K-means, EOF and SOM | Winter extreme wind clusters and synoptic patterns |

In the literature, there are significant studies on wind trends and regional extreme conditions in Türkiye. Conversely, there are few studies that examine, at a national scale, extreme wind speeds, the number of days on which these speeds are exceeded, and their seasonal and temporal trends, all derived from long-term station observations. This gap in the literature necessitates a comparison of how extreme wind varies in terms of speed and frequency across Türkiye's different geographical environments.

This study aims to examine the spatial distribution of extreme wind speeds, the number of exceedance days, and their seasonal and temporal trends during winter and summer using daily maximum wind speed records from 79 stations operated by the Turkish State Meteorological Service (TSMS), with an overall observation period of 1975-2023. The analysis focused on December, January, February, June, July, and August. Only series with at least 40 valid season-years were included in the trend analyses. Station-year records that did not meet the data-completeness criterion were excluded, and missing observations were not imputed. For each station, year, and calendar month, the P90 wind speed was calculated; the mean of the annual P90 values across valid years was then used as the station- and month-specific long-term threshold. Days on which the daily maximum wind speed equaled or exceeded this threshold were identified as exceedance days. Seasonal exceedance counts were standardized to 90 valid days, and trends were evaluated using the Mann-Kendall test, Sen's slope estimator, and the Benjamini-Hochberg false discovery rate (BH-FDR) correction. A P95 analysis was conducted to assess the sensitivity of the findings to percentile selection. The homogeneity of the seasonal P90 and P95 wind speed series was examined using the Pettitt test, standard normal homogeneity test (SNHT), Buishand range test, and von Neumann ratio test. This study contributes to the existing literature by evaluating extreme wind speeds separately from exceedance frequencies and by as-

sessing the sensitivity of the P90 findings through a P95 analysis.

## 2. Data and Methods

The daily maximum wind speed records obtained from the General Directorate of Meteorology (MGM) are expressed in metres per second (m/s). The analyses cover 79 stations distributed across Türkiye and the overall observation period from 1975 to 2023 (Figure 1). The number of valid years per station varies by calendar month. Station numbers, coordinates, elevation, the number of valid years for the selected months and the proportion of missing data are presented in Supplementary Table S1. For a month-year group to be considered valid, at least 90 per cent of the expected daily observations must be present. This percentage-based criterion is generally consistent with the RClimDex approach of allowing a maximum of three missing days per month and ensures that a common rule is applied to months of varying lengths [21]. Groups that did not meet this condition were excluded.

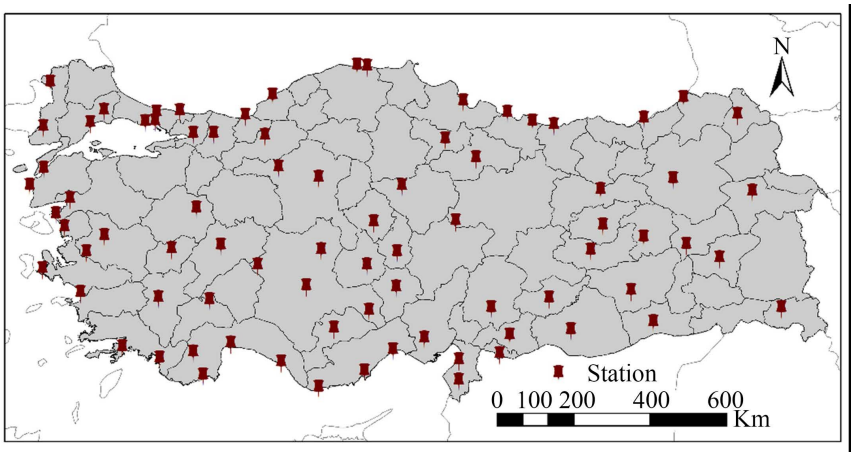



Figure 1. A map showing the locations of the 79 meteorological stations used in the study.

Following the data adequacy check, the Pettitt test, the Standard Normal Homogeneity Test (SNHT), the Buishand Range test and the Von Neumann ratio test were applied to the seasonal P90 and P95 wind speed series for the winter and summer seasons. The p-values for the tests were calculated using 30,000 Monte Carlo permutations. Whilst the Pettitt, SNHT and Buishand Range tests were used to identify potential points of change, the Von Neumann ratio test—which does not specify a particular break year—was treated as a complementary test to assess the overall homogeneity of the series. The 1 percent significance level proposed by Wijngaard *et al.* [22] was used as the basis for classifying the series. Accordingly, if the null hypothesis that the series is homogeneous was rejected in none or one of the four tests, the series was classified as Class 1 (usable); if rejected in two tests, as Class 2 (doubtful); and if rejected in three or four tests, as Class 3 (suspicious). As single-station absolute homogeneity tests cannot definitively distinguish between actual regional climate changes and the effects of variations in

station, instrument or observation conditions, the identified potential breaks were evaluated as a supplementary indicator of data quality. The overall data processing and analysis workflow followed in this study is summarized in Figure 2.

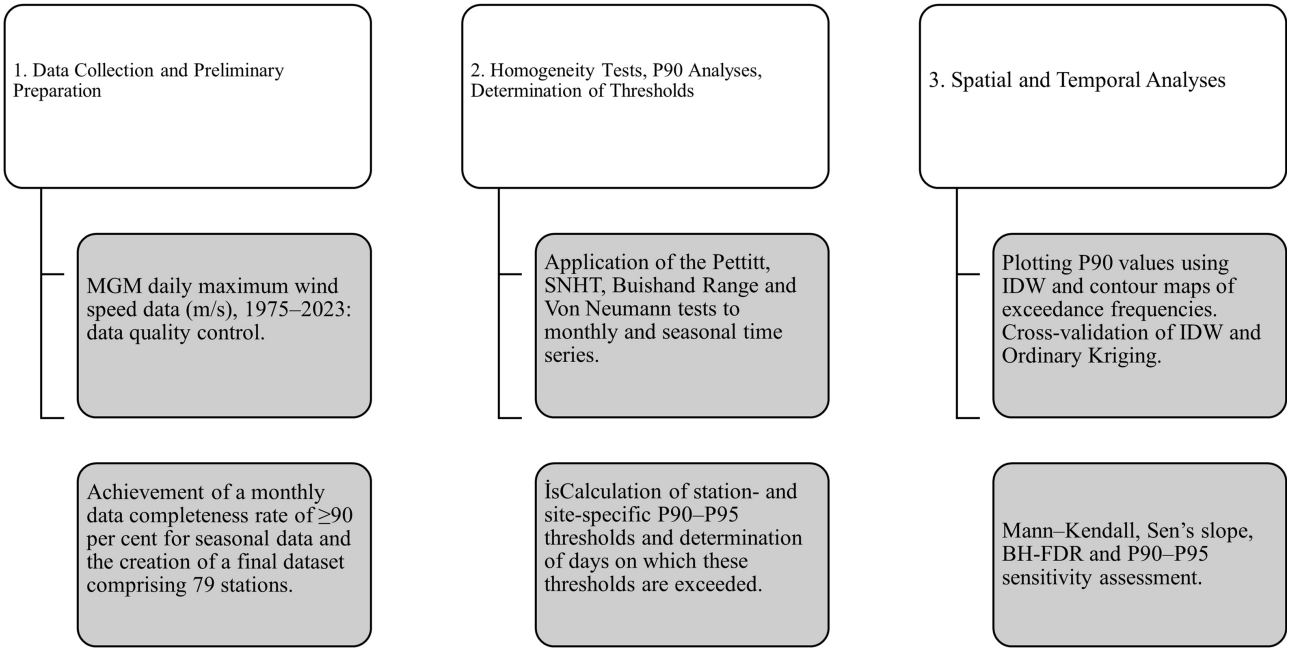



Figure 2. Flowchart of the data processing and analysis procedure used in the study.

The study was limited to the months of December, January, February, June, July and August. The P90 of the daily maximum wind speeds for the relevant calendar month was calculated for each station and year; the average for the relevant years was used as the station's own long-term P90 wind speed threshold specific to its observation series and the month in question. The annual average number of exceedance days was obtained by counting the days on which the daily maximum speed was equal to or higher than this threshold. In this way, extreme wind speed and its frequency of occurrence were examined as separate indicators. This relative definition represents high wind conditions according to local climatology. The calculations were also repeated for P95; whilst the results were used for sensitivity analysis, the main maps and assessments were based on P90. Long-term wind speeds for the selected months were depicted using the IDW method in the ArcGIS 10.8 environment, whilst the annual average number of exceedance days was shown using contour maps. In the IDW application, the power parameter was set to 2, and exactly 12 stations were used in a single-sector standard search neighborhood. The radius of the circular search neighborhoods was set at approximately 4.657˚, and the source coordinate system was defined as GCS WGS 1984. As the geostatistical layer was exported directly, no separate raster cell resolution was used. To evaluate the spatial prediction performance, IDW and Ordinary Kriging were subjected to cross-validation using the same station data. For Ordinary Kriging, a stable semivariogram model was selected. The methods were com-

pared using mean error (ME) and root mean square error (RMSE), with an absolute ME closer to zero and a lower RMSE indicating better predictive performance.

For temporal analysis, the monthly exceedance days have been combined at winter and summer levels. The winter season comprises January and February of the relevant year, relative to the previous year's range, whilst the summer comprises June, July and August of the same year; data sufficiency was required for all three months. As the number of valid observations ranged from 86 to 91 in winter and from 88 to 92 in summer, the number of exceedance days used solely in the seasonal trend analysis has been standardized to 90 days using the following equation. Standardized exceedance frequency = 90 × (number of seasonal exceedance days/number of valid observations in the season). Ninety days represent approximately one meteorological season, whilst the requirement for 90 per cent monthly data completeness limits any overscaling that might arise from missing observations. The normalisation of exceedance days relative to the valid observation period is consistent with the approach used in studies on percentile-based climate indicators and event frequency [23]-[25]. Only time series with at least 40 valid seasonal years were included in the trend analysis. The significance and direction of monotonic trends in the standardized time series were determined using the two-sided Mann-Kendall test [26] [27], whilst the magnitude of change was determined using the Sen slope [28]. In the Mann-Kendall analysis, the Z-statistic adjusted for equal observations and continuity was used; Sen slopes were reported in the form of days per 10 years, obtained by multiplying the annual slope by 10. To control for false positives arising from multiple tests within the station network, BH-FDR correction was applied to the p-values obtained from the Mann-Kendall test [29] [30]. The correction was carried out separately for the winter-P90, summer-P90, winter-P95 and summer-P95 families; a corrected p-value of $<0.05$ was taken as the significance criterion. Trend analyses covered all stations that met the data adequacy criteria. Canakkale, Samsun, Ardahan and Adana were selected solely for the detailed graphs in order to illustrate different geographical environments and trend classes, in addition to having sufficient data lengths. Assessments at the national level, however, were based on all time series that met the data adequacy criteria. Data processing, homogeneity checks, percentile and trend calculations were carried out in the Python environment using pandas and NumPy; graph and table checks were performed in Microsoft Excel; and maps of location, wind speed and exceedance days, as well as spatial cross-validation, were generated in ArcGIS 10.8.

## 3. Findings

Extreme wind conditions in Türkiye were assessed on the basis of station- and site-specific long-term P90 wind speeds and the annual average number of days on which these speeds were reached or exceeded. The findings present, in turn, the spatial distribution of wind speeds, followed by that of the number of days on which these speeds were exceeded, and then the seasonal trends.

In winter, wind speeds ranged from 6.6 - 22.9 m/s in December, 7.2 - 23.0 m/s

in January and 7.5 - 23.0 m/s in February. Bozcaada recorded the highest speeds in all three months, whilst Canakkale and Hopa also stood out for their high values. The lowest speeds were recorded in Mus in December, and in Agri in January and February. The spatial distribution revealed that high speeds were particularly concentrated in north-western Türkiye and at certain coastal stations exposed to maritime influences, whilst the inland and eastern regions exhibited a more fragmented pattern (Figure 3). In summer, wind speeds ranged from 6.4 - 15.6 m/s in June, 6.1 - 16.7 m/s in July and 5.8 - 16.4 m/s in August. Bozcaada again ranked first in all months, whilst Kirsehir was the inland station where the second-highest speeds were recorded across all three months. Whilst high wind speeds varied by month in Canakkale, Kahramanmaras, Diyarbakır and Mardin, the lowest levels were recorded in Alanya during all three months. The concentration of high wind speeds during the summer months not only along the coast but also around certain stations in Central, Eastern and South-Eastern Anatolia indicates that the spatial distribution exhibits a multi-centered and localized pattern.

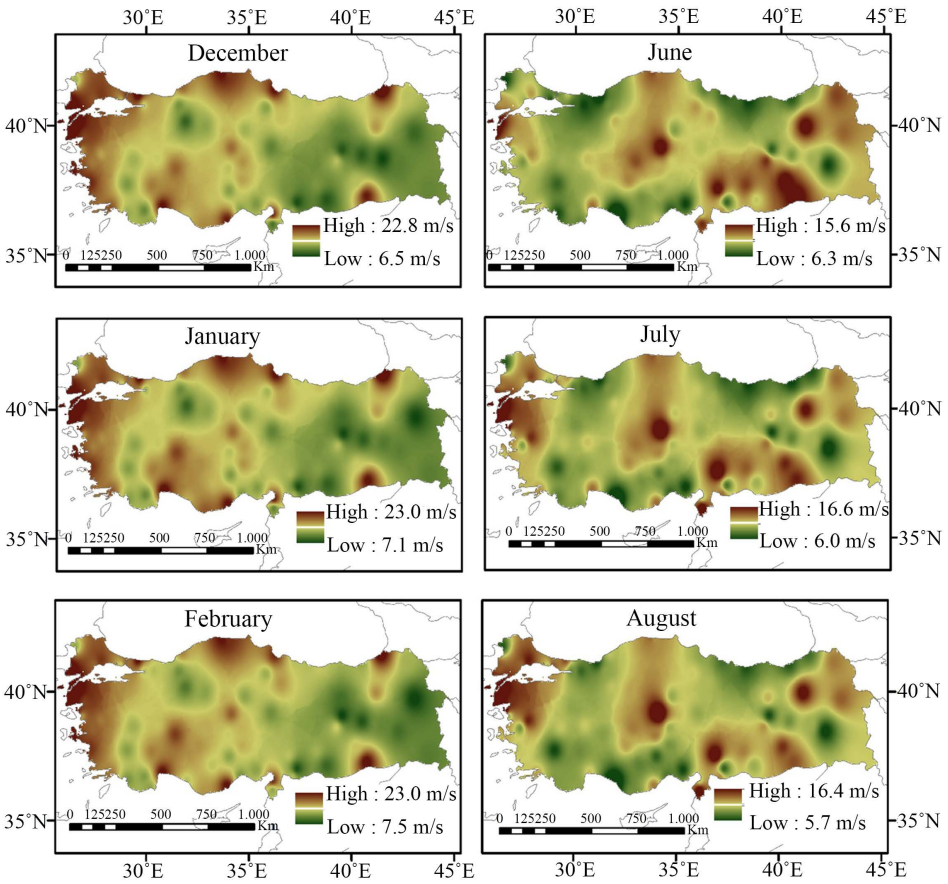



**Figure 3.** Long-term P90 wind speed maps generated using the IDW method for the selected six-month period. The points represent the meteorological stations used in the analysis, whilst the colour scales indicate the minimum and maximum speeds for each month (1975-2023).

In cross-validation, the ME results for both methods were found to be close to zero, and no significant systematic bias was observed. Ordinary Kriging yielded a

lower RMSE in December, January, July and August, whilst IDW yielded a lower RMSE in February and June. The six-month average RMSE was 2.1752 m/s for IDW and 2.1508 m/s for Kriging, with the difference in favour of Kriging being only 1.12 per cent. As the prediction performances were similar and IDW is simple, deterministic and consistently applicable to monthly maps, IDW was retained for visualizations.

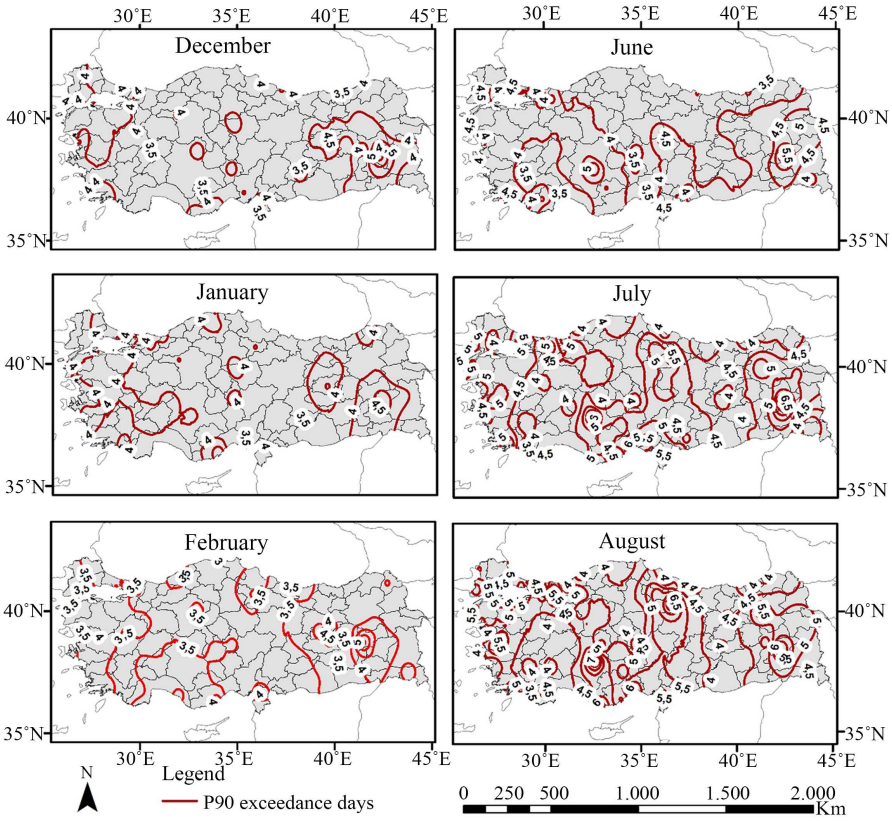



**Figure 4.** Spatial distribution of the annual average number of days (days per year) on which the daily maximum wind speed is equal to or higher than the station- and month-specific long-term P90 threshold during the winter and summer months.

The annual average number of days exceeding the threshold ranged from 3.2 - 5.6 days per year in December, 3.4 - 4.9 days per year in January, and 2.9 - 5.5 days per year in February. The highest frequency was recorded in Tatvan in December and January, and in Muş in February; Tunceli, Şile and Silifke also stood out in certain months. The lowest figures were recorded at the Adıyaman, Adana and Kocaeli stations, respectively. Rather than a continuous regional belt, localised clusters were observed in certain basin and valley areas of Eastern Anatolia and in various coastal regions (**Figure 4**). Annual averages in summer range from 3.18 - 5.7 days/year in June, 3.0 - 7.0 days/year in July and 3.3 - 7.2 days/year in August. Tatvan recorded the highest frequency in June and July, whilst Konya did so in August. Tokat recorded a figure of 7.1 days/year, very close to that of Konya. The rise in the number of stations with a monthly average exceeding 5 days/year—to

22 in July and 26 in August—indicates that high frequencies became more widespread in the second half of the summer. During this period, distinct clusters were not confined to the coastal regions; they also emerged in Central and Eastern Anatolia and the inland areas of the Black Sea region.

When the two sets of maps were compared, it was found that the areas with the highest wind speeds did not coincide with those having the highest number of days exceeding the threshold. Although Bozcaada recorded the highest speeds throughout the entire six-month period under review, it did not rank first in terms of frequency every month. In contrast, Tatvan, Muş, Konya and Tokat stood out for their number of days exceeding the threshold in certain months, even though their speeds were not consistently among the highest. In winter, high wind speeds were more pronounced in the northwest and along the coast, whilst high frequencies were concentrated at certain stations in Eastern Anatolia; in summer, both indicators exhibited a multi-centred distribution across coastal and inland areas. Seasonal trend analyses of exceedance frequencies standardized to 90 valid days showed that significant decreases predominated after BH-FDR correction. Because two winter series did not meet the minimum requirement of 40 valid sharply season-years, the winter analyses included 77 stations, whereas the summer analyses included all 79 stations. In winter, significant decreases were identified at 50 stations, significant increases at 2 stations, and non-significant trends at 25 stations. The corresponding numbers for summer were 42, 13, and 24, respectively. Thus, decreases constituted the majority in both seasons, while the number of stations showing significant increases was higher in summer than in winter. Canakkale, Samsun, Ardahan, and Adana were selected for detailed graphical presentation because they had sufficiently long records and represented contrasting geographical settings: the Marmara-Aegean transition zone, the central Black Sea coast, the high plateau of north-eastern Anatolia, and the Cukurova Plain, respectively. These stations were selected solely to illustrate contrasting geographical settings and trend classes.

Whilst a significant decrease of −2.0 days per 10 years was observed in winter in Canakkale, the decrease of −1.3 days per 10 years in summer was not found to be significant. The summer series showed high variability in the 1990s and early 2000s, but generally declined in the subsequent period. The strongest winter trend among the selected stations was observed in Samsun; the decrease was calculated as −4.6 days per 10 years in winter and −3.0 days per 10 years in summer. In Ardahan, statistically significant decreases of −2.5 and −2.7 days per 10 years were also identified for winter and summer, respectively, with lower frequencies becoming more prevalent after the 2010s. In Adana, the winter trend was not found to be significant, and the Sen trend was calculated as 0.0 days per 10 years. In summer, however, a statistically significant increase of +3.7 days per 10 years was observed across the entire study period; the series showed particularly higher values from the 2010s onwards. These contrasting patterns indicate that the predominant decrease observed nationwide did not occur in the same direction across all stations and seasons (**Figure 5**).

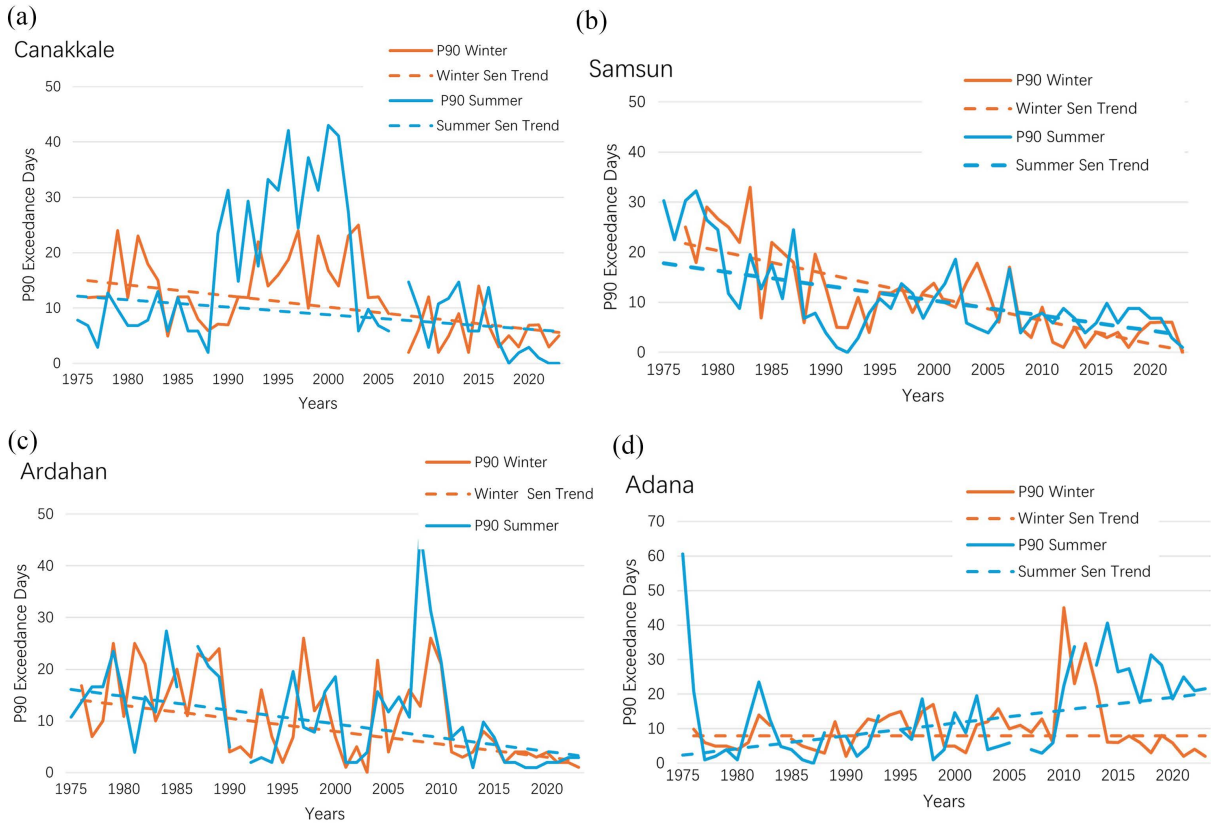



**Figure 5.** Temporal variation in 90-day standardized exceedance frequencies for the winter and summer periods in Canakkale, Samsun, Ardahan and Adana (1975-2023). (a) Canakkale—Winter: significant decrease ($Z = -3.06$; $\tau b = -0.315$; pFDR = 0.0038; Sen slope = −2.00 days/decade). Summer: non-significant decrease ($Z = -1.91$; $\tau b = -0.194$; pFDR = 0.0770; Sen slope = −1.33 days/decade). (b) Samsun—Winter: significant decrease ($Z = -5.52$; $\tau b = -0.562$; pFDR = $3.31 \times 10^{-7}$; Sen slope = −4.64 days/decade). Summer: significant decrease ($Z = -4.15$; $\tau b = -0.419$; pFDR = 0.000125; Sen slope = −2.98 days/decade). (c) Ardahan—Winter: significant decrease ($Z = -3.78$; $\tau b = -0.383$; pFDR = 0.0004; Sen slope = −2.50 days/decade). Summer: significant decrease ($Z = -3.26$; $\tau b = -0.336$; pFDR = 0.0023; Sen slope = −2.67 days/decade). (d) Adana—Winter: no significant trend ($Z = 0.05$; $\tau b = 0.006$; pFDR = 0.9634; Sen slope = 0.00 days/decade). Summer: significant increase ($Z = 3.23$; $\tau b = 0.339$; pFDR = 0.0024; Sen slope = +3.72 days/decade).

Homogeneity tests were applied not to the exceedance frequency series, but to the seasonal P90 and P95 wind speed series. Of the stations shown as examples in the graphs, the complete winter and summer P90-P95 series for Canakkale and Samsun were classified as Class 3, whilst all of Adana's series were classified as Class 1. Ardahan's winter P90, winter P95 and summer P90 series were classified as Class 3, whilst its summer P95 series was classified as Class 2. In the winter season, 14 of the P90 series were classified as Class 1, 8 as Class 2 and 57 as Class 3, whilst for the P95 series these figures were 17, 11 and 51 respectively. In the summer season, 8, 11 and 60 stations for the P90 series, and 11, 12 and 56 stations for the P95 series were classified as Class 1, Class 2 and Class 3 respectively. Accordingly, the Class 3 proportions were calculated as 72.2 per cent for winter and 75.9 per cent for summer in the P90 series, and 64.6 per cent and 70.9 per cent respectively in the P95 series. These classifications were used as supplementary data quality indicators; no adjustments were applied to the series for homogeni-

zation purposes, and Class 2 - 3 series were not automatically excluded from the analysis. However, the high proportion of Class 3 series in particular was taken into account when interpreting the results. In the P95 sensitivity analysis, it was found that the exceedance frequency trend classes were consistent with the P90 results at 74 out of the 77 stations analyzed in winter (96.1 per cent) and at 74 out of the 79 stations analysed in summer (93.7 per cent). Of the 74 stations that remained in the same trend class in both percentiles during winter, 49 showed a significant decrease, 2 showed a significant increase and 23 showed a non-significant trend; the significance classes for Karaman, Sariyer and Yozgat varied depending on the choice of percentile. In summer, of the 74 stations that remained in the same class in both percentiles, a significant decrease was observed at 41, a significant increase at 11, and a non-significant trend at 22; class differences were observed in Alanya, Hakkâri, Nevşehir, Niğde and Çeşme. At no station was a change in trend—from a significant increase to a significant decrease, or from a significant decrease to a significant increase—detected as a result of the transition from P90 to P95.

## 4. Discussion and Conclusion

In this study, the spatial and temporal characteristics of extreme wind conditions in Türkiye during the winter and summer periods were assessed using daily maximum wind speed records from 79 meteorological stations, covering the overall observation period from 1975 to 2023. Treating the local P90 wind speed and the number of days exceeding this threshold as separate indicators has enabled a combined analysis of areas where high wind speeds occur and those where such conditions recur more frequently. The spatial pattern observed in the extreme wind speed maps—where the highest winter speeds are concentrated in northwestern Türkiye, particularly around Bozcaada and Canakkale, and at certain coastal stations exposed to maritime influences—is consistent with increased cyclonic activity in the Mediterranean Basin during the cold season, strong pressure gradients and the exposure of coastlines to air currents [10] [20]. The location and orientation of the Dardanelles Strait, situated in the transitional zone between the Marmara and Aegean Seas, are among the local geographical factors contributing to the high wind speeds observed at Bozcaada and Canakkale. Despite the narrowing of the wind speed range between stations during the summer, the occurrence of locally high wind speeds not only along the coast but also at some stations in Central, Eastern and South-Eastern Anatolia necessitates a combined assessment of the regional atmospheric circulation characteristic of the summer season and topographical diversity. The gradient between the high-pressure system over the Balkans and the Black Sea and the thermal low-pressure area developing around the Persian Gulf supports northerly Etesian winds in the eastern Mediterranean and the Aegean [11] [31].The modification of this regional circulation at a local scale by land-sea temperature differences, elevation, the orientation of mountain ranges, the openness of plateaus and plains, and valley systems provides a geographical

framework that explains the differentiation observed between coastal and inland areas in summer maps [3] [32]. A comparison of wind speed maps with maps showing the number of days on which wind speeds exceeded thresholds has revealed that areas with high extreme wind speeds do not always coincide with those where such conditions occur more frequently. Whilst Bozcaada and Canakkale stand out for their high wind speeds, the higher number of exceedance days at certain stations—such as Tatvan, Tunceli, Mus and Konya Airport—is due to the percentile threshold being determined according to each station's own wind climatology. This has enabled stations with different absolute wind speeds to be compared within their own local conditions. It has been established that the speed and frequency of extreme winds exhibit distinct spatial characteristics. Similarly, in studies based on local percentile thresholds, the speed and annual frequency of high winds are treated as separate indicators [4]. Temporal analyses show that this spatial variability is also reflected in seasonal trends. In the basic P90 analysis, a significant decrease in the frequency of winter exceedances was observed at 50 of the 77 stations that met the data adequacy criterion, a significant increase at 2, and a non-significant trend at 25. Of the 79 stations assessed in summer, a significant decrease was observed at 42, a significant increase at 13, and a non-significant trend at 24. The fact that Canakkale showed a decrease only in the frequency of winter exceedances, despite its high wind speeds, demonstrates that the level of extreme wind speeds in a region and the recurrence of these conditions over time do not necessarily change in the same direction. Whilst a decrease was observed in both seasons in Samsun, situated between the narrow coastal strip along the Black Sea and the Northern Anatolian Mountains, and in Ardahan, located on a high, continental plateau, an increase was recorded only in summer in Adana, situated in the Cukurova Plain between the Mediterranean Sea and the Taurus Mountains. The decreases in average wind speed identified by Yilmaz [13] during the winter period from 1989 to 2018 in Samsun and during the summer period from 1959 to 2018 in the Central Black Sea region, although based on different time periods and indicators, are consistent with our results for Samsun in terms of trend. The decrease in summer winds reported in the same study for North-Eastern Anatolia also provides a regional counterpart to the summer trend observed in Ardahan. Adana's location on a plain exposed to maritime air currents, the topographical barrier formed by the Taurus Mountains, the land-sea thermal contrast that becomes pronounced in summer, and the seasonal variability in the Eastern Mediterranean circulation provide a geographical context for assessing the increase observed here. These differing trends demonstrate that changes in extreme wind conditions in Türkiye are not uniform across the country; rather, coastal location, continentality, elevation, topographical openness and regional atmospheric circulation must be considered in conjunction with patterns that vary by station and season. The P90 and P95 trend classes showed a match at 74 out of 77 stations (96.1 per cent) in winter, and in summer at 74 out of 79 stations (93.7 per cent), and the fact that no change in direction was observed between a signif-

icant increase and a significant decrease at any station, demonstrates that the underlying temporal pattern is largely preserved regardless of the choice of percentile. However, the fact that a significant proportion of the seasonal P90 and P95 wind speed series, on which homogeneity tests were applied, were classified as Class 3 highlights the importance of station history in terms of data quality. As changes in station location, anemometer height, measurement system and surface characteristics in the station's vicinity can cause discontinuities in wind records [33], homogeneity classes were used as a complementary indicator of data quality rather than as an automatic exclusion criterion. A comparison of spatial forecasting performance using alternative methods, and the joint evaluation of wind speed maps alongside maps showing the number of days with wind speeds exceeding a certain threshold, have also enabled the integration of the speed, frequency and distribution aspects of extreme wind climatology. Overall, the study presents an integrated geographical assessment demonstrating that Türkiye is not a homogeneous wind region; rather, extreme winds vary on a regional scale depending on the coastal-inland contrast, topography and seasonal atmospheric circulation. The findings can be utilised to prioritise detailed local investigations in the fields of transport safety, coastal and infrastructure planning, agricultural activities, disaster preparedness and wind energy studies. In future, the combined analysis of spring and autumn periods, high-temporal-resolution wind gust records, detailed station metadata and synoptic circulation fields based on reanalysis data will enable the identified regional variations to be linked more precisely to physical processes.

## Author Contributions

All authors contributed to the study and participated in drafting or critically revising the manuscript. All authors read and approved the final manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

[1] Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., *et al.* (2021) Weather and Climate Extreme Events in a Changing Climate. In: Masson-Delmotte, V., *et al.*, Eds., *Climate Change* 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 1513-1766.

[2] Hochman, A., Marra, F., Messori, G., Pinto, J.G., Raveh-Rubin, S., Yosef, Y., *et al.* (2022) Extreme Weather and Societal Impacts in the Eastern Mediterranean. *Earth System Dynamics*, **13**, 749-777. https://doi.org/10.5194/esd-13-749-2022

[3] Sahin, S. and Türkeş, M. (2013) Contemporary Surface Wind Climatology of Türkiye. *Theoretical and Applied Climatology*, **113**, 337-349. https://doi.org/10.1007/s00704-012-0789-5

[4] Jiang, Y., Miao, Y., Zhao, Y., Liu, J. and Gao, Y. (2023) Extreme-Wind Events in

China in the Past 50 Years and Their Impacts on Sandstorm Variations. *Frontiers in Earth Science*, **10**, Article ID: 1058275. https://doi.org/10.3389/feart.2022.1058275

[5] Kunz, M., Mohr, S., Rauthe, M., Lux, R. and Kottmeier, C. (2010) Assessment of Extreme Wind Speeds from Regional Climate Models—Part 1: Estimation of Return Values and Their Evaluation. *Natural Hazards and Earth System Sciences*, **10**, 907-922. https://doi.org/10.5194/nhess-10-907-2010

[6] Vagenas, C., Anagnostopoulou, C. and Tolika, K. (2017) Climatic Study of the Marine Surface Wind Field over the Greek Seas with the Use of a High Resolution RCM Focusing on Extreme Winds. *Climate*, **5**, Article No. 29. https://doi.org/10.3390/cli5020029

[7] Platonov, V., Kozlov, F. and Boiko, A. (2023) Extreme Wind Speed Long-Term Trends Evaluation in the Russian Arctic Based on the COSMO-CLM 36-Year Hindcast. *Environmental Sciences Proceedings*, **27**, Article No. 6. https://doi.org/10.3390/ecas2023-15126

[8] Kruglova, E. and Myslenkov, S. (2023) Influence of Long-Term Wind Variability on the Storm Activity in the Caspian Sea. *Water*, **15**, Article No. 2125. https://doi.org/10.3390/w15112125

[9] Alimohamadian, L. and Mostafazadeh, R. (2025) Frequency Analysis and Trend of Maximum Wind Speed for Different Return Periods in a Cold Diverse Topographical Region of Iran. *Climate*, **13**, Article No. 138. https://doi.org/10.3390/cli13070138

[10] Flaounas, E., Davolio, S., Raveh-Rubin, S., Pantillon, F., Miglietta, M.M., Gaertner, M.A., *et al.* (2022) Mediterranean Cyclones: Current Knowledge and Open Questions on Dynamics, Prediction, Climatology and Impacts. *Weather and Climate Dynamics*, **3**, 173-208. https://doi.org/10.5194/wcd-3-173-2022

[11] Tyrlis, E. and Lelieveld, J. (2013) Climatology and Dynamics of the Summer Etesian Winds over the Eastern Mediterranean. *Journal of the Atmospheric Sciences*, **70**, 3374-3396. https://doi.org/10.1175/jas-d-13-035.1

[12] Dadaser-Celik, F. and Cengiz, E. (2014) Wind Speed Trends over Türkiye from 1975 to 2006. *International Journal of Climatology*, **34**, 1913-1927. https://doi.org/10.1002/joc.3810

[13] Yilmaz, E. (2021) Türkiye'de rüzgâr hizi verilerinin homojenleştirilmesi ve eğilimleri. *Ankara Üniversitesi Dil ve Tarih-Coğrafya Fakültesi Dergisi*, **61**, 185-233. https://doi.org/10.33171/dtcfjournal.2021.61.1.8

[14] Gumus, V., Simsek, O. and Seaid, M. (2023) Investigating Recent Changes in the Wind Speed Trends over Türkiye. *Acta Geophysica*, **71**, 1305-1319. https://doi.org/10.1007/s11600-022-01011-2

[15] Akpınar, E., Akpınar, S. and Balpetek, N. (2018) Statistical Analysis of Wind Speed Distribution of Türkiye as Regional. *Journal of Engineering Technology and Applied Sciences*, **3**, 35-55. https://doi.org/10.30931/jetas.407141

[16] Köroğlu, T. and Ekici, E. (2024) A Comparative Study on the Estimation of Wind Speed and Wind Power Density Using Statistical Distribution Approaches and Artificial Neural Network-Based Hybrid Techniques in Çanakkale, Türkiye. *Applied Sciences*, **14**, Article No. 1267. https://doi.org/10.3390/app14031267

[17] Karataş, K. and Bıçakcı, C. (2025) Creation of Wind Speed Maps and Determination of Wind Energy Potential with Geographic Information Systems: The Case of Kırklareli Province, Türkiye. *Sustainability*, **17**, Article No. 1185. https://doi.org/10.3390/su17031185

[18] Şahin, C. (2020) Sakarya Nehri Deltası'nda Uzun Süreli Rüzgar ve Dalga İklimi Değişimleri. *Deu Muhendislik Fakultesi Fen ve Muhendislik*, **22**, 353-368.

https://doi.org/10.21205/deufmd.2020226505

[19] Kır, G., Ülke Keskin, A. and Zeybekoğlu, U. (2023) Karadeniz Bölgesi Meteoroloji Gözlem İstasyonlarının Rüzgâr Hızı Değerleri Kullanılarak Kümelenmesi. *Ordu Üniversitesi Bilim ve Teknoloji Dergisi*, **13**, 44-58. https://doi.org/10.54370/ordubtd.1275677

[20] Başar Görgün, U.G. and Menteş, Ş.S. (2024) Analyzing Wintertime Extreme Winds over Türkiye and Their Relationships with Synoptic Patterns Using Cluster Analysis. *Atmosphere*, **15**, Article No. 196. https://doi.org/10.3390/atmos15020196

[21] Zhang, X. and Yang, F. (2004) RClimDex (1.0) User Manual. Climate Research Branch, Environment Canada.

[22] Wijngaard, J.B., Klein Tank, A.M.G. and Können, G.P. (2003) Homogeneity of 20th Century European Daily Temperature and Precipitation Series. *International Journal of Climatology*, **23**, 679-692. https://doi.org/10.1002/joc.906

[23] Zhang, X., Alexander, L., Hegerl, G.C., Jones, P., Tank, A.K., Peterson, T.C., *et al.* (2011) Indices for Monitoring Changes in Extremes Based on Daily Temperature and Precipitation Data. *WIREs Climate Change*, **2**, 851-870. https://doi.org/10.1002/wcc.147

[24] Zong, X., Yin, Y., Yin, M., Hou, W., Deng, H. and Cui, T. (2023) Occurrence and Hotspots of Multivariate and Temporally Compounding Events in China from 1961 to 2020. *NPJ Climate and Atmospheric Science*, **6**, Article No. 168. https://doi.org/10.1038/s41612-023-00491-3

[25] Vogel, F., Putero, D., Bonasoni, P., Cristofanelli, P., Zanatta, M. and Marinoni, A. (2025) Saharan Dust Transport Event Characterization in the Mediterranean Atmosphere Using 21 Years of *In-Situ* Observations. *Atmospheric Chemistry and Physics*, **25**, 15453-15468. https://doi.org/10.5194/acp-25-15453-2025

[26] Mann, H.B. (1945) Nonparametric Tests against Trend. *Econometrica*, **13**, 245-259. https://doi.org/10.2307/1907187

[27] Kendall, M.G. (1975) Rank Correlation Methods. 4th Edition, Charles Griffin.

[28] Sen, P.K. (1968) Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, **63**, 1379-1389. https://doi.org/10.1080/01621459.1968.10480934

[29] Benjamini, Y. and Hochberg, Y. (1995) Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society Series B*: *Statistical Methodology*, **57**, 289-300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

[30] Wilks, D.S. (2006) On "Field Significance" and the False Discovery Rate. *Journal of Applied Meteorology and Climatology*, **45**, 1181-1189. https://doi.org/10.1175/jam2404.1

[31] Ziv, B., Saaroni, H. and Alpert, P. (2004) The Factors Governing the Summer Regime of the Eastern Mediterranean. *International Journal of Climatology*, **24**, 1859-1871. https://doi.org/10.1002/joc.1113

[32] Soukissian, T. and Sotiriou, M. (2022) Long-Term Variability of Wind Speed and Direction in the Mediterranean Basin. *Wind*, **2**, 513-534. https://doi.org/10.3390/wind2030028

[33] Wan, H., Wang, X.L. and Swail, V.R. (2010) Homogenization and Trend Analysis of Canadian Near-Surface Wind Speeds. *Journal of Climate*, **23**, 1209-1225. https://doi.org/10.1175/2009jcli3200.1

## Supplementary

**Table S1.** Location, elevation, and monthly data availability of 79 meteorological stations.

| No. | Station name | Latitude (˚N) | Longitude (˚E) | Elev. (m) | Valid years | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Dec. | Jan. | Feb. | Jun. | Jul. | Aug. |
| 1 | Adana | 37.0041 | 35.3443 | 23 | 49 | 48 | 49 | 47 | 47 | 48 |
| 2 | Adıyaman | 37.7553 | 38.2775 | 672 | 47 | 47 | 46 | 47 | 47 | 47 |
| 3 | Afyonkarahisar | 38.7380 | 30.5604 | 1034 | 49 | 47 | 48 | 48 | 47 | 47 |
| 4 | Ağrı | 39.7253 | 43.0522 | 1646 | 46 | 44 | 44 | 47 | 47 | 47 |
| 5 | Akçakoca | 41.0895 | 31.1374 | 10 | 49 | 48 | 48 | 48 | 47 | 47 |
| 6 | Akhisar | 38.9118 | 27.8233 | 92 | 48 | 48 | 48 | 48 | 48 | 48 |
| 7 | Aksaray | 38.3706 | 33.9987 | 970 | 49 | 49 | 49 | 49 | 47 | 48 |
| 8 | Akşehir | 38.3688 | 31.4297 | 1002 | 48 | 48 | 48 | 48 | 48 | 48 |
| 9 | Alanya | 36.5507 | 31.9803 | 6 | 47 | 48 | 47 | 47 | 47 | 48 |
| 10 | Amasya | 40.6668 | 35.8353 | 409 | 49 | 49 | 49 | 49 | 49 | 49 |
| 11 | Anamur | 36.0686 | 32.8649 | 2 | 48 | 48 | 48 | 49 | 49 | 49 |
| 12 | Ankara | 39.9727 | 32.8637 | 891 | 48 | 46 | 46 | 47 | 47 | 47 |
| 13 | Antakya | 36.2048 | 36.1513 | 104 | 49 | 48 | 48 | 48 | 49 | 49 |
| 14 | Antalya | 36.9063 | 30.7990 | 64 | 48 | 46 | 46 | 48 | 47 | 48 |
| 15 | Ardahan | 41.1061 | 42.7055 | 1827 | 49 | 49 | 49 | 49 | 47 | 47 |
| 16 | Ayvalık | 39.3113 | 26.6861 | 4 | 49 | 48 | 48 | 48 | 48 | 48 |
| 17 | Beypazarı | 40.1608 | 31.9172 | 682 | 48 | 47 | 47 | 46 | 48 | 48 |
| 18 | Bingöl | 38.8847 | 40.5007 | 1139 | 47 | 47 | 47 | 47 | 47 | 46 |
| 19 | Bolu | 40.7329 | 31.6022 | 743 | 49 | 48 | 48 | 48 | 48 | 48 |
| 20 | Bozcaada | 39.8326 | 26.0728 | 30 | 44 | 40 | 43 | 45 | 44 | 46 |
| 21 | Burdur | 37.7220 | 30.2940 | 957 | 48 | 48 | 47 | 48 | 48 | 48 |
| 22 | Çanakkale | 40.1410 | 26.3993 | 6 | 49 | 48 | 48 | 48 | 48 | 48 |
| 23 | Çeşme | 38.3038 | 26.3724 | 5 | 49 | 48 | 48 | 47 | 48 | 47 |
| 24 | Cihanbeyli | 38.6506 | 32.9219 | 973 | 49 | 48 | 48 | 48 | 48 | 48 |
| 25 | Çorlu | 41.1798 | 27.8160 | 145 | 49 | 46 | 44 | 48 | 47 | 48 |
| 26 | Denizli | 37.7620 | 29.0921 | 425 | 49 | 48 | 48 | 48 | 48 | 48 |
| 27 | Dikili | 39.0737 | 26.8880 | 3 | 49 | 48 | 48 | 48 | 48 | 48 |
| 28 | Diyarbakır | 37.8973 | 40.2027 | 674 | 49 | 49 | 49 | 49 | 49 | 49 |
| 29 | Edirne | 41.6767 | 26.5508 | 51 | 49 | 48 | 48 | 48 | 48 | 48 |
| 30 | Edremit | 39.5896 | 27.0192 | 21 | 49 | 48 | 48 | 47 | 48 | 48 |
| 31 | Elazığ | 38.6443 | 39.2561 | 989 | 49 | 48 | 49 | 49 | 48 | 48 |
| 32 | Elmalı | 36.7372 | 29.9121 | 1095 | 46 | 47 | 47 | 48 | 48 | 48 |
| 33 | Ereğli | 37.5255 | 34.0485 | 1046 | 49 | 49 | 49 | 49 | 49 | 49 |

**Continued**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | Erzincan | 39.7523 | 39.4868 | 1216 | 45 | 46 | 46 | 46 | 46 | 46 |
| 35 | Erzurum | 39.9529 | 41.1897 | 1758 | 48 | 45 | 48 | 48 | 48 | 47 |
| 36 | Fethiye | 36.6266 | 29.1238 | 3 | 45 | 46 | 45 | 45 | 45 | 45 |
| 37 | Finike | 36.3024 | 30.1458 | 2 | 49 | 48 | 48 | 47 | 48 | 48 |
| 38 | Florya | 40.9758 | 28.7865 | 37 | 48 | 47 | 46 | 48 | 46 | 47 |
| 39 | Gaziantep | 37.0585 | 37.3510 | 854 | 48 | 49 | 49 | 49 | 49 | 49 |
| 40 | Gemerek | 39.1850 | 36.0805 | 1182 | 48 | 49 | 49 | 48 | 49 | 49 |
| 41 | Giresun | 40.9227 | 38.3878 | 38 | 49 | 48 | 48 | 49 | 49 | 49 |
| 42 | Hakkâri | 37.5745 | 43.7388 | 1727 | 48 | 48 | 48 | 47 | 47 | 47 |
| 43 | Hopa | 41.4066 | 41.4330 | 33 | 49 | 49 | 49 | 49 | 49 | 49 |
| 44 | İnebolu | 41.9789 | 33.7636 | 64 | 49 | 47 | 47 | 47 | 47 | 47 |
| 45 | İpsala | 40.8900 | 26.3900 | 81 | 48 | 46 | 46 | 45 | 46 | 45 |
| 46 | İskenderun | 36.5924 | 36.1582 | 4 | 49 | 48 | 49 | 48 | 49 | 49 |
| 47 | Kadıköy | 40.9883 | 29.0190 | 5 | 46 | 46 | 46 | 47 | 48 | 48 |
| 48 | Kahramanmaraş | 37.5760 | 36.9150 | 572 | 49 | 49 | 47 | 49 | 49 | 49 |
| 49 | Karaman | 37.1932 | 33.2202 | 1018 | 48 | 49 | 49 | 49 | 49 | 49 |
| 50 | Bozkurt | 41.9597 | 34.0037 | 167 | 46 | 46 | 44 | 48 | 47 | 47 |
| 51 | Kilis | 36.7085 | 37.1123 | 640 | 47 | 47 | 47 | 46 | 46 | 46 |
| 52 | Kırşehir | 39.1639 | 34.1561 | 1007 | 49 | 48 | 48 | 48 | 48 | 48 |
| 53 | Kocaeli | 40.7663 | 29.9173 | 74 | 42 | 42 | 41 | 42 | 41 | 41 |
| 54 | Konya | 37.9837 | 32.5740 | 1031 | 44 | 41 | 42 | 45 | 45 | 44 |
| 55 | Kuşadası | 37.8597 | 27.2652 | 25 | 49 | 48 | 48 | 47 | 48 | 47 |
| 56 | Kütahya | 39.4171 | 29.9891 | 969 | 49 | 48 | 48 | 48 | 48 | 47 |
| 57 | Manisa | 38.6153 | 27.4049 | 71 | 49 | 48 | 48 | 48 | 48 | 48 |
| 58 | Mardin | 37.3103 | 40.7284 | 1040 | 46 | 46 | 48 | 48 | 49 | 48 |
| 59 | Marmaris | 36.8395 | 28.2452 | 16 | 49 | 48 | 48 | 47 | 47 | 48 |
| 60 | Mersin | 36.7808 | 34.6031 | 7 | 46 | 47 | 47 | 47 | 47 | 47 |
| 61 | Muş | 38.7509 | 41.5023 | 1322 | 48 | 49 | 49 | 48 | 49 | 49 |
| 62 | Nevşehir | 38.6163 | 34.7025 | 1260 | 49 | 49 | 49 | 49 | 49 | 49 |
| 63 | Niğde | 37.9587 | 34.6795 | 1211 | 49 | 49 | 49 | 49 | 49 | 49 |
| 64 | Ordu | 40.9838 | 37.8858 | 5 | 48 | 49 | 49 | 49 | 49 | 49 |
| 65 | Rize | 41.0400 | 40.5013 | 3 | 47 | 48 | 48 | 48 | 48 | 48 |
| 66 | Sakarya | 40.7676 | 30.3934 | 30 | 49 | 48 | 48 | 48 | 48 | 47 |
| 67 | Samsun | 41.3442 | 36.2564 | 4 | 49 | 47 | 48 | 49 | 49 | 49 |
| 68 | Şanlıurfa | 37.1608 | 38.7883 | 550 | 49 | 48 | 49 | 49 | 48 | 48 |
| 69 | Sarıyer | 41.1464 | 29.0502 | 59 | 49 | 48 | 48 | 48 | 48 | 48 |
| 70 | Şile | 41.1688 | 29.6007 | 83 | 48 | 48 | 47 | 45 | 47 | 47 |

**Continued**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 71 | Silifke | 36.3824 | 33.9373 | 10 | 49 | 49 | 49 | 49 | 49 | 49 |
| 72 | Tatvan | 38.5033 | 42.2808 | 1665 | 48 | 49 | 49 | 49 | 49 | 46 |
| 73 | Tekirdağ | 40.9585 | 27.4965 | 4 | 46 | 46 | 46 | 46 | 46 | 46 |
| 74 | Tokat | 40.3312 | 36.5577 | 611 | 49 | 49 | 49 | 49 | 48 | 49 |
| 75 | Tunceli | 39.1058 | 39.5408 | 981 | 49 | 49 | 49 | 49 | 49 | 48 |
| 76 | Ünye | 41.1430 | 37.2930 | 16 | 49 | 48 | 48 | 49 | 48 | 48 |
| 77 | Uşak | 38.6712 | 29.4040 | 919 | 49 | 48 | 48 | 47 | 45 | 48 |
| 78 | Yozgat | 39.8243 | 34.8159 | 1301 | 48 | 49 | 49 | 48 | 48 | 48 |
| 79 | Zonguldak | 41.4492 | 31.7779 | 135 | 49 | 48 | 47 | 46 | 48 | 48 |

Note: The nominal study period is 1975-2023 for all stations. A valid year for a given month is a month-year group with at least 90% of the expected daily observations available. The missing data percentage was calculated using only the six selected months.