Asian Journal of Water, Environment and Pollution. Vol. 23, No. 1 (2026), pp. 249-260.
doi: 10.36922/AJWEP025370289

ORIGINAL RESEARCH ARTICLE

Long-term wind energy potential analysis in Vietnam's central highlands using the innovative trend analysis method

Do Quang Linh[1,2†], Tran Duc Dung[2,3†], and Dang Truong An[2,4*]

[1]Department of Environmental Management and Informatics, Faculty of Environment, University of Science, Ho Chi Minh City, Vietnam
[2]Vietnam National University-Ho Chi Minh City, Ho Chi Minh City, Vietnam
[3]Institute for Environment and Resources, Ho Chi Minh City, Vietnam
[4]Department of Oceanology, Meteorology and Hydrology, Faculty of Physis-Physis Engineering, University of Science, Ho Chi Minh City, Vietnam
***Corresponding author:** Dang Truong An (dtan@hcmus.edu.vn)
[†]*These authors contributed equally to this work.*

Received: September 10, 2025 ; 1st revised: October 22, 2025; 2nd revised: October 23, 2025; Accepted: October 30, 2025; Published online: November 18, 2025

Abstract: Understanding long-term trends in local wind resources is a critical prerequisite for sustainable energy planning. This study provides a detailed investigation of historical wind-speed trends in Vietnam's Central Highlands, a region with significant untapped wind power potential. We employed the advanced innovative trend analysis (ITA) method to analyze a 30-year (1985–2014) daily wind-speed dataset from four key meteorological stations, which was rigorously checked for homogeneity. While the observational period concluded in 2014, we established a critical historical baseline and a robust methodological framework. Unlike conventional monotonic tests, the graphical ITA method detected and visualized hidden, non-linear trends across different data sub-series. The analysis revealed highly heterogeneous and localized trend patterns. A statistically significant decreasing trend was identified at Bao Loc station during the wet season ($p<0.05$). In contrast, stations like Ayun Pa exhibited opposing trends between seasons, indicating an intensification of wind seasonality. This study demonstrates that a granular, site-specific, and methodologically advanced understanding of wind resource dynamics is essential, revealing nuances completely overlooked by traditional methods and providing crucial insights for climate-resilient energy planning.

Keywords: Climate change; Innovative trend analysis; Renewable energy; Trend analysis; Wind speed; Central highlands

1. Introduction

The global imperative to transition away from fossil fuels and mitigate the impacts of anthropogenic climate change has positioned renewable power at the forefront of international energy policy.[1,2] As outlined in the Paris Agreement and subsequent climate accords, a rapid and substantial scaling-up of clean energy sources is essential to limit global warming.[3] Among these sources, wind energy has emerged as a mature, cost-competitive, and scalable technology, accounting for a significant and growing share of new power generation capacity worldwide.[4,5] The long-term viability and financial feasibility of wind energy projects, however, are fundamentally dependent on the stability and characteristics of the local wind climatology.[6] As multi-decade investments, wind farms are highly sensitive to even minor long-term variations in wind speed, as the power output is proportional to the cube of wind speed.[7] Therefore, a comprehensive understanding of historical and potential future wind-speed trends is not merely an academic exercise but a critical component of risk assessment, resource planning, and ensuring the economic sustainability of wind power investments.[8] Climate change itself introduces a profound layer of uncertainty into wind resource assessment. Shifting large-scale atmospheric circulation patterns, alterations in land-sea temperature gradients, and changes in surface roughness can lead to significant long-term trends in near-surface wind speeds.[9,10] This phenomenon, variably described in the literature as "global stilling" (a widespread decrease in wind speeds) or "brightening" (a more recent reversal or increase), has been observed in numerous regions globally, with considerable spatial and temporal heterogeneity.[11,12] For instance, studies have reported significant decreasing trends across large parts of the Northern Hemisphere for several decades,[13] while more recent analyses suggest a reversal of this trend since around 2010 in several areas.[14] These changes directly impact the energy yield of existing and planned wind farms, highlighting the critical need for robust, data-driven analysis of local wind speed trends as an essential prerequisite for resource assessment and project planning.[15]

Conventionally, trend detection in hydro-meteorological time series has been dominated by methods such as linear regression and nonparametric tests, such as the Mann–Kendall (MK) test.[16,17] While the MK test is robust against non-normally distributed data and has been widely applied in climate studies,[18,19] it possesses a significant limitation: it is designed to detect only monotonic trends (i.e., a consistent increase or decrease over the entire period) and yields a single statistic for the entire time series.[20] This approach is incapable of identifying hidden or non-monotonic trends, trend-free periods, or, crucially, different trend behaviors within different parts of a data distribution (e.g., trends in low vs. high wind speeds).[21] This can lead to an oversimplified or even misleading interpretation of how a climate variable is truly changing over time. For wind energy applications, where high wind speeds are of primary interest, a method that only reports the average trend may mask a significant strengthening or weakening of the most productive wind events.[22]

To overcome these limitations, the Innovative Trend Analysis (ITA) method, developed by Sen,[23] offers a powerful graphical and numerical technique. ITA does not require strict assumptions about data distribution, serial correlation, or monotonicity. Its primary strength lies in its ability to visually and quantitatively assess trends across the entire range of data values.[24,25] By splitting a time series into two and plotting the sorted values against each other, ITA can reveal whether trends are occurring preferentially in low, medium, or high-value sub-series.[26] This granular level of insight is of high practical importance for applications like wind energy, providing a more nuanced understanding of resource evolution than traditional methods.[27] The method's utility has been demonstrated across a wide range of hydro-meteorological variables, including rainfall, temperature, and streamflow,[28-30] but its application to detailed wind resource assessment remains an emerging area of research.

Vietnam's Central Highlands is a region of growing strategic interest for wind energy development due to its favorable topography, including plateaus and mountain ranges that can enhance wind flow.[31] The Vietnamese government's national energy strategy, outlined in the Power Development Plan VIII, has set ambitious targets for renewable energy deployment to meet rapidly growing electricity demand while pursuing decarbonization goals.[32] However, long-term, site-specific analyses of wind speed trends in this specific region are scarce in the scientific literature. Existing resource maps are often based on shorter time periods or large-scale reanalysis data, which may not capture localized climatic shifts.[33] Understanding how the wind climate in the Central Highlands has evolved over the past several decades is crucial for validating these maps, de-risking investments, and ensuring that future development is based on a sound understanding of the resource's historical behavior and potential future trajectory.

This study, therefore, aims to provide the first detailed, long-term wind speed trend analysis for the Central Highlands of Vietnam using the state-of-the-art ITA method. By leveraging a multi-decade dataset from a network of meteorological stations, we seek to move beyond simple monotonic trend detection to uncover the complex, and potentially non-linear, dynamics of the regional wind climate. The specific objectives of this research are (i) to analyze annual and seasonal (wet and dry season) wind speed trends from 1985 to 2014 at four key meteorological stations representing the diverse geography of the Central Highlands; (ii) to utilize the unique graphical capabilities of the ITA method to identify non-monotonic trends and assess how trend magnitudes vary across different wind speed categories (low, medium, and high); and (iii) to discuss the critical implications of these findings for wind energy resource assessment, project development, and sustainable energy policy in Vietnam.

2. Data and methodology

2.1. Study area and data

The study was conducted in the Central Highlands of Vietnam (Figure 1), a region characterized by a series of plateaus and mountainous terrain with elevations ranging from approximately 150 m to over 2,500 m above sea level. This complex topography significantly influences local and regional atmospheric circulation, creating unique microclimates and potentially favorable conditions for wind energy generation. The climate is dominated by a tropical monsoon pattern, distinctly divided into two seasons: a wet season, typically from May to October, driven by the moisture-laden southwest monsoon, and a dry season, from November to April, influenced by the cooler and drier northeast monsoon. This pronounced seasonality has direct implications for wind resource availability throughout the year.

For this study, we utilized a long-term daily wind speed dataset from four meteorological stations strategically distributed across the study area. The data, covering the 30-year period from January 1, 1985, to December 31, 2014, was obtained from the official archives of Vietnam's National Centre for Hydro-Meteorological Forecasting (Table 1). This specific period was selected as it represented the longest available continuous record for which data quality and homogeneity could be rigorously verified across all selected stations. Efforts to extend the dataset to more recent years were hindered by inconsistencies in data reporting and the lack of comparable, quality-controlled records after 2014.

Rigorous data pre-processing and quality control procedures were implemented. The daily data series for each station were first checked for completeness, and outliers were scrutinized using standard statistical methods. Crucially, to ensure the validity of the trend analysis, all time series were subjected to homogeneity testing. We employed the non-parametric Pettitt's test and the Standard Normal Homogeneity Test at a 95% confidence level to detect any potential non-climatic breakpoints resulting from station relocation, instrumentation changes, or alterations in the surrounding

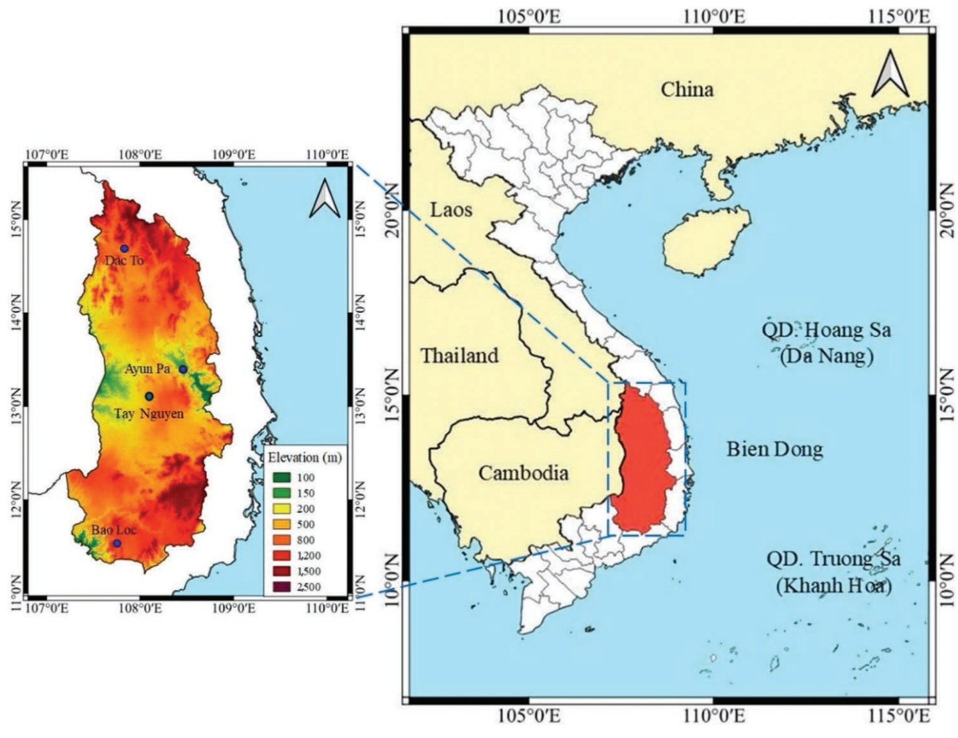

Figure 1. Map of the study area with gauge locations shown in blue circles

Table 1. Geographic coordinates and details of the selected meteorological stations

Station	Longitude (°E)	Latitude (°N)	Elevation (m)	Max (m/s)	Min (m/s)	Mean (m/s)	SD	Sk	Ks
Bao Loc	107.789	11.547	846	14	0	1.03	1.26	1.07	1.03
Dak To	107.763	14.342	615	14	0	0.66	1.24	2.19	5.66
Ayun Pa	107.506	14.655	164	21	0	1.36	1.69	0.96	0.40
Tay Nguyen	108.078	13.164	753	13	0	1.18	0.06	0.23	−0.28

Abbreviations: Ks: Kurtosis; SD: Standard deviation; Sk: Skewness.

environment. No significant inhomogeneities were detected in the time series used for this study, confirming their suitability for long-term trend analysis. Following quality assurance and homogeneity checks, the cleaned daily data were aggregated to create three distinct time series for each station: (i) annual mean wind speed, (ii) wet-season mean wind speed (May to October), and (iii) dry-season mean wind speed (November to April).

2.2. The ITA method

The ITA method, developed by Sen,[23,24,34] is a powerful graphical and numerical technique for trend detection that overcomes many of the limitations of conventional methods, such as the MK test. The core strength of ITA lies in its ability to visually identify non-monotonic trends, sub-trends, and trend variations across the full spectrum of data values without assumptions of serial independence or specific data distributions. The procedural steps of the ITA method are as follows.

2.2.1. Time series bisection

The data of the entire time series (e.g., annual mean wind speed from 1985 to 2023), with n data points, were divided into two equal-length sub-series. The first sub-series comprised the first $n/2$ values, and the second sub-series comprised the last $n/2$ values. If n was an odd number, the middle value was omitted to ensure equal lengths. This bisection established a direct comparison between the first and second halves of the observational period.

2.2.2. Independent sorting

Each of the two sub-series was independently sorted in ascending order. This critical step removed the time-order dependence *within* each sub-series, allowing for a direct comparison of their statistical distributions. The result was two ordered series: x for the first half and yn for the second half, where $I = 1, 2., n/2$.

2.2.3. Cartesian coordinate plotting

A two-dimensional Cartesian graph was plotted. The sorted values of the first sub-series (x) were shown on the horizontal axis (abscissa), and the sorted values of the second sub-series (yn) were illustrated on the vertical axis (ordinate).

2.2.4. The 1:1 (no-trend) line

A line with a 45° angle ($y = x$) was drawn on the graph. This line served as the reference for trend identification. If all data points (xa, y) fell directly on this 1:1 line, it indicated that the statistical distribution of the data had not changed between the first and second halves of the record, signifying a “no-trend” scenario.

2.2.5. Graphical trend interpretation

The position of the data points relative to the 1:1 line provided a direct visual assessment of the trend. If the data points were clustered in the upper triangular area, above the 1:1 line ($ye > x$), it signified an increasing trend. Conversely, if the points were clustered in the lower triangular area, below the 1:1 line ($ye < x$), it indicated a decreasing trend.

2.2.6. Non-monotonic trends

A key advantage of ITA is its ability to reveal trends within different segments of the data. For instance, points corresponding to low wind speeds (lower-left of the graph) might fall on the 1:1 line (no trend), while points for high wind speeds (upper-right) might lie significantly above the line, indicating that only strong wind events were intensifying. This level of detail was masked by traditional methods. A generic illustration of the ITA plot is shown in Figure 2.

2.2.7. Significance testing

To assess the statistical significance of the observed trend, confidence limits for Sen’s slope were calculated. The significance of the trend was assessed based on the approach proposed by Sen.[34]

3. Results and discussion

The ITA method was applied to the annual, wet-season, and dry-season average wind-speed time series for each

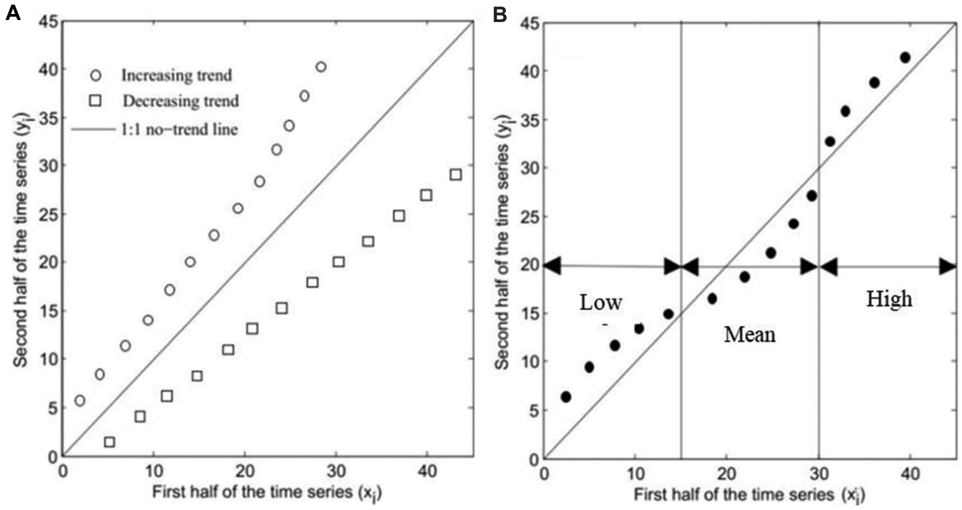

Figure 2. Generic illustration of the innovative trend analysis plot. (A) Examples of increasing (circles) and decreasing (squares) monotonic trends. (B) How trends can be analyzed for different data segments, such as low, mean, and high values.

Table 2. Wind-speed trend, slope, and significance levels for the period 1985–2014 determined by the innovative trend analysis method

Station	Features	Slope	
		Significance level (α=0.05)	Significance level (α=0.01)
Bao Loc	AMW	−0.0132	0.0016
	RSW	−0.0131	0.0018
	DSW	−0.0133	0.0017
Dak To	AMW	−0.0452	0.0027
	RSW	−0.0532	0.0024
	DSW	−0.0373	0.0030
Ayun Pa	AMW	−0.015	0.0013
	RSW	−0.0113	0.0011
	DSW	−0.0187	0.0009
Tay Nguyen	AMW	−0.0244	0.0011
	RSW	−0.0265	0.0008
	DSW	−0.0223	0.0013

Abbreviations: AMW: Annual mean wind; DSW: Dry-season wind; RSW: Rainy season wind.

Table 3. Wind-speed trend, slope, and significance levels for the period 1985–2014 determined using the Man–Kendall method

Station	Features	Man–Kendall test	*p*-value	Sen's slope
Bao Loc	AMW	−145	0.010	−0.022*
	RSW	−129	0.022	−0.023*
	DSW	−125	0.027	−0.018*
Dak To	AMW	−139	0.014	−0.037*
	RSW	−156	0.005	−0.042**
	DSW	−103	0.068	−0.035**
Ayun Pa	AMW	−187	0.001	−0.015**
	RSW	−123	0.030	−0.011*
	DSW	−175	0.002	−0.020*
Tay Nguyen	AMW	−213	0.0002	−0.022**
	RSW	−241	0.0002	−0.025**
	DSW	−183	0.0011	−0.021**

Notes: *significance level at α=0.05, **significance level at α=0.01.
Abbreviations: AMW: Annual mean wind; DSW: Dry-season wind; RSW: Rainy season wind.

meteorological station. The results reveal a complex and highly localized pattern of wind speed changes across the Central Highlands, providing nuanced insights that would be obscured by conventional trend analysis techniques.

3.1. Overview of regional wind-speed trends

Table 2 presents the quantitative results from the ITA, including the calculated trend slope and the significance levels for each time series at the selected stations. A broad overview reveals a predominant, although mostly non-significant, decreasing trend in annual mean wind speeds across several stations (e.g., Dak To, Ayun Pa, Tay Nguyen) (Table 2). The negative slope values indicate that, on average, the wind speeds show decreasing trends across all stations. For comparison, Table 3 shows the results from a traditional MK test, which largely identified statistically significant decreasing trends at nearly all stations. While the MK test flagged these monotonic trends, it failed to capture the underlying complexities revealed by the ITA method.

The most critical finding from the ITA overview is the heterogeneity of these trends. The standout result is the statistically significant decreasing trend in wet-season wind speeds at Bao Loc, with a positive slope that is significant at the $\alpha = 0.05$ level. This is the only statistically significant trend identified across all the analyzed series using the ITA significance test, making it a focal point for discussion. It suggests a tangible enhancement of the wind resource during the crucial monsoon period at this high-elevation location. This heterogeneity immediately underscores the primary theme of our findings: wind speed trends in the Central Highlands are not uniform and must be evaluated on a site-specific basis. A simple regional average would mask both the significant increase at Bao Loc and the subtle seasonal shifts occurring elsewhere.

3.2. Detailed analysis of annual wind speed trends

The ITA plots for annual mean wind speed (Figure 3) provide a powerful visual narrative that complements the quantitative data in Table 2. At Dak To (Figure 3, top right panel), the data points are tightly clustered around the 1:1 no-trend line across the entire range of wind speeds. This confirms the absence of any significant or meaningful trend, indicating a remarkably stable annual wind climate at this location over the past three decades. This stability serves as an important baseline when contrasted with the more dynamic behavior observed at other sites.

The plot for Bao Loc (Figure 3, top left panel) shows that most data points are scattered slightly below the 1:1 line, corresponding to the weak, non-significant decreasing trend in annual wind speed reported in Table 2. The deviation from the line is minor and inconsistent, suggesting that while there might be a slight long-term decrease, it is not a strong or uniform signal.

A more distinct pattern is visible for Ayun Pa (Figure 3, bottom left panel) and Tay Nguyen (Figure 3, bottom right panel). Here, a majority of the data points, particularly those representing medium- to high-wind speeds (in the central and upper-right portions of the plot), fall consistently below the 1:1 line. This suggests a persistent, although statistically non-significant

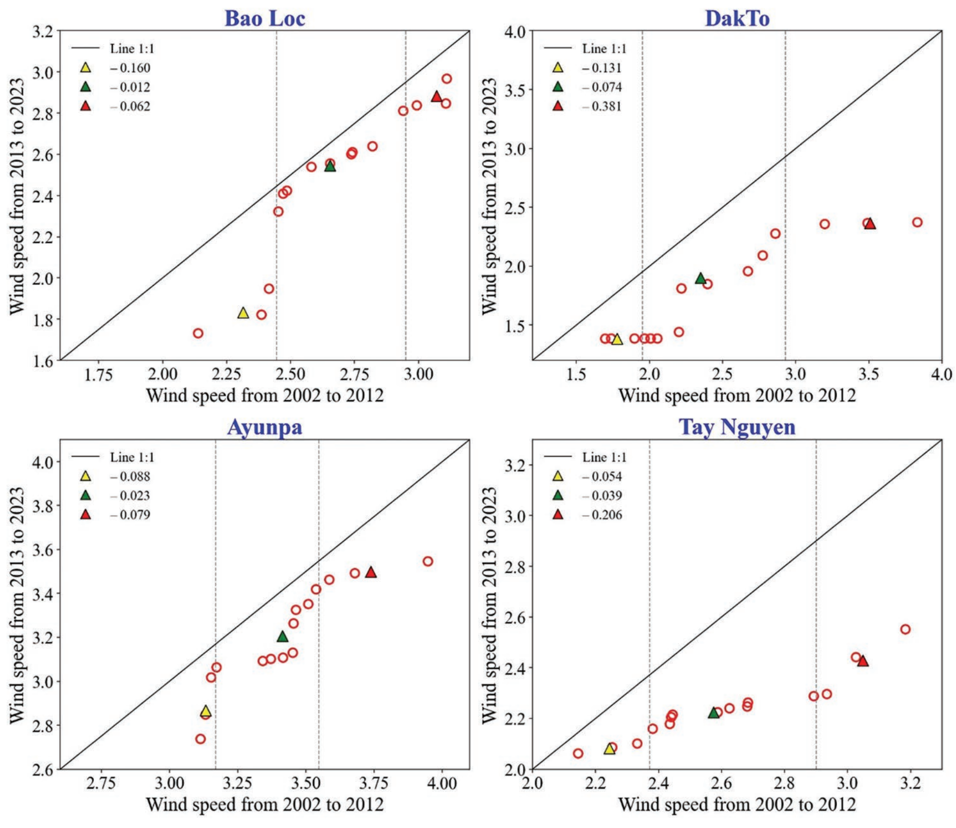

Figure 3. Innovative trend analysis results for annual mean wind speed at four representative locations (1985–2014). Data points are categorized into low (yellow triangles), medium (green triangles), and high (red triangles) intensity values to visualize trends across the data spectrum.

according to ITA, weakening of annual average winds at these stations. Critically, the ITA plot reveals that this decreasing trend is more pronounced at higher wind speeds, as the points deviate further from the 1:1 line at higher wind speed values. This is a crucial insight for wind power assessment, as it implies a potential reduction in the most energy-productive wind events, a detail that a single trend statistic would fail to capture. Collectively, these plots demonstrate that even when overall annual trends are not statistically significant, the ITA method can uncover subtle yet important differences in the long-term behavior of the wind climate across locations and wind-speed intensities.

3.3. An intensification of contrasts for seasonal dynamics

The most compelling findings of this study emerge from the seasonal analysis, which reveals divergent trends between the wet and dry seasons, suggesting a potential shift in the region's wind seasonality.

3.3.1. Wet-season trends

The ITA plot for the wet season at Bao Loc (Figure 4, top left panel) provides striking visual confirmation of the decreasing trend. Nearly all data points, from low to high wind speeds, are located in the upper triangle, clearly above the 1:1 line (Figure 4). The deviation is particularly pronounced at medium and high wind speeds, indicating that the most substantial increases have occurred during the stronger wind events of the monsoon season. This finding is of paramount importance for wind energy development, as it suggests an enhancement of the resource during an already productive period, which could significantly improve the capacity factor and economic viability of projects in this specific area. In contrast, Ayun Pa (Figure 4, bottom left panel) also shows a tendency for a decreasing wet-season trend. While not statistically significant, the graphical plot shows a clear majority of points lying above the 1:1 line. This suggests that the stronger monsoon-season winds may not be confined to Bao Loc but may reflect a broader, although weaker, trend in other parts of the highlands.

3.3.2. Dry-season trends

The dry-season analysis shows a starkly different trend. At both Bao Loc (Figure 5, top left panel) and Ayun

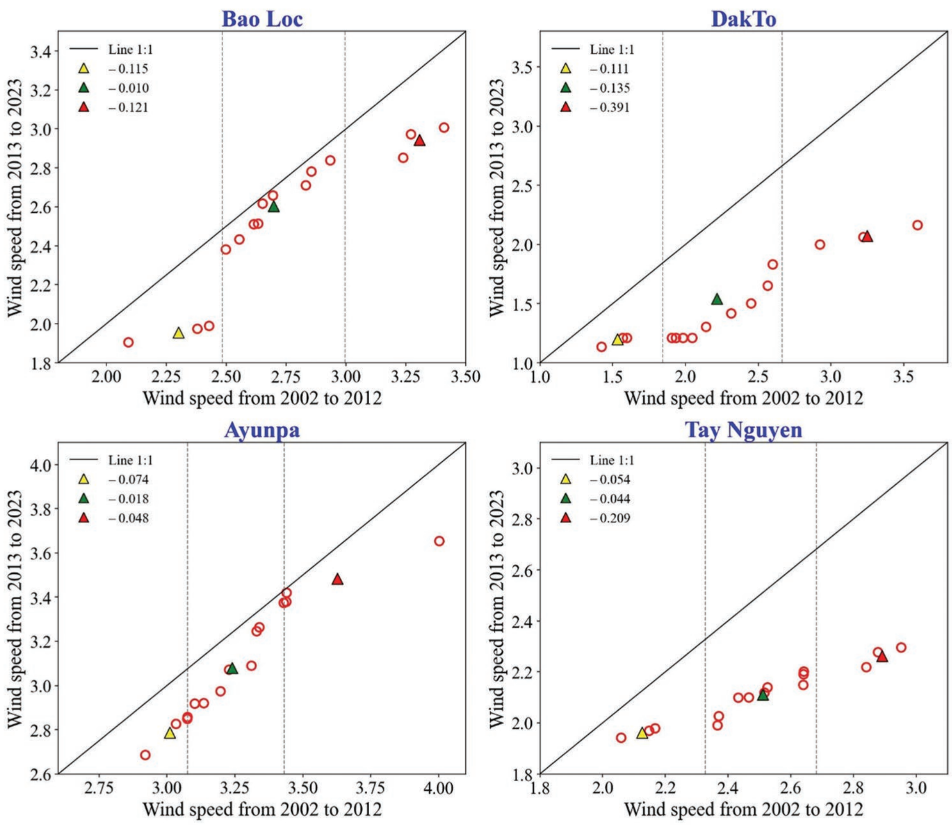

Figure 4. Innovative trend analysis results of rainy wind speed of four locations, divided into low, medium, and high intensity (yellow, green, and red triangles, respectively) (1985–2014).

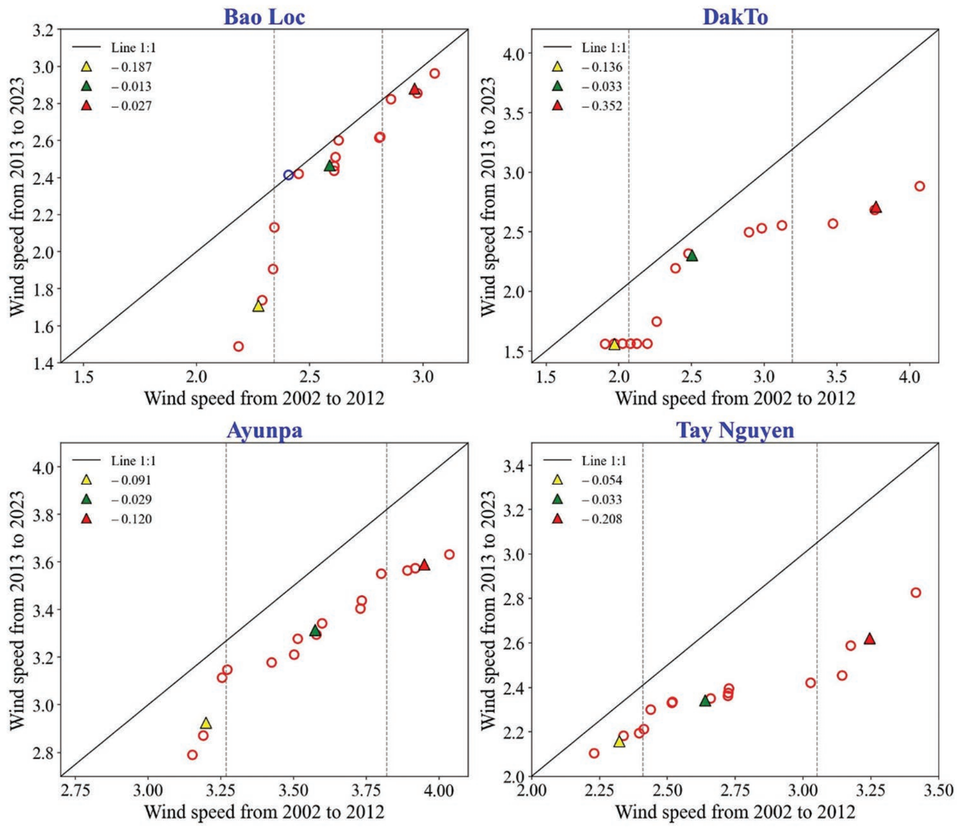

Figure 5. Innovative trend analysis results for dry-season mean wind speed (1985–2014). The plots for Bao Loc and Ayun Pa show a consistent decreasing trend, contrasting with their wet-season behavior.

Pa (Figure 5, bottom left panel), the ITA plots show a clear decreasing trend, with the majority of data points falling below the 1:1 line (Figure 5). This indicates a weakening of the winds associated with the northeast monsoon period. The consistency of this decreasing trend across all wind speed categories (low, medium, and high) at Ayun Pa is particularly evident.

3.3.3. Synthesis of seasonal dynamics

The results for Ayun Pa are particularly illuminating. The station exhibits a decreasing trend induring the wet and dry seasons. This has significant implications for wind power generation, as it would lead to greater variability in power output between across seasons. This critical insight is made possible entirely by the separate seasonal analysis and the detailed visualization provided by the ITA method, a finding completely masked by both annual-level analysis and traditional monotonic tests like MK. Figure 6 provides a spatial summary, visually representing the heterogeneous nature of these trends across wet and dry seasons, as well as at the annual scale (Figure 6A-C).

3.4. Potential climatological drivers of observed trends

To explore the underlying physical mechanisms driving the observed trends, particularly the intensification of seasonality, we conducted a preliminary correlation analysis between the seasonal wind speed time series at key stations (Bao Loc and Ayun Pa) and major climate indices: the Southern Oscillation Index (SOI) for El Niño-Southern Oscillation (ENSO) and the Dipole mode index (DMI) for the Indian ocean dipole (IOD). Monthly index data were obtained from the National Oceanic and Atmospheric Administration's physical sciences laboratory and averaged for the wet and dry seasons to match the wind-speed data.

The results in Table 4 reveal notable correlations. At both Bao Loc and Ayun Pa, wet-season wind speeds exhibit a statistically significant positive correlation with the SOI. Since positive SOI values correspond to La Niña conditions, this suggests that La Niña phases, which are known to intensify the Southwest Monsoon in Southeast Asia, are associated with higher wind speeds in the Central Highlands. The observed decreasing

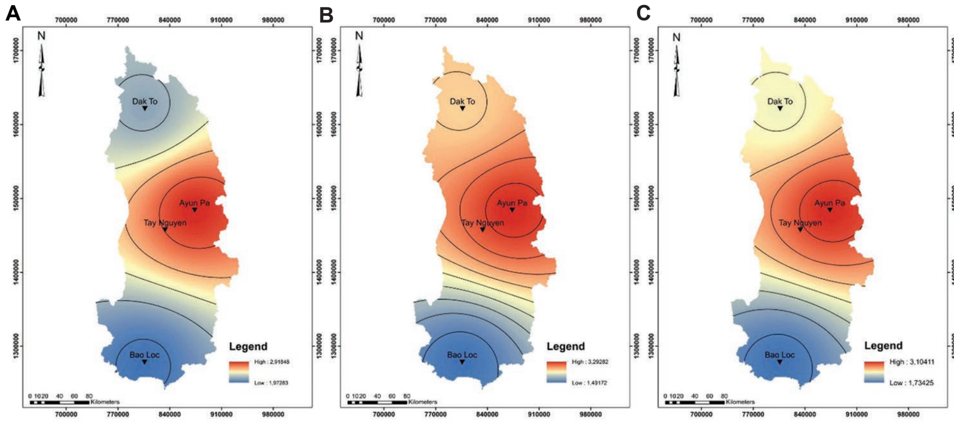

Figure 6. Spatial distribution of seasonal and annual wind speed trends at representative stations (1985–2014). Trends are represented by black arrows at each station's location. (A) Wet season. (B) Dry season. (C) Annual.

Table 4. Pearson correlation coefficients (r) between seasonal mean wind speed and climate indices for the period 1985–2023

Station	Season	SOI (ENSO)	DMI (IOD)
Bao Loc	Wet	0.41*	0.15
	Dry	−0.12	−0.09
Ayun Pa	Wet	0.38*	0.11
	Dry	0.05	−0.17

Note: *Indicates statistical significance at $p<0.05$.
Abbreviations: DMI: Dipole mode index; ENSO: El Niño-Southern Oscillation; IOD: Indian Ocean Dipole; SOI: Southern Oscillation index.

trend in wet-season winds at Bao Loc could therefore be linked to a potential shift toward more frequent or intense La Niña-like conditions or an enhanced regional sensitivity to them over the past decades. While correlation does not imply causation, this strong statistical link suggests that ENSO is a significant modulator of monsoon wind strength in the region and warrants further investigation.

Conversely, during the dry season, driven by the Northeast Monsoon, the correlations are weaker and mostly non-significant. This indicates that dry season wind patterns may be influenced by a different set of local or regional factors not captured by these large-scale indices. The opposing seasonal trends observed at Ayun Pa may thus reflect a complex interplay of large-scale forcing (stronger monsoon response during La Niña) and localized changes that weaken the northeast winds. This analysis provides a crucial layer of physical context to our statistical findings, linking site-specific trends to broader climate system dynamics.

3.5. Discussion and implications

The results from this study reveal a complex pattern of wind speed changes across the central highlands (Figure 6). The discrepancy between the MK results (Table 3) and the ITA results (Table 2) suggests widespread significant decreasing trends, highlighting the core strength of our chosen methodology. The MK test, by design, provides a single, "averaged" statistic for a monotonic trend over the entire time series. It can detect a general tendency but is blind to the underlying complexities. In contrast, the ITA plots (e.g., Figure 3 for Tay Nguyen) visually demonstrate that while many points lie below the 1:1 line (leading to the negative MK statistic), the deviation is not uniform across all wind speed categories, and the overall trend is not strong or consistent enough to be deemed statistically significant by the more robust ITA test. This implies that while a slight "stilling" may have occurred, it is not a uniform, monotonic process—a critical detail for resource assessment that traditional methods would overlook.

First, the highly localized nature of wind trends is the most significant finding. The decrease in wet-season winds at Bao Loc with the stable conditions at Dak To and Ayun Pa. This underscores the profound risk of extrapolating findings from one location to another.

Second, the change in seasonal wind patterns, as observed at Ayun Pa, has direct and critical implications for grid management and project economics. For project developers, this translates to more volatile revenue streams and a lower annual capacity factor than would be estimated from annual mean wind speeds alone. This heightened seasonality poses challenges for negotiating stable power purchase agreements and requires more sophisticated energy storage solutions or grid balancing mechanisms to ensure a reliable power supply throughout the year.

Furthermore, a major consideration is that our dataset concludes in 2014. Several global and regional studies have indicated a potential reversal of long-term "stilling" trends around 2010, a phenomenon often termed "global brightening." It is therefore possible that the subtle decreasing trends observed at several stations in our study may have stabilized or even reversed in the most recent decade. This limitation underscores the necessity for continuous monitoring and future studies incorporating more recent data to confirm current trends. Consequently, while our findings provide an invaluable historical baseline, they should be used with caution as the sole basis for forecasting future resource availability for projects planned today.

Finally, the study's reliance on four point-based stations for a large, topographically diverse region is a recognized limitation. While these stations provide high-quality, reliable data, they may not capture the full spatial heterogeneity of wind patterns. Future research should aim to integrate these ground-truth observations with high-resolution reanalysis products, such as Fifth Generation European Centre for Medium-Range Weather Forecast Reanalysis, to develop a more spatially comprehensive understanding of wind trend dynamics across the Central Highlands.

4. Conclusion

This study employed the ITA method to conduct the first detailed, long-term (1985–2014) investigation of wind speed trends in Vietnam's Central Highlands. Our main conclusions are as follows:

Trends are highly localized and complex: our analysis revealed a complex mosaic of trends, decisively demonstrating that a "one-size-fits-all" regional assessment is inadequate. We identified a statistically decreasing trend in wet-season wind speed at Bao Loc, stable conditions at Dak To and Ayun Pa.

Seasonality is intensifying: The change in decreasing wet-season winds and dry-season winds at key station points to a potential shift toward greater seasonal contrast in the region's wind climate, with critical implications for energy production forecasting and grid stability. Our findings suggest a potential link between this change of large-scale climate patterns, such as like ENSO.

Methodology matters: The study confirms the exceptional utility of the ITA method. Its ability to visualize trends across the entire data range revealed nuances—such as trends varying with wind speed intensity—that are completely overlooked by traditional monotonic tests like MK.

The strengths of this study lie in its use of a long, homogenized, high-quality observational dataset and a sophisticated analytical method. However, two primary limitations must be acknowledged: first, the data record ends in 2014, precluding the analysis of potential trend shifts in the most recent decade and second, the spatial density of the station network is low, limiting the generalizability of the findings across the entire region. Future work should focus on acquiring recent observational data and integrating high-resolution reanalysis data to overcome these limitations. Furthermore, attribution studies should be expanded to investigate the underlying atmospheric and oceanic drivers behind these observed trends.

In conclusion, this study's findings send a clear message to wind energy developers, investors, and policymakers. In an era of climatic uncertainty, a granular, site-specific, and methodologically advanced understanding of wind resource dynamics is not merely beneficial but absolutely essential. This study not only provides a critical evidence base for climate-resilient wind energy planning in Vietnam but also establishes a methodological benchmark for robust wind resource assessment in other topographically complex and monsoon-driven regions worldwide, ensuring the sustainable and successful development of future wind energy projects.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: All authors
Investigation: All authors
Methodology: All authors
Writing–original draft: All authors
Writing–review & editing: All authors

Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev*. 2019;24:38-50.
   doi: 10.1016/j.esr.2019.01.006
2. International Renewable Energy Agency. *Global Energy Transformation: A Roadmap to 2050*. United Arab Emirates: IRENA; 2019.
3. IPCC. *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: Cambridge University Press; 2021.
4. Saidur R, Islam MR, Rahim NA, Solangi KH. A review on global wind energy policy. *Renew Sust Energ Rev*. 2011;15(4):225-235.
   doi: 10.1016/j.rser.2010.12.009
5. GWEC. *Global Wind Report 2023. Global Wind Energy Council*; 2023.
6. Pryor SC, Barthelmie RJ, Bukovsky MS, *et al*. Climate change impacts on wind energy: A review. *Renew Sust Energ Rev.* 2020;121:109693.
   doi: 10.1016/j.rser.2019.109693
7. Emeis S. *Wind Energy Meteorology: Atmospheric Physics for Wind Power Generation*. Berlin: Springer; 2018.
8. Staffell I, Pfenninger S. The increasing variability of potential wind power generation. *Energy*. 2018;145:814-826.
   doi: 10.1016/j.energy.2017.12.050
9. Torralba V, Doblas-Reyes FJ, Gonzalez-Reviriego N, *et al.* The unpredictable nature of near-surface wind speeds over Europe. *Nat Clim Chang*e. 2017;7(8):565-569.
   doi: 10.1038/nclimate3336
10. Zeng Z, Ziegler AD, Searchinger T, *et al*. A reversal in global terrestrial stilling and its implications for vegetation and wildfire. *Nat Clim Change*. 2019;9(12):979-985.
    doi: 10.1038/s41558-019-0622-6
11. McVicar TR, Roderick ML, Donohue RJ, *et al*. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *J Hydrol*. 2012;416-417:182-205.
    doi: 10.1016/j.jhydrol.2011.10.024
12. Dunn RJH, Azorin-Molina C, Mears CA, *et al.* The long-term satellite-derived surface radiative budget using ISCCP-FH and its extension to CERES. *J Geophys Res Atmos*. 2016;121:4138-4162.
    doi: 10.1002/2015JD024519
13. Vautard R, Cattiaux J, Yiou P, Thépaut JN, Ciais P. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nat Geosci*. 2010;3(11):756-761.
    doi: 10.1038/ngeo979
14. Zhang K, Wang D. A comprehensive analysis of near-surface wind speed trends over China from 1961 to 2017. *Int J Climatol*. 2021;41(2):1189-1205.
    doi: 10.1002/joc.6723
15. Fant C, Schlosser CA, Strzepek K. The impact of climate change on wind and solar resources in southern Africa. *Appl Energy*. 2016;161:556-564.
    doi: 10.1016/j.apenergy.2015.10.092
16. Mann HB. Nonparametric tests against trend. *Econometrica*. 1945;13(3):245-259.
    doi: 10.2307/1907187
17. Kendall MG. *Rank Correlation Methods*. London: Charles Griffin; 1975.
18. Gocic M, Trajkovic S. Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Glob Planet Change*. 2013;100:172-182.
    doi: 10.1016/j.gloplacha.2012.10.014
19. Asfaw A, Simane B, Hassen A, Bantider A. Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *Weather Clim Extremes*. 2018;19:29-41.
    doi: 10.1016/j.wace.2017.12.002
20. Önöz B, Bayazit M. Block bootstrap for Mann-Kendall trend test of serially dependent data. *Hydrol Process*. 2012;26(23):3552-3560.
    doi: 10.1002/hyp.8438
21. Caloiero T, Coscarelli R, Ferrari E. Application of the innovative trend analysis method for the trend assessment of rainfall in southern Italy. *Water*. 2021;13(15):2119.
    doi: 10.3390/w13152119
22. El-Far EA, El-Diasty M. Innovative trend analysis of wind speed in Egypt. *Renew Energ Focus*. 2023;44:345-357.
    doi: 10.1016/j.ref.2022.12.008
23. Sen Z. Innovative trend analysis methodology. *J Hydrol Eng*. 2012;17(9):1042-1046.
    doi: 10.1061/(asce)he.1943-5584.0000556
24. Sen Z. Trend identification simulation and application. *J Hydrol Eng*. 2014;19(3):635-642.
    doi: 10.1061/(asce)he.1943-5584.0000811
25. Wu H, Zuo J. A systematic review of innovative trend analysis method: Methodology, applications, and future directions. *Water Resour Manag*. 2021;35:1903-1921.
    doi: 10.1007/s11269-021-02831-w
26. Akgül M, Şen Z, Yeleğen MO. Innovative trend analyses of water quality parameters in a megacity of Istanbul, Turkey. *Environ Monit Assess*. 2022;194(3):195.
    doi: 10.1007/s10661-022-09855-y
27. de Lucena AJ, de Vasconcelos PC, de Lima FJL, *et al*.

Wind speed trends for the northeast coast of Brazil. *Renew Energy.* 2021;164:1144-1157. doi: 10.1016/j.renene.2020.09.112
28. Alashan S. Application of innovative trend analysis method on precipitation and temperature variables over Saudi Arabia. *Arab J Geosci*. 2020;13(21):1146. doi: 10.1007/s12517-020-06132-0
29. Meshram SG, Singh VP, Meshram C. Long-term trend and variability of precipitation in the semi-arid region of India using innovative trend analysis. *Hydrol Sci J.* 2020;65(6):990-1002. doi: 10.1080/02626667.2020.1718873
30. Tfi B, Ghrab S. Analysis of precipitation and temperature trends using innovative trend analysis method in northern Tunisia. *Model Earth Syst Environ.* 2023;9(1): 819-835. doi: 10.1007/s40808-022-01584-6
31. Ninh NQ, Binh DV, Nam NH, *et al*. Renewable energy in Tay Nguyen: Potential and challenges. *J Sci Technol*. 2020;11:1-10. [In Vietnamese]
32. World Bank. *Vietnam's Solar and Wind Power Potential: A Roadmap to 2030*. United States: World Bank; 2020.
33. Hahmann AN, Sīle T, Witha B, *et al*. The new european wind atlas. *J Phys Conf Ser*. 2020;1452:012002. doi: 10.1088/1742-6596/1452/1/012087
34. Sen Z. Innovative trend significance test and applications. *Theor Appl Climatol*. 2017;127(3-4):939-947. doi: 10.1007/s00704-015-1681-x