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Assessing wind power generation potential over South Asia using wind speed observation and reanalysis datasets

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Abstract
Wind energy has exceptional and untapped potential in South Asia, a region characterized by a diverse climate and geography. The novelty of this research lies in using systematic selection threshold criteria, ensuring a comprehensive representation of wind speed patterns to determine wind energy generation potential classification and standardize wind anomaly over diverse topographic and climatic conditions of South Asia. Further, using reanalysis products (ERA5, JRA55, NCEP/NCAR), a multi-reanalysis ensemble (MRE), and wind speed trends, this work systematically evaluates the reliability and accuracy of the performance of reanalysis products to perceive uncertainty in reanalysis products. For this determination, a 10 m above ground level (AGL) of wind speed was utilized for 1973–2005. A high percentage of stations with missing wind speed values is identified in the study, emphasizing the importance of data quality. Overall, providing strong correlations, low bias, and close alignment with observed data, JRA55 is a reliable choice for wind energy assessments and climate studies. Also, the research reveals a downward trend in annual mean wind speed ($-$ 0.010 ms^{-1}year^{-1}) in South Asia, aligning with the global terrestrial stilling phenomenon, although significant localized variations exist. The findings based on the localized regions, such as the Hyderabad Airport station, offer Excellent prospects for developing wind energy yield when classified. The reasons for inconsistencies between reanalysis products and observations are examined. A robust systematic threshold criteria research method is delineated to enhance data quality, revealing insights into spatial coverage, station selection, and biases. Ultimately, the study contributed to South Asia's climate resilience, policymakers, regional climate dynamics, and sustainable development of renewable energy sources.

Keywords Systematic threshold criteria · Wind speed trends · Reanalysis products · Terrestrial stilling · Wind energy assessment · Standardized anomaly

1 Introduction

Due to the need to reduce environmental impacts and transition to sustainable alternatives, renewable energy has become a pivotal topic within the international energy sector (Miao et al. 2020; Deng et al. 2021; Davidson and Millstein 2022). It is essential to understand regional wind speed trends and variability for optimizing wind turbine efficiency and investments within the wind power industry, since wind dynamics and the space–time variability of wind are essential to meteorology, climate studies, and various applied sciences (Dong et al. 2020; Miao et al. 2020; Li et al. 2020; Fan et al. 2021; Khan et al. 2024). Wind datasets are crucial because of not only wind energy and climatology but also regional wind speed trends and variability that are relevant to wind-sensitive structures, such as high-rise buildings and long-span bridges (Chu et al. 2021; Jiang et al. 2023). According to recent research (Zeng et al. 2018; Miao et al. 2020; Fan et al. 2021; Dunn et al. 2022), the wind speed in oceanic regions is on the rise, whereas the wind speed over land areas is on the decline. These findings emphasize the importance of understanding regional wind dynamics, as well as their implications for assessing wind energy. Geographically, South Asia offers significant potential for wind energy development. Due to these features,

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wind power suits many regions with high winds. Assessing wind resources in this region is extremely important to optimize renewable energy projects and ensure sustainable energy generation (Khan et al. 2019; Khan and Dairaku 2024). A significant portion of South Asia's energy demand is met by wind power, contributing to reduced greenhouse gas emissions and fossil fuel dependence (Fan et al. 2021; Li et al 2020). According to recent studies (Khan et al. 2020; Li 2023; Garland et al. 2024), climate change is not only important for reducing greenhouse gas emissions with wind energy, but it also affects wind resource availability and operational risks. Therefore, comprehensive wind energy studies are necessary for the region to utilize its renewable energy resources effectively.

An analytical approach to assessing wind speed changes has emerged because of the lack of long-term availability, disjunct sampling, quality of datasets, and homogeneous historical wind speed observations (Larsén and Mann 2006; Li 2018). Inconsistencies in spatial and temporal contexts often affect the robustness of trend examination derived from observational data (Dong et al. 2020; Fan et al. 2021; Dunn et al. 2022). By selecting datasets based on robust threshold criteria, long-term wind speed variations can be reliably represented, mitigating these issues. For wind speed studies to be more accurate, careful data curation and threshold setting are essential. Further, recent studies (Zeng et al. 2018; Fan et al. 2021) have adopted an approach to data selection that involves global-scale station selection criteria, at least 15 days of data available in one month. This may not be a comprehensive representation of long-term trends. Additionally, some studies (Molina et al. 2021, 2023) have considered arbitrary thresholds (the minimum percentage of data required for inclusion in research) of daily time steps at each station for the continental-level analysis, which may not be reflective of the true wind speed variability due to a lack of clear rationale. These research works have heavily relied on datasets such as the "Global Surface Summary of the Day-GSOD" and "HadISD (Hadley Integrated Surface Database)." For country-specific analyses, some academic endeavors work removed all wind speed data that are greater than or equal to 30 knots (Libanda and Paeth 2023). Moreover, months with less than 26 days of observations are rejected and set as missing (Utrabo-Carazo et al. 2022). These studies, without justification by statistical analysis or empirical validation, select the datasets. In the context of country-level studies, data sources such as "Ogimet (weather information service)," "The Spanish Meteorological Agency (AEMET)," and "the Portuguese Sea and Atmosphere Institute (IPMA)" have been used in this work, respectively. The present studies in the field of wind energy assessment have often applied arbitrary thresholds for data inclusion in published literature, such as 50% and 90% of monthly and daily time steps at each station (Zeng et al. 2018; Fan et al. 2021; Molina et al. 2021, 2023). A standardized approach is needed to ensure more reliable and representative datasets for these criteria across different studies, which can lead to variability in results and interpretations.

Recent studies (Sawadogo et al. 2019; Dong et al. 2020; Miao et al. 2020; Deng et al. 2021; Zha et al. 2021; Dunn et al. 2022; Utrabo-Carazo et al. 2022) found that the average wind speed on the planet's land surface has been substantially decreasing since the 1960s, a phenomenon called'terrestrial stilling' (Zeng et al. 2018) that can be attributed to climate change. However, changes in this terrestrial stilling trend have been observed since the early 2010s, particularly over North America, Europe, and Asia (Fan et al.2021). This terrestrial stilling has important implications in the wind energy sector, hydrology, and environmental impact assessment fields. Although observations of these changes have been made in station data, it remains important to examine whether these changes have been reflected in global reanalysis products. This evaluation is crucial and particularly necessary given that reanalysis products are widely used in diverse applications, such as wind resource assessment and climate modeling. For wind energy development to be sustainable, particularly in regions such as South Asia, it is necessary to understand long-term trends in average wind speed.

Reanalysis datasets that integrate historical weather data with modern meteorological models can enhance wind resource assessments. Combining these datasets with observations in situ can help researchers better understand wind patterns (Ebita et al. 2011). With this synergy, wind resource assessments can be more accurate, as reanalysis datasets can fill in the gaps and extend the coverage period of wind data. Validating the reliability of reanalysis datasets by comparing them with observed data is crucial for ensuring they accurately reflect real-world conditions, ultimately strengthening the overall analysis. In the other research work, reanalysis products have also been subjected to uncertainty assessments. A study by (Torralba et al. 2017) examined global wind speed trends between 1980 and 2015 using three reanalysis products. These studies all reported an increasing and decreasing trend in wind speed over the oceans and over land, respectively. Nevertheless, reanalysis products reported significant differences in declining trends over land, which was also found by Wohland et al. (2019) in their comparison of four such reanalysis products. These two aforementioned studies did not verify reanalysis outputs with observations, preventing a true assessment of their fidelity to true wind speed trends. Studies such as Ramon et al. (2019), which examined the trends in wind speed from 1980 to 2017 using five global reanalysis products, and Miao et al. (2020), which demonstrated tendencies in the Northern Hemisphere between 1980 and 2016, reveal considerable diversity in wind speed characteristics, including average speeds, annual variations, and long-term trends. Nevertheless, as is the case with most previous studies examining wind speed trends over land, they did not incorporate the trend classification of wind power potential at the regional scale. The classification is based on calculated wind power density values derived from wind speed data. Afterward, regions are categorized according to their wind potential in seven dissimilar categories (Elliott et al. 1991).

For wind resource assessments, threshold criteria are crucial for ensuring the validity and accuracy of selected datasets. Nevertheless, these criteria often lead to inconsistencies due to their arbitrary nature, causing bias and variability in the results. This inconsistency can be mitigated by establishing robust, systematic threshold criteria. Research integrity is maintained by selecting representative and unbiased datasets using a systematic approach. Based on the existing literature, systematic basis threshold criteria for the data selection at the existing weather locations, and statistical analysis have been neglected which is very crucial for the data quality and spatial cover of the research domain. The literature indicates the existence of a study gap that focuses on a comprehensive and systematic comparison of wind field data from the observations and reanalysis datasets at the station locations in more detail over subcontinent regions is yet to be published. To develop wind energy resources as well as research on regional climate, it is important to evaluate the reliability and accuracy of reanalysis datasets over the subcontinent and different regions. Moreover, it is observed that, based on the literature publications, wind energy potential is not classified at the regional scale in the research domain of subcontinent regions, which is crucial information for the wind power investor and decision maker.

The research aims to perform a comparative analysis to determine the reliability and accuracy of different reanalysis products and a multi-reanalysis ensemble (MRE) to identify significant variations and biases across different data availability thresholds. This study will also investigate the implications of varying threshold criteria on spatial coverage, station selection, and resultant biases in wind speed trend analysis while acknowledging the potential limitations of assessing a wider geographical area. Global reanalysis products like ERA5, JRA55, and NCEP/NCAR have been used, but systematic selection criteria have not been extensively addressed. The outcome of this study will be wind energy generation potential classification and standardized wind anomalies over the diverse topographic and climatic conditions of South Asia. This study aims to bridge this gap by introducing a method for data selection, which forms a critical aspect of its novelty.

The novelty of this research lies in the use of systematic selection threshold criteria, ensuring a comprehensive representation of wind speed patterns to determine wind energy generation potential classification and standardize wind anomaly over diverse topographic and climatic conditions of South Asia. Unlike previous studies that have often applied arbitrary thresholds, this research systematically evaluates the data availability at multiple thresholds to select the most appropriate dataset. Employing this approach enhances the reliability of the dataset by reducing biases associated with incomplete data.

This manuscript unfolds structure as follows. Section 2 describes the data and methods. The results Section is 3. Sections 4 and 5 present the discussion and conclusions of this research, respectively.

2 Study domain, data and methods

2.1 South Asian region

South Asia region consists of the following countries, including Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka. Various climatic zones characterize this region, ranging from arid and semi-arid zones to tropical and subtropical areas. Due to a diverse geographic area and high population density, there is an increasing demand for renewable energy resources, particularly wind power. Consequently, South Asia has become an increasingly important area of interest when it comes to assessing wind power potential, which is of great importance to the goal of addressing the problem of energy sustainability in the region.

2.2 Meteorological observations

Developed and maintained by the Met Office Hadley Centre, HadISD (Hadley Integrated Surface Database) is an invaluable resource for climate researchers. HadISD provides long-term, high-quality observations of surface climate variables like wind speed (m/s) to understand past climate variations and conditions. An outstanding feature is its comprehensive and spatially extensive data set, which integrates various data sources, including land weather stations, ship data, and buoy data. With its integration of coastal and inland climate conditions, HadISD allows researchers to conduct regional and global climate studies on a broad range of climate conditions. Quality control procedures are implemented on the dataset, including outlier detection and homogenization techniques, ensuring data reliability and consistency. Researchers can explore long-term trends and variability in climate by using HadISD since it covers multiple decades over a wide range of latitudes. Climate monitoring impacts assessments, and model evaluations are among their applications in addition to climate research. HadISD, which continues to be maintained and updated by the Met Office Hadley Centre, plays a crucial role in contributing to our understanding of historical climate patterns and provides critical data for climate change studies (Dunn et al. 2019, 2022).

2.3 Reanalysis products

Three different institutions produce reanalyses of 10 m AGL winds, including ERA5(Fifth Generation ECMWF Reanalysis) from ECMWF (European Centre for Medium-Range Weather Forecasts); the National Centers for Environmental Prediction/National Center for Atmospheric Research, Reanalysis Project 1 from NCEP/NCAR; the Japanese 55-year Reanalysis (JRA-55) from the Japan Meteorological Agency (JMA) and finally, high-quality observation of HadISD from the Hadley Integrated Surface Database. Hourly data are calculated to the daily mean for all the datasets. All utilized reanalysis products (ERA5, NCEP/NCAR, JRA-55) are regridded by the bilinear (bill) interpolation method (Ramon et al. 2019) at a latitude–longitude grid spacing of 0.1 degrees. Detailed information is provided in Table 1, including full name, institutional affiliation, time resolution, variable, research period, horizontal grid spacing, and URL. A lot of wind energy resources are evaluated with these state-of-the-art reanalysis products (Ramon et al. 2019; Miao et al. 2020; Molina et al. 2021; Samal 2021; McKenna et al. 2022). As part of the analysis, the hindcast periods (1973–2005) for each HadISD station selected in each dataset are compared to these aforementioned reanalysis products (Fig. 1: a total of 60 stations were analyzed). The period 1973 to 2005 for analysis is due to the availability of the observation dataset (HadISD) of wind speed in the subcontinent region.

ERA5 represents atmospheric conditions comprehensively and stands out as one of the most popular global reanalysis products developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 product provides valuable insight into past weather and climate dynamics by the assimilation of vast amounts of observational data. Its fine-grained representation of atmospheric processes makes it an indispensable tool for climate, meteorology, and environmental studies. ERA5 has a 31-km spatial resolution and hourly temporal resolution, giving it the ability to describe atmospheric processes with great precision. Among these are high-quality reanalysis datasets widely used for scientific research and decision-making processes, representing improved depictions of near-surface winds, temperatures, and other meteorological parameters (Hersbach et al. 2020).

This project, commonly referred to as NCEP/NCAR or R1, represents the culmination of much effort placed into atmospheric reanalysis by the National Centers for Environmental Prediction and the National Center for Atmospheric Research. A collaboration between NCEP and NCAR has produced a comprehensive, well-used reanalysis dataset through this groundbreaking project. With its extensive collection of observational data, NCEP/NCAR R1 can provide valuable insights into historical climate patterns and weather patterns. This reanalysis provides climatology, meteorology, and climate change researchers with a robust foundation for climate change studies spanning 1948 to the present. It provides a reasonably accurate representation of atmospheric phenomena due to its horizontal grid resolution of approximately 2.5 degrees. In studying past weather and climate variability, NCEP/NCAR or R1 has become a valuable resource due to its extensive temporal coverage and accessibility (Kalnay et al. 1996).

The Japanese 55-year Reanalysis, developed by the Japan Meteorological Agency, stands out as a significant achievement in atmospheric reanalysis. A comprehensive historical record of the Earth's atmosphere, JRA-55 covers a substantial period from 1958 to the present, making it an indispensable resource for climatology and meteorology. Detailed investigations of atmospheric phenomena are

Table 1 Outline of the observation datasets and three global reanalysis products evaluated in this academic work

In situ and reanalysis datasets			Time resolution	Variable (10-m)	Period	Horizontal grid spacing	URL
Name	Full name	Institution					
HadISD	Hadley Integrated Surface Database (HadISD)	Met Office Hadley Centre	Sub-daily (3, 6, 12-h)	Wind Speed	1973–2005	Surface Meteorological Station	https://www.metoffice.gov.uk/hadobs/
ERA5	ECMWF Fifth Major Global Reanalysis	ECMWF	1-h	SfcWind (Uas,Vas)		0.25° × 0.25°	ERA5| ECMWF
NCEP/NCAR or R1	National Centers for Environmental Prediction/National Center for Atmospheric Research, Reanalysis Project 1	NCEP/NCAR	6-h			1.875° × 2.5°	National Centers for Environmental Information (NCEI) (noaa.gov)
JRA-55	Japanese 55-year Reanalysis	JMA				1.25° × 1.25°	JRA-55 project (kishou.go.jp)

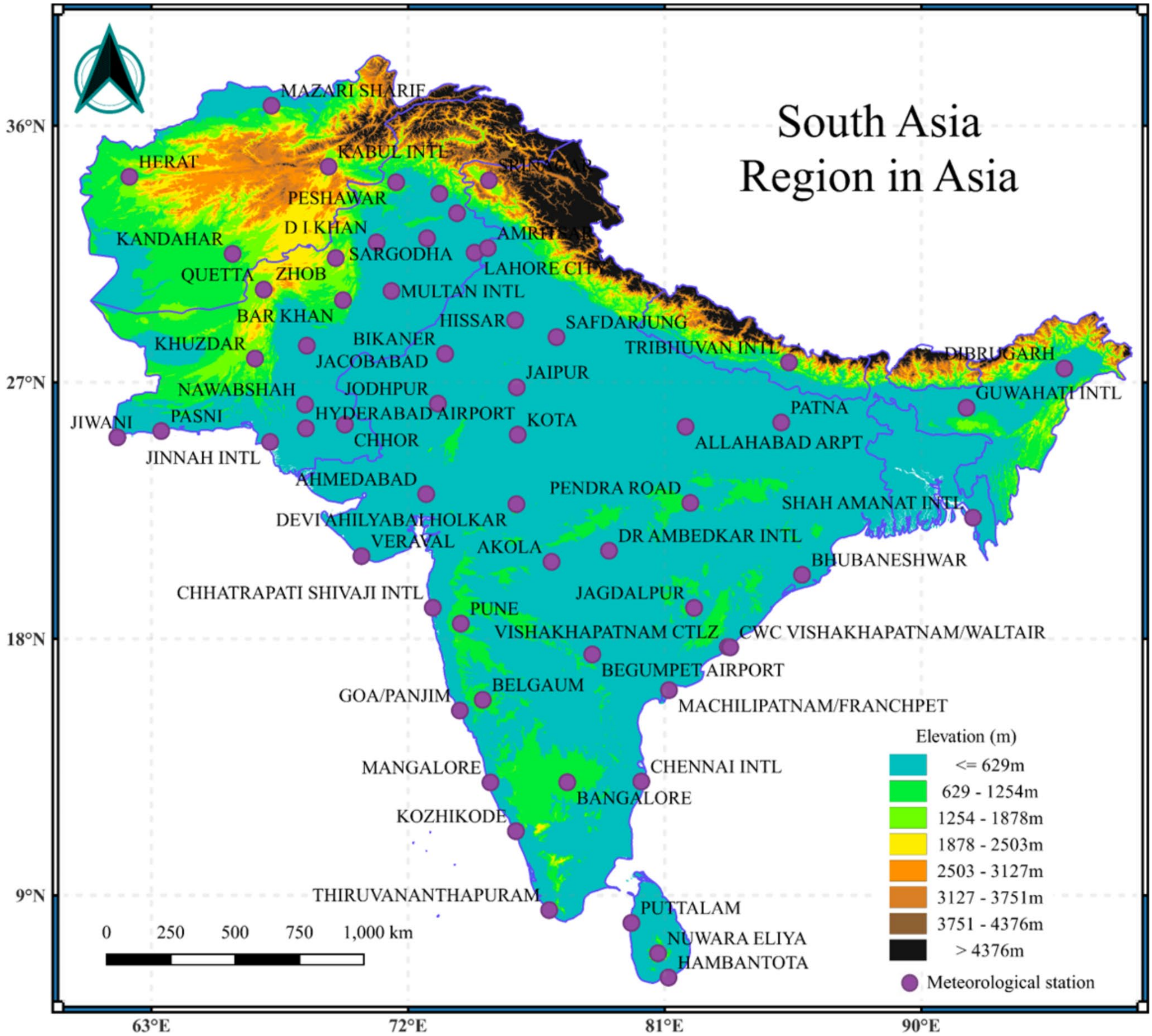

Fig. 1 Topographic map of South Asia and wind available stations (Khan et al. 2024)

possible using this reanalysis dataset with its high spatial resolution, and a horizontal grid spacing of approximately 1.25 degrees. In a robust representation of past weather and climate conditions, JRA-55 draws upon various observational information, including data from radiosondes, satellites, and surface observations. JRA-55 is frequently relied upon by scientists and researchers worldwide to provide rich historical insights into climate variability, weather patterns, and long-term climate change. A commitment to advancing our understanding of our planet's atmosphere and its interactions is reflected in its development and continual updates by the JMA (Ebita et al. 2011).

2.4 Threshold criteria and statistical analysis

It is crucial for the quality and accuracy of wind speed trend assessments that the selection of weather stations and the application of data availability thresholds are considered. This study presents a systematic method for selecting thresholds that are more comprehensive and objective than previous approaches (Zeng et al. 2018; Ramon et al. 2019; Fan et al. 2021; Molina et al. 2021, 2023). To optimize wind speed trend analysis accuracy in the South Asia region, the focus is on striking a balance between data availability and spatial coverage.

Threshold definition: in the context of data availability, a threshold represents the minimum percentage of data required for inclusion in research. It serves as a criterion for selecting stations or locations based on the completeness of available data. For instance, consider a hypothetical weather station with daily wind speed data for a period of 33 years (1973–2005). Suppose set a data availability threshold of 178 of 80%. In that case, the station must have at least 80% of its data available (i.e., not missing) during the 33-year period 179 to be considered for analysis. The formula for data availability threshold is expressed below in Eq. (1).

$$\text{Data availability percentage} = \left(\frac{\text{Number of days with available data}}{\text{Total number of days during the study period}}\right) \times 100 \quad (1)$$

An analysis of wind speed trends based on varying threshold criteria is presented in this study to determine how they affect the spatial coverage, station selection, and bias introduced into the analysis. Maintaining data quality and comprehensiveness while covering a broader geographic area can be challenging. The following steps are followed by this method: (1) Data availability thresholds and spatial coverage, (2) Statistical indices, (3) Reanalysis product comparison, (4) Mann–Kendall nonparametric test and Sen's slope estimation, (5) The standardized anomaly index.

2.5 Data availability thresholds and spatial coverage

Data availability thresholds and spatial coverage: a threshold criterion for data availability is adopted to ensure the selection of stations representing high-quality data. The present study considers stations with daily wind speed data available during the hindcast period (1973–2005) and multiple threshold criteria applied to know the data available. Data availability thresholds impact spatial coverage, station selection, and potential biases introduced into wind speed trend analysis. The present study aims to determine the perfect balance between data availability and spatial representation by systematically varying the threshold from 80 to 99%.

Statistical indices: by comparing in situ observations from the HadISD dataset with the reanalysis products (ERA5, JRA55, NCEP/NCAR), we evaluate the performance and reliability of the selected reanalysis products using a suite of statistical indices. Several different indices can be used to determine the level of accuracy. For example, Standard Deviation of Wind Speed (σ; m/s; Eq. 2), Root Mean Square Error (RMSE; m/s; Eq. 3) (Ramon et al. 2019), Mean Bias (MB; m/s; Eq. 4), Pearson Correlation Coefficient (R; Eq. 5), Coefficient of Determination (R^2; Eq. 6), (Molina et al. 2021), and Climatological Mean Wind Speed (CM; m/s; Eq. 7) (Li et al. 2019). Based on these metrics, the accuracy and consistency of the products produced by the reanalysis process to examine how closely they match the HadISD observations.

$$\sigma = \sqrt{\frac{\sum (W_i - \mu)^2}{N}} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{n} (\text{M}_i - \text{O}_i)^2} \quad (3)$$

$$\text{MB} = \frac{1}{N}\sum_{i=1}^{\text{n}} (\text{M}_i - \text{O}_i) \quad (4)$$

$$\text{R} = \frac{\sum_{i=1}^{\text{n}} (\text{M}_i - \bar{\text{M}})(\text{O}_i - \bar{\text{O}})}{\sqrt{\sum_{i=1}^{\text{n}} (\text{M}_i - \bar{\text{M}})^2}\sqrt{\sum_{i=1}^{\text{n}} (\text{O}_i - \bar{\text{O}})^2}} \quad (5)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\text{O}_i - \text{M}_i)^2}{\sum_{i=1}^{n} (\text{O}_i - \bar{\text{O}})^2} \quad (6)$$

$$\text{CM} = \frac{1}{N}\sum_{\text{i}=1}^{\text{n}} W_{\text{i}} \quad (7)$$

where, σ (sigma) = the Standard Deviation of wind speed (m/s), RMSE = Root Mean Squared Error (m/s), MB = Mean Bias (m/s), R = Pearson Correlation Coefficient, R^2 = Coefficient of Determination, CM = Climatological Mean (m/s), N = the number of data points (measurements), W_i = individual wind speed measurement at different data points, μ (mu) = the mean (average) wind speed, ***i*** = 1, 2,3…n, M_i = Model wind speed, O_i = Observe wind speed, $\overline{M}$ = Model mean wind speed, $\bar{O}$ = Observe mean wind speed, $\sum$ (summation) = Taken over these measurements from i = 1 to i = N, where N is the total number of points.

Reanalysis product comparison: comparing the outputs from ERA5, JRA55, NCEP/NCAR, and a multi-reanalysis ensemble (MRE), analyzed the results from these reanalysis products. The MRE was constructed by integrating the outputs of the individual reanalysis products. This provides a comprehensive dataset that capitalizes on each product's strengths. Through this ensemble approach, biases, and uncertainties inherent in any single reanalysis product are mitigated while substantially improving the robustness and reliability of the analysis. By comparing different reanalysis products with varying thresholds of data availability, we can identify significant variations and biases.

This advances the current state of knowledge concerning assessing wind speed trends in South Asia by applying systematic selection criteria and comprehensive statistical analysis. This study contributes valuable insight into the suitability of global reanalysis data for wind energy development in the region by addressing the limitations of previous research and providing a rigorous framework for threshold selection.

Applied the Mann–Kendall nonparametric test and Sen's slope estimation: to determine the trend of wind speeds during the specified periods. The Mann–Kendall (M–K) nonparametric test does not require the data to follow the normal distribution, making it a suitable method for trend analysis. In addition to being nonparametric, the M–K test can also assess trends in non-linear time series data (Fan et al. 2021; Zeng et al. 2018). Nonparametric methods such as the Mann–Kendall test and Sen's slope estimation were selected to determine the trends in wind speed variations that may not follow normal distribution and linearity. We used a 95% confidence level in the Mann–Kendall test and the upper and lower limits of the confidence interval of Sen's slope value to indicate the trend's uncertainty.

The standardized anomaly index (Koudahe et al. 2017): applied to reveal the interannual variability of land surface wind speed for the period of 1973 to 2005. The observation annual mean wind speed time series is compared to three reanalysis products and an MRE.

$$W' = \frac{X - \overline{X}}{\sigma} \tag{8}$$

where W' = Standardized anomalies of wind speed, X=Annual average wind speed, $\overline{X}$= Mean wind speed, σ= Standard deviation.

The study employs systematic selection criteria, which become particularly pertinent considering this variability. The evaluation of data reliability directly influences spatial coverage and station selection, as described in the above bolt points, to address the challenges posed by missing data. A range of acceptable threshold values between 80 and 99% was established to ensure the completeness and statistical significance of the data for reliable analysis. Based on these criteria, meaningful assessments of wind speed trends in South Asia should be created based on a balance between data availability and completeness. This study's use of this method enhances the reliability of our analyses, particularly when analyzing reanalysis products such as ERA5, JRA55, and NCEP/NCAR.

2.6 Wind energy potential

A project involving wind energy must evaluate wind power and regional wind speed, which are crucial information. By applying the power law method to extrapolate the wind speed to the desired hub height of the wind turbine, the potential of Wind Power Density (WPD) can be calculated. Further, regions classify wind power at the desired hub height based on international standards.

2.6.1 Extrapolating wind speeds to turbine hub height

To compute the WPD most studies extrapolate the surface wind speed (at 10 m) to the desired hub height with different approaches due to the unavailability of the wind speed at a general elevation Z. Therefore, the power-law model is used to estimate the wind speed at various hub heights (z). This study examines, the power law method applied to extrapolate 10 m wind speeds to 100 m of turbine hub height. It is expressed as (Hueging et al. 2013; Khan et al. 2019; Moemken et al. 2018; Reboita et al. 2021).

$$\text{Wind speed } (w_{100m}) = w_{10m}\left(\frac{Z_{100m}}{Z_{10m}}\right)^{\alpha} \tag{9}$$

where w_{100m} is the wind speed at the wind turbine of desired hub height (z_{100m}), z_{10m} is the reference height, w_{10m} is the wind speed at the original height (z_{10m})/reference height, and α is the surface roughness coefficient (power-law exponent), which depends on the characteristics of the region (Amjad et al. 2015). Power-law exponents can be approximated in numerous ways. According to an early study, α equals 1/7 (≈ 0.14), Hermann Schlichting (1968) when certain conditions are met (neutral conditions and flat terrain). As specified by (Justus 1978), an approximation is more complex. The value of α can be obtained from the following expression:

$$\alpha = \frac{0.37 - 0.088\ln(v_{10})}{1 - 0.088\ln(Z_{10}/10)} \tag{10}$$

The International Electrotechnical Commission (IEC) provides guidelines for the design of wind turbines and suggests power-law exponents of 0.2 and 0.14 are used for onshore (International electrotechnical commission 2005) and offshore (International electrotechnical commission 2019) areas, respectively. Different extrapolation methods influence wind speed characteristics at hub height. For instance, (Moemken et al. 2018) reported that in comparison with the methods listed above, Justus (1978) approximation shifts wind probability density functions up in speed. The International Electrotechnical Commission suggested the method we used for this study, as well as that employed in several further research works (Hueging et al. 2013; Moemken et al. 2018). Besides, if near-surface wind speeds at 10 m are available, the roughness coefficient (α = 1/7) at the reference height is assumed to be constant for wind speed, as it is appropriate for open land surfaces e.g., Akinsanola (2017,

2021) and Sawadogo (2019). Hence, following the IEC guidelines, this study uses power-law exponents (α) of 0.2 for onshore areas.

Part of this study quantifies wind energy changes resulting from variations in wind speeds and compares the reanalysis products and observations to determine these variations. Adapted from Elliott et al. (1991) classified the annual mean wind speed into seven levels to identify which class of wind speed significantly affects wind energy output, as tabulated in Table 2. A study is then conducted to determine if the changes in wind speed frequency at each level are significant.

2.6.2 Wind power density (WPD)

Entrepreneurs want to know whether a given region can generate a significant amount of energy, as well as its variability over time. Wind speed is projected at the desired 100 m height using the hindcast periods (1973–2005) by a power-law method. This study used a physical transformation (Libanda and Paeth 2023) called WPD to assess the amount of energy available in South Asia. The WPD (unit: W/m^2) is an important measure for assessing the potential of wind energy generation in a location (Khan et al. 2019; Reboita et al. 2021), and is defined in the equation as

$$\mathrm{WPD} = \frac{1}{2}\rho_{\mathrm{air}}\ \mathrm{w}^3 \tag{11}$$

where ρ_{air} is air density $(\mathrm{kg/m^3})$ and w is the wind speed $(\mathrm{m/s})$ at the sought-after hub height. ρ_{air} (air density) can be approximated in several ways. According to the expression (Ronaldo dos Santos Custódio 2009), the air density at Z height is as follows:

$$\rho_{\mathrm{air}} \cong \frac{353.4\left(1-\frac{Z}{45271}\right)^{5.2624}}{273.15+\mathrm{T}} \tag{12}$$

where Z denotes the desired height (m) and T represents air temperature (°C).
The International Standard Atmosphere (Cavcar 2000) specifies that $1.213\ \mathrm{kg/m^3}$ is the density of air at 100 m. Akinsanola et al. (2021), Khan et al. (2019) and Khan and Dairaku (2024) used air density (ρ_{air}) constant values of $1.225\ \mathrm{kg/m^3}$ based on the standard conditions. Hence, based on literature reviews this study followed the International Standard value of air density (ρ_{air}), which is 1.225 $\mathrm{kg/m^3}$ at 288.15 K and 1000 hPa. A schematic flowchart of the research is illustrated in Fig. 2.

In wind energy potentials, wind resources are often considered in addition to cut-out wind speeds, however, coastal regions with high wind resources may be subject to increased cyclone risks, which require careful siting of wind turbines and risk assessment (Li and Suresh Kumar 2021; Li & Kumar 2023).

3 Results

3.1 Evaluation of data reliability

Data reliability is an important aspect of our study, particularly concerning the available weather stations that can provide wind speed measurements. As shown in Fig. 3, the percentage of wind speed values that possess missing and non-missing values from these stations is presented comprehensively for the South Asia region during the period 1973–2005. Among the 60 weather stations, there is substantial variation in the availability of data. The missing wind speed ranges from 0 to 79%, indicating substantial variation in data completeness across stations. These analyses can be significantly impacted e.g., accuracy and robustness by such variations in data availability. Further, when significant amounts of data are missing, wind resource assessments and power generation forecasts can be inaccurate, affecting the development of policies and planning for the energy industry.

Station 41759-PAS (Pasni) possesses the greatest percentage of missing wind speed observations (79%). On the other hand, several stations in the study, including station 42647-AHM (Ahmadabad), station 42754-DEV (Devi Ahilyabai Holkar), and station 43371-THI (Thiruvananthapuram), displayed exceedingly small missing values during the study period. There is a heterogeneity in the availability of data within our dataset that is evident in these disparities.

Table 2 Adapted from Elliott et al. (1991) concerning wind power density classification at 10 m and 100 m AGL

Wind power class (Effect)	Wind speeds at 10 m (m/s)	Wind power density at 10 m (W/m^2)	Wind speed at 100 m (m/s)	Wind power density at 100 m (W/m^2)
1 (Poor)	0–4.4	0–52.2	0–6.2	0–146.9
2 (Marginal)	4.4–5.1	52.2–81.3	6.2–7.2	146.9–228.7
3 (Moderate)	5.1–5.6	81.3–107.6	7.2–7.9	228.7–302.8
4 (Good)	5.6–6	107.6–132.3	7.9–8.5	302.8–372.5
5 (Excellent)	6–6.4	132.3–160.6	8.5–9.0	372.5–452.0
6 (Excellent)	6.4–7.0	160.6–210.1	9.0–9.9	452.0–591.5
7 (Excellent)	> 7.0	> 210.1	> 9.9	> 591.5

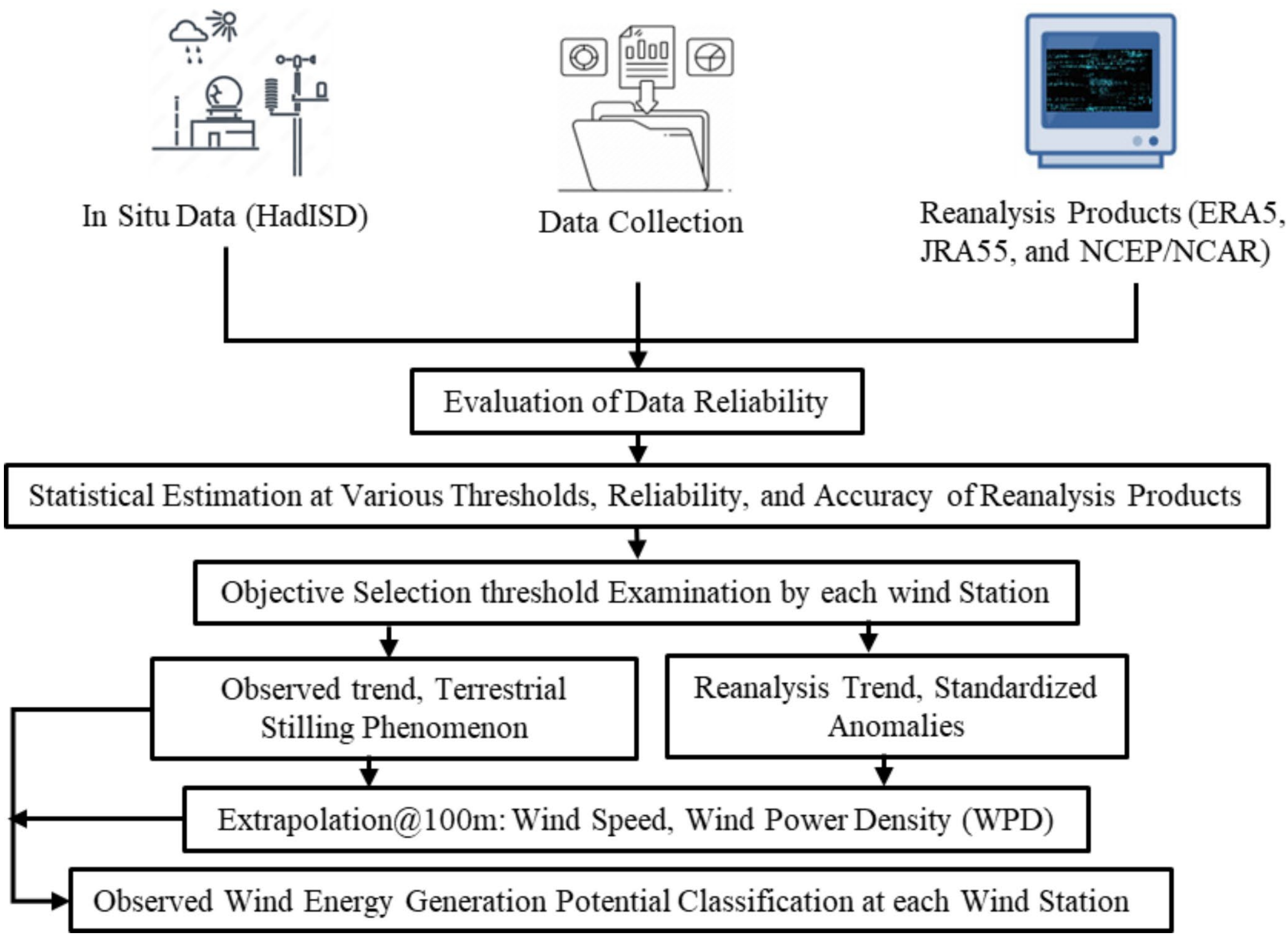

Fig. 2 A schematic flowchart of the research

On average, the dataset has a missing value rate of 13%, indicating that approximately 13% of wind speed measurements for all 60 stations are unavailable for analysis. Considering variations in data availability requires careful consideration of station-specific limitations during our analysis. Our results may be biased or uncertain in areas where stations (e.g.: 43295-BAN, 43284-MAN, 43279-CHE, 43128-BEG, 43003-CHH, 28670-DR, 42647-AHM, 42492-PAT, 42410-GUW, 42131-HIS) have high percentages of missing values. However, wind speed patterns can be more reliably interpreted through stations with complete datasets.

3.2 Statistical estimation at various thresholds

This section details the systematic statistical estimation of wind speed characteristics across South Asia based on various percent thresholds applied to reanalysis products (ERA5, JRA55, and NCEP/NCAR), MRE, and observation datasets (HadISD). Examining threshold data availability, Climatological Mean, and statistical indices aim to provide a comprehensive analysis of the accuracy and reliability of these datasets in capturing the region's wind climatology. Through this multifaceted approach, identify each dataset's strengths and limitations in terms of its ability to represent both average conditions and variability in wind speed across diverse geographies and climate zones.

According to Fig. 4a, different thresholds of data availability result in varying numbers of stations available for analysis. The spatial coverage and representativeness of the dataset are significantly impacted by the number of stations. A considerable number of stations are available for analysis at bottom-level thresholds such as 80% and 85%, ensuring a more comprehensive dataset. However, increasing the threshold could potentially introduce bias because of the integration of wind speed data with lower accuracy. By maintaining a 90% threshold, data availability and accuracy are balanced, while maintaining spatial coverage. At this stage, reductions in reanalysis data bias are acceptable if achieved by reducing the number of stations and thus reducing their spatial coverage. There is a significant reduction in the number of stations when thresholds of 95% and 99% are

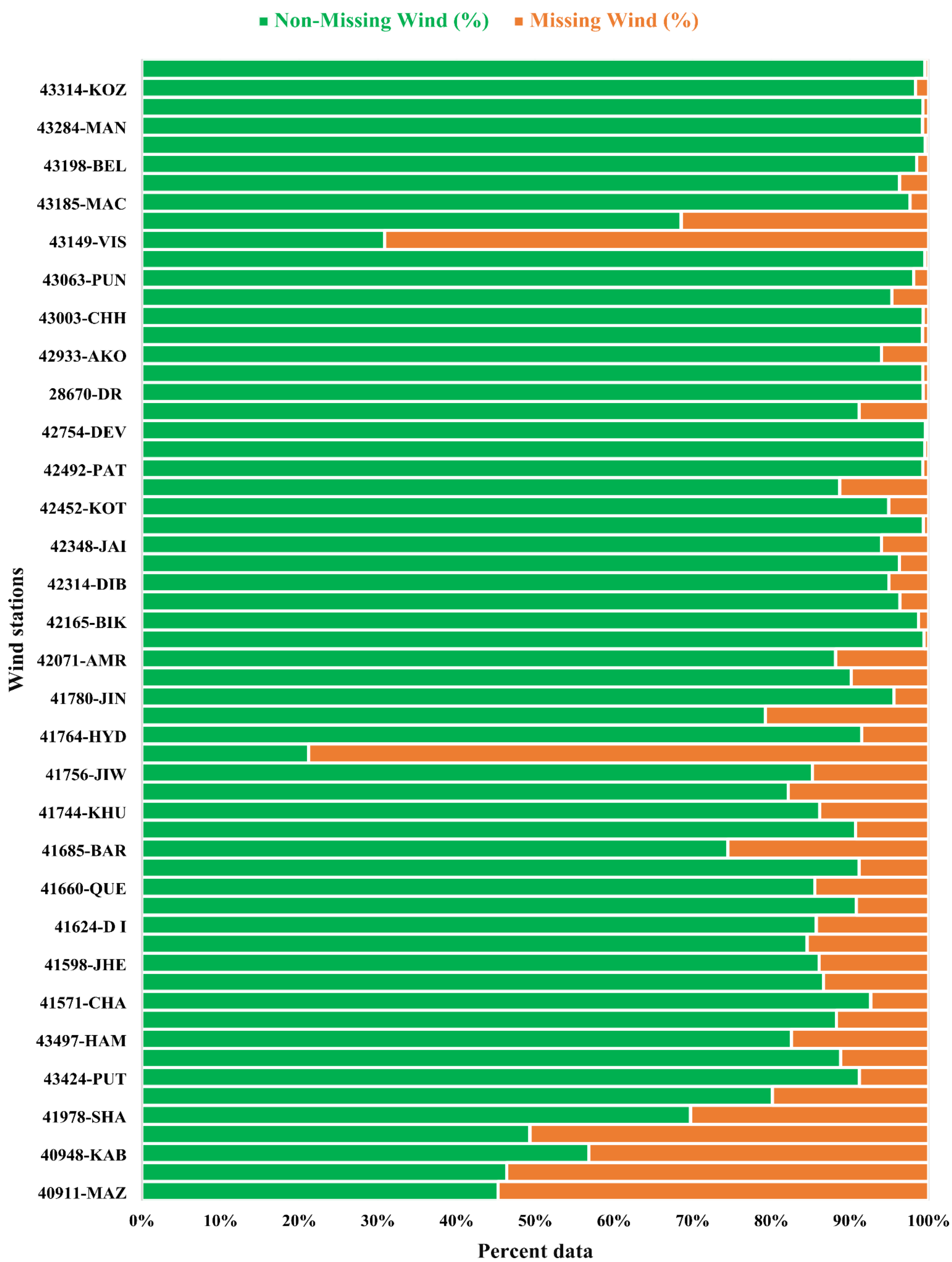

Fig. 3 The percentage of missing and non-missing values daily mean wind speed at 60 stations in South Asia, duration 1973–2005

used, which results in a smaller spatial coverage and may not adequately represent the wind characteristics across regions and limitations on assessment at a wider area, but possibly more accurate data. The result of these station counts suggests that when selecting a threshold for wind speed trend analysis, it is essential to carefully balance the adjustment between data availability and representativeness.

Figure 4b demonstrates Climatological Mean (m/s) values for the long-term average wind speed of three products, MRE and HadISD, at different data availability thresholds. According to JRA55, values close to HadISD observations consistently occur across all thresholds, indicating the product's ability to accurately represent Climatological Mean wind speeds. It is clear from this that JRA55 has proven to be reliable when assessing wind resources in South Asia. Based on the ERA5 product, Climatological Mean values are like those obtained by JRA55, however, some deviations depend on the threshold. A potential overestimation of wind speed consistently can be seen in NCEP/NCAR's Climatological Mean values compared to JRA55 and ERA5. When evaluating wind resources using NCEP/NCAR, this should be taken into consideration. MRE is closely followed by JRA55 in terms of Climatological

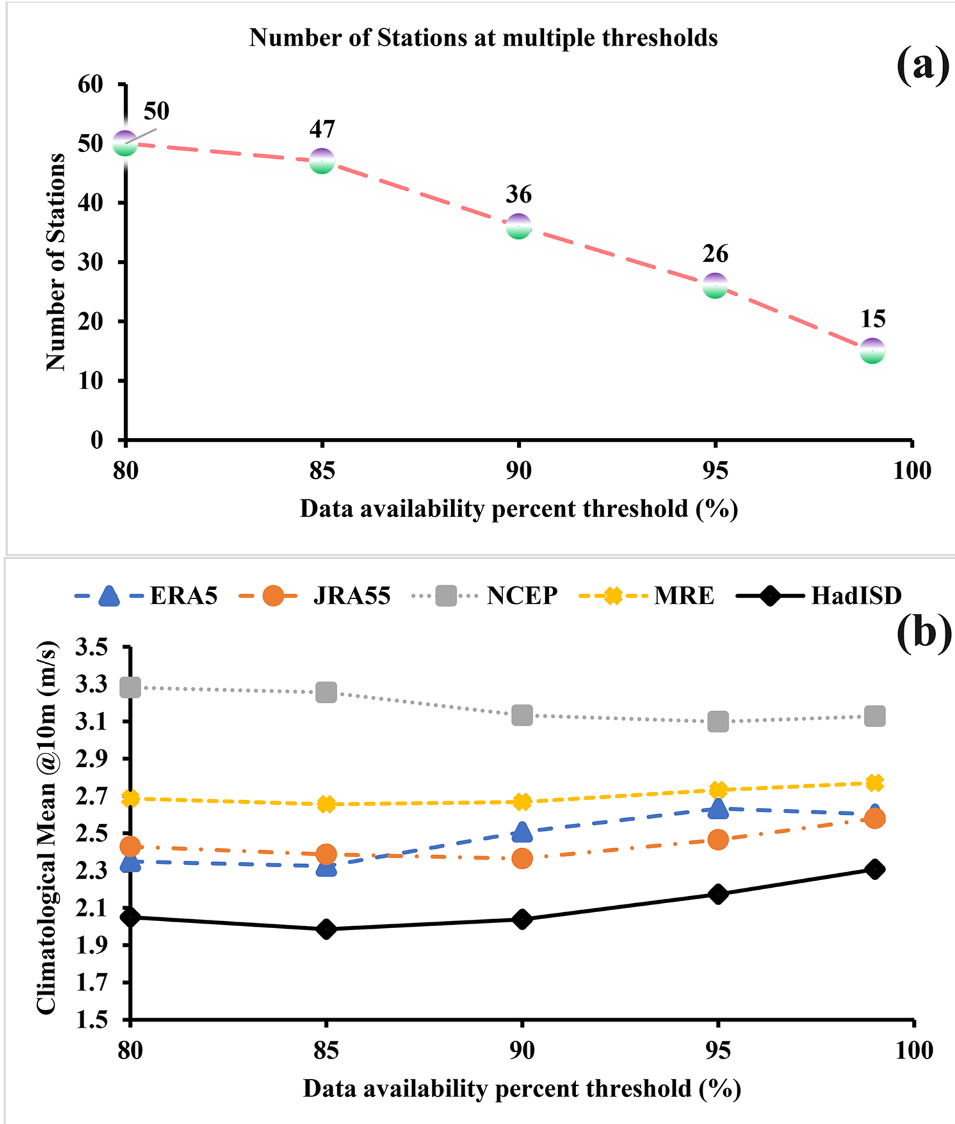

Fig. 4 As visualized in Fig. 3, **a** evaluation of the different thresholds of data availability results in varying numbers of stations available for analysis, **b** demonstrates Climatological Mean (m/s) values for long-term average wind speed data coming from various reanalysis products, as well as HadISD at different data availability thresholds

Mean values, expressing the accuracy of its representation of long-term wind speed averages.

These Climatological Mean values provide insight into the long-term characteristics of wind speeds represented by the reanalysis of products. As an effective product for assessing wind resources, JRA55 offers valuable insights based on a robust approach that closely matches observations.

A detailed analysis of the Mean Bias (m/s) for wind speed data was obtained from different reanalysis products (ERA5, JRA55, NCEP/NCAR, and MRE) at various data availability thresholds is shown in Fig. 5a. These reanalysis products are evaluated in terms of their accuracy and reliability in representing observed wind speeds based on their Mean Bias as a crucial indicator. Overall, the bias values for JRA55 decrease as the percent threshold increases, demonstrating its most consistent and satisfactory performance across all threshold limits. The existence of this inverse relationship between threshold values and wind speed data demonstrates JRA55's accuracy in capturing wind speed information. Meanwhile, ERA5 demonstrates slightly inconsistent behavior concerning bias values when thresholds are varied. It is noteworthy that it excels at thresholds of 80% and 85% but exhibits increased biases at higher threshold levels (90%, 95%, and 99%) compared to other reanalysis products, which indicates that ERA5's performance deviates from this trend. The NCEP/NCAR consistently displays supreme bias values across all thresholds, indicating that the NCEP/NCAR exhibits Poor performance in representing observed wind speed data as compared to other reanalysis products. The MRE and NCEP/NCAR followed consistent behavior like JRA55. However, their bias values as the threshold increases are not in an acceptable range compared to JRA55. Selecting an appropriate data availability threshold is essential to ensure the accuracy of

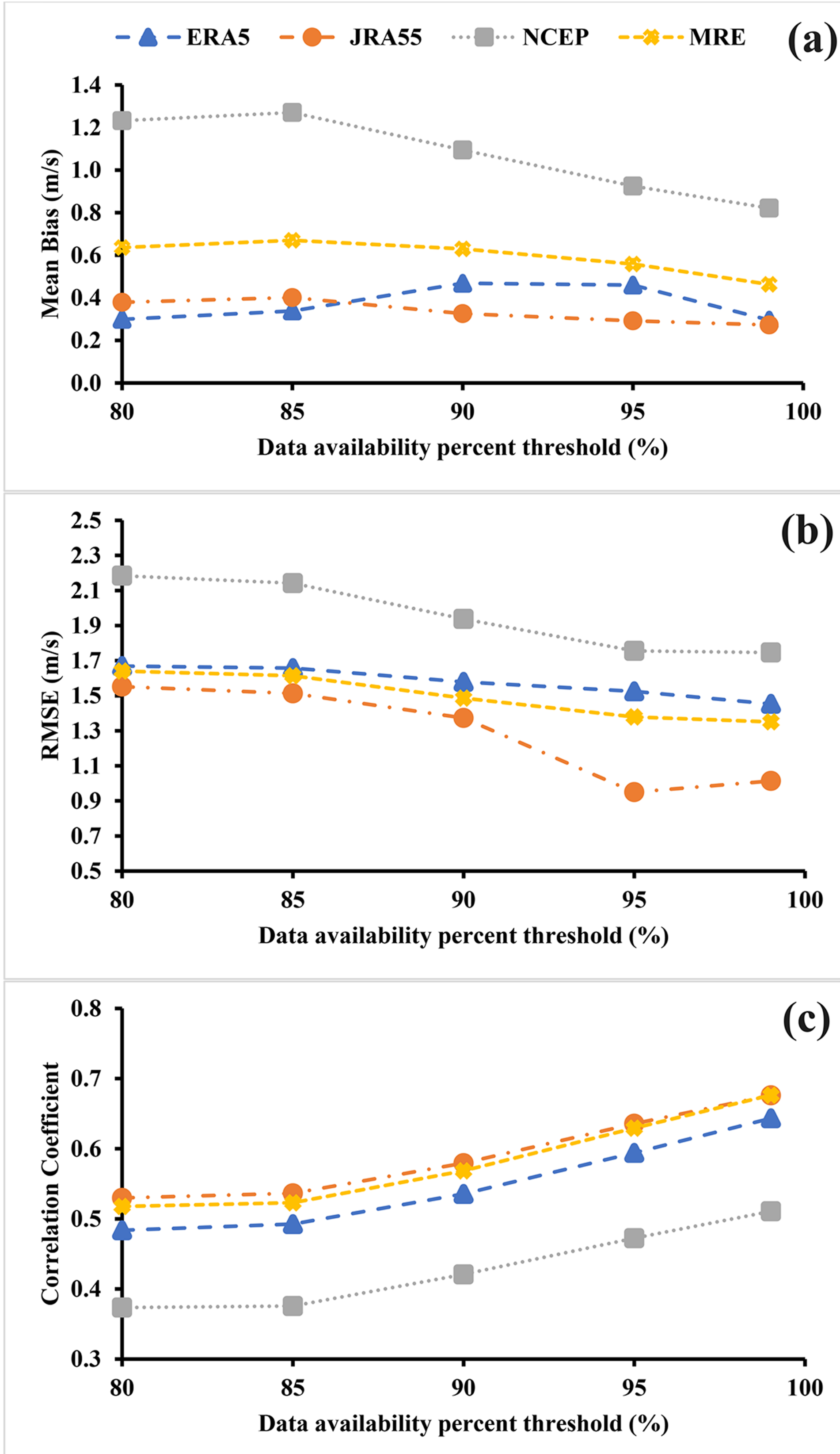

Fig. 5 Present a detailed analysis of the **a** Mean Bias (m/s), **b** RMSE (m/s), and **c** correlation coefficient values for wind speed data obtained from different reanalysis products such as ERA5, JRA55, NCEP/NCAR, and MRE at various data availability thresholds

wind speed trend assessments. Based on its consistent performance across a variety of thresholds, consequently, all reanalysis products (ERA5, NCEP/NCAR) and MRE offer valuable insights, but JRA55 has shown reliability in this regard.

RMSE (Root Mean Square Error) values at various data availability thresholds are presented in Fig. 5b for wind speed data obtained from the three reanalysis products and MRE. For assessing the overall goodness-of-fit between reanalysis products and observed data, RMSE provides a critical metric. JRA55 exhibits RMSE patterns across the thresholds, with the lowest RMSE values observed at the 90% to 95% threshold compared to other reanalysis products. However, as the threshold increases to 99%, RMSE values tend to rise slightly for the JRA55 datasets and other products, indicating a decline in accuracy. In contrast to ERA5 and JRA55, NCEP/NCAR consistently exhibits observed wind speeds with higher RMSE values, suggesting that reanalysis-derived wind values are less accurate than those provided by JRA55. A similar pattern of RMSE values appears in MRE and JRA55, with lower RMSE values at 90% to 95% thresholds and higher values at higher thresholds to a limited extent. As a result, MRE is Marginally like JRA55 in capturing wind patterns as compared to ERA5. It is important to recognize the data accuracy and data availability in these RMSE statistics. Overall, higher thresholds provide better accuracy but may limit spatial coverage, while lower thresholds extend wider spatial coverage at a decline in accuracy. Summing up, the results of the Mean Bias in Fig. 5a demonstrate that, despite the modest similarities in RMSE patterns between ERA5 and JRA55, it is essential to consider that JRA55 generally exhibits more minor errors than other reanalysis datasets. There is a need to take a balanced approach when choosing data availability thresholds, considering the accuracy requirements and the spatial coverage required for specific applications.

Figure 5c presents correlation coefficient values for wind speed data generated by different reanalysis products and threshold datasets. Observation datasets and reanalysis products are correlated via correlation coefficients. A consistent correlation coefficient of the highest positive value between JRA55 and observed wind speed values across all thresholds indicates a robust linear relationship between these variables. For example, JRA55 and observed wind speed values are correlated at 0.54 (at 85% threshold), indicating a strong relationship between these variables. These values continue to remain robust at increasing thresholds (0.68 substantial positively correlated value at 99%threshold), providing evidence of the reliability of JRA55. There is a close follow-up positive 0.49 value at the 85% threshold with ERA5, which has slightly lower correlation coefficient values compared to JRA55 but is still robust at all thresholds. However, NCEP/NCAR appears to display a little bit of Moderate correlation coefficient values, which is indicative of a linear relationship, despite its lower Mean Bias and RMSE values. At all the threshold values, MRE exhibits a close correlation with JRA55. Because of the correlation coefficient outcomes, it is obvious that JRA55 is the first choice due to consistent performance and ERA5 is the second priority can capture linear relationships between the reanalysis and observed wind speed data, making them suitable choices for assessing wind energy development.

Additional empirical analyses are depicted in Figures S2 and S3 including an increase from 75 to 99% with a step size of 1%. Comparing climatological means and mean bias plots (Figures S2 and S3) shows a close agreement of ERA5 with JRA55 indicating high consistency between them in representing wind characteristics. Nevertheless, the correlation graph (S3) indicates that the MRE tends to be more consistent towards JRA55 than ERA5. Based on this result highlights the slightly higher mean bias in ERA5, which suggests systematic deviations under certain conditions when compared to JRA55. These findings emphasize that JRA55 showed the best accuracy in terms of wind dynamics through the use of real-world observational data, underscoring its robustness for wind resource assessments.

3.3 Examination of climatology at 90% threshold

This section focuses on climatology at a 90% data availability threshold to evaluate the performance of reanalysis products (ERA5, JRA55, NCEP/NCAR) and MRE. Examination results through the statistical evaluation of the climatology of the daily wind speed for the South Asian region based on data from 1973 to 2005, using SA-36 (South Asia; 36 No. of stations) station's mean values for each matrix are summarized in Table 3. These findings comprehensively compare the evaluated datasets, highlighting their strengths and limitations in capturing regional wind climatology. Wind speed characteristics in the region are represented in these statistics using reanalysis products.

JRA55 consistently exhibited impressive results among the evaluated metrics, with a Mean Bias (MB) of approximately 0.33 m/s, a Root Mean Square Error (RMSE) of approximately 1.00 m/s, and a Correlation Coefficient (CC) of approximately 0.58. Furthermore, the ERA5 product exhibits reasonable results for the second choice to use after JRA55, indicating that South Asian wind climatology can be adequately represented based on the MB of 0.47 m/s, the RMSE of 1.58 m/s, and the CC of 0.54, which are all satisfactory. In contrast, NCAR displays a higher bias, larger RMSE, and a low correlation presented by the values of 1.09 m/s, 1.94 m/s, and 0.42, respectively. Implying that it may not be as accurate in capturing daily wind speed

Table 3 Climatology statistics of daily average wind speed at 10 m AGL (above ground level) comparing reanalysis products with observations in South Asia, summarized by mean values across all regions with a 90% threshold

Dataset	SD (m/s)	RMSE (m/s)	Mean bias (m/s)	Pearson correlation coefficient, R	Coefficient of determination (R^2)	Climatological mean (m/s)
ERA5	1.30	1.58	0.47	0.54	0.33	2.51
JRA55	0.94	0.99	0.33	0.58	0.38	2.36
NCEP/NCAR	1.07	1.94	1.09	0.42	0.22	3.13
Multi-Reanalysis Ensemble (MRE)	0.99	1.49	0.63	0.57	0.37	2.67
HadISD	1.46					2.04

characteristics in this region. Meanwhile, NCAR, although still producing reasonable results overall, demonstrates slightly higher discrepancies across various statistical measures and its output than observations. Moreover, the MRE demonstrates intermediate results across all metrics, falling between JRA55 and ERA5. According to these findings, it may be possible for multiple reanalysis datasets to be combined to reduce uncertainties and improve the reliability of estimated wind speeds by reducing uncertainties derived from a single dataset.

JRA55 is a reliable choice since it has demonstrated a low bias, high accuracy, strong Correlations, and the closest Climatological Mean to observed data. While ERA5 demonstrates strong correlations, it exhibits some biases and overestimations in climatology. The NCEP/NCAR demonstrates the highest bias and RMSE value, indicating a lower accuracy level and linear correlation. It is important to note that the performance of MRE closely resembles that of JRA55. Overall, the results indicate that JRA55 represents daily wind speed better than other datasets, is less biased, and is more in agreement with observed data (HadISD) than the other global reanalysis products. These findings contribute valuable information that can be utilized in the selection of the most appropriate reanalysis dataset for assessing wind resources in the region and promoting the development of this renewable energy form.

Figures 6 and 7 heatmap demonstrate the comprehensive analysis of daily wind speed climatology across 36 weather stations in the subcontinent region at a 90% threshold. As illustrated in Fig. 6a, the Mean Bias (MB) of JRA55 consistently shows the lowest bias at most locations, supporting the finding that the predicted wind speed is more closely aligned with the observed speed. As an example, at station 41640-LAH (Lahore), JRA55 has an MB of 0.11 m/s, while ERA5, NCEP/NCAR, and MRE depict higher biases of 0.71 m/s, 2.38 m/s, and 1.07 m/s, respectively. Accordingly, JRA55 exhibits superior performance in capturing the characteristics of local winds. However, it is observed from the reanalysis of product results that some of the stations are overestimating and underestimating, which indicates a mix of positive and negative biases. An RMSE of 0.74 m/s as presented in Fig. 6b at station 28670-DR (Dr. Ambedkar Airport) demonstrates that JRA55 consistently shows lower RMSE values than ERA5, NCEP/NCAR, and MRE, which display 0.95 m/s, 0.97 m/s, and 0.85 m/s, respectively. With such a low RMSE, JRA55 can accurately replicate observed wind patterns. This finding is further supported by the correlation coefficients (Fig. 6c), where JRA55 exhibits the highest correlation across most stations. This correlation coefficient of JRA55 (0.86) is significantly higher than that of ERA5 (0.78), NCEP/NCAR (0.59), and MRE (0.82), demonstrating that JRA55 is well converging with the observed data at station 427540-DEV (Devi Ahilyabai Holkar) for example. These metrics illustrate JRA55's ability to accurately predict wind speeds across several Subcontinent landscapes, including coastal and inland areas.

A comparison between the climatological means and standard deviation of wind speeds for similar datasets and stations is provided in Fig. 7. Subcontinent's climatological mean (Fig. 7a) demonstrates significant spatial variability. As an example, station 41764-HYD (Hyderabad Airport) depicts a mean wind speed of 4.05 m/s in ERA5, whereas these values are lower for stations such as JRA55 (3.38 m/s), NCEP/NCAR (3.91 m/s), and MRE (3.78 m/s). This variability is indicative of the diverse wind climate in the region that has been influenced by the complex topography of the region, which includes the Arabian Sea sides, the Himalayas, and the coastal areas.

Considering the standard deviation (SD) metric to indicate wind speed variability (Fig. 7b) provides insight into temporal variability. One noteworthy feature of station 41764-HYD is its high variability in the observation datasets (HadISD; SD: 3.36 m/s). This station region is called the wind corridor in Pakistan; no reanalysis product has fully captured wind variability. Displayed a standard deviation of 2.24 m/s, 1.77 m/s, 1.54 m/s, 1.77 m/s are the ERA5, JRA55, NCEP/NCAR, and MRE, respectively. Therefore, reanalysis products can approximately mean wind conditions. However, capturing extreme variability of wind speed remains a challenge. According to the broad climatological overview, monsoon patterns influence prevailing winds in the subcontinent regions, and these patterns vary significantly seasonally and geographically. A coastal station generally experiences higher wind speeds and more significant variability due to maritime influences, whereas a more stable wind pattern characterizes an inland station.

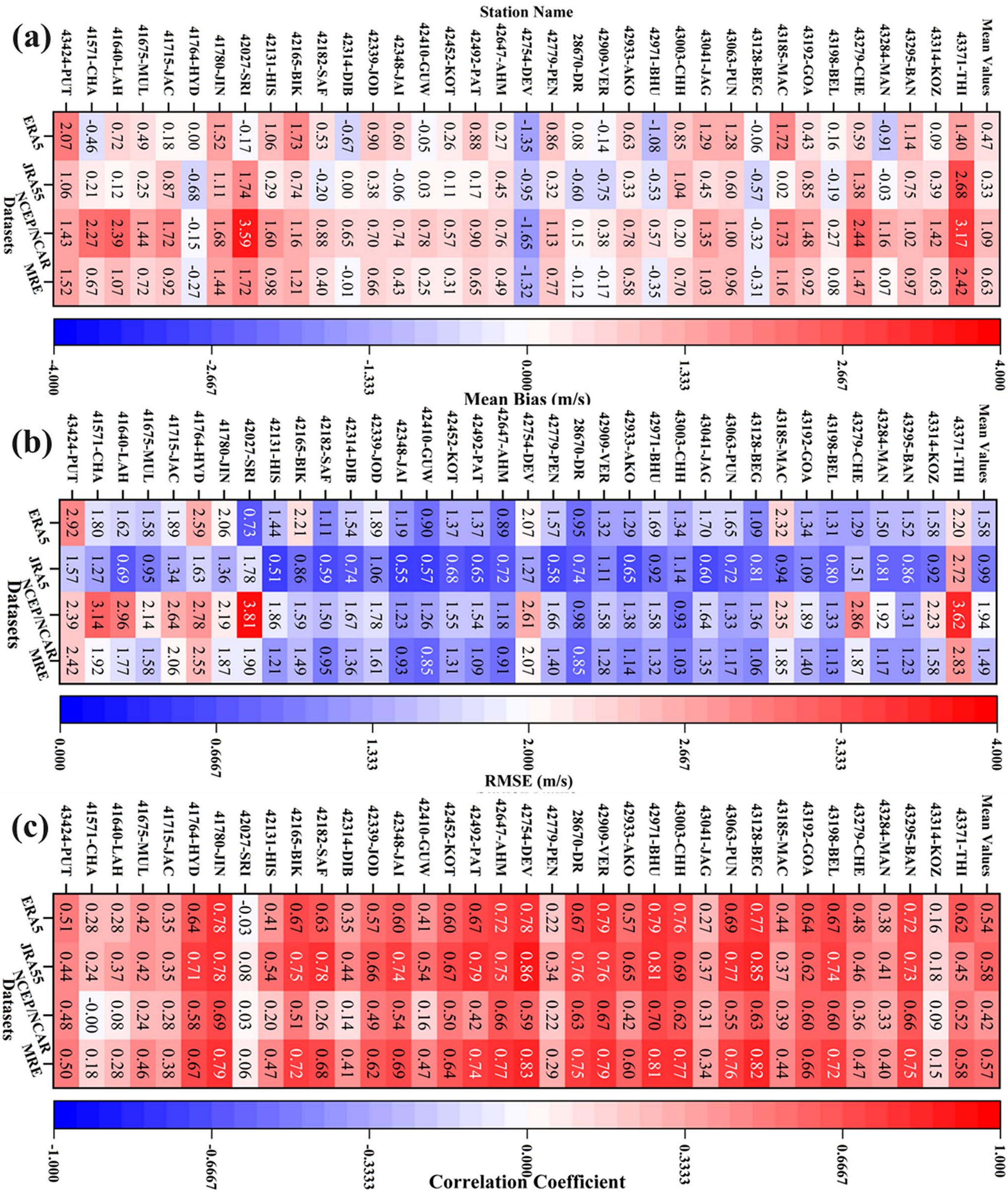

Fig. 6 Evaluation of climatology statistics [**a** Mean Bias (m/s), **b** RMSE (m/s), and **c** correlation coefficient] of daily wind speed (10 m) between reanalysis products and observations in South Asia

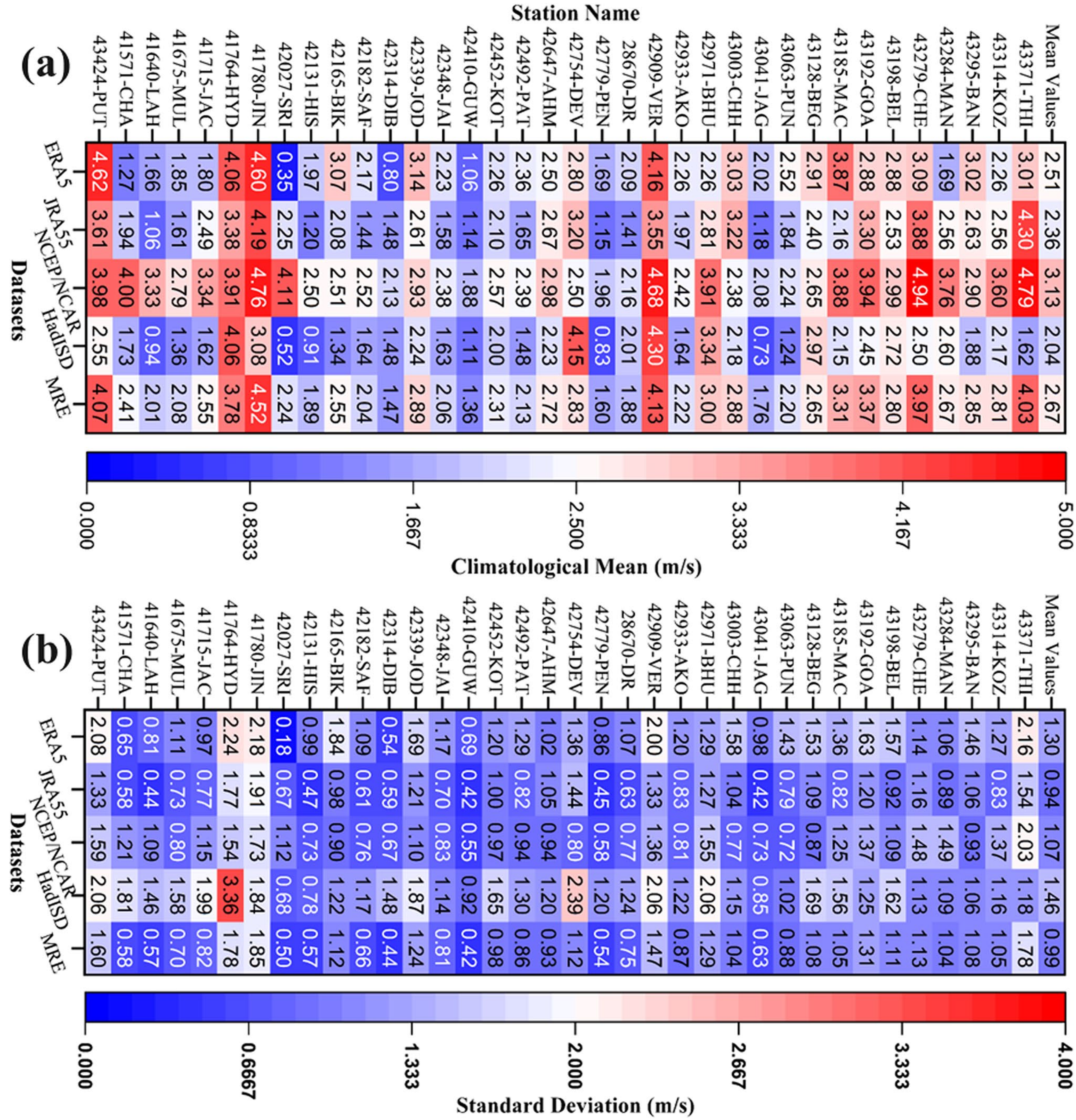

Fig. 7 Same as Fig. 6, **a** Climatological Mean (m/s), **b** Standard Deviation (m/s)

There were some discrepancies and limitations with JRA-55 and ERA5, such as spatial coverage and temporal consistency, although they displayed better skill than NCEP/NCAR. We aim to minimize error contributions by combining the three products, MRE, and capturing the standard signal. Moreover, this study demonstrates that each dataset exhibits long-term characteristics of wind speed and variability through analysis of Mean Bias, RMSE, Correlation Coefficient, Climatological Means, and Standard Deviation. Numerous South Asian applications benefit from these insights, including climate modeling, assessments of renewable energy resources, and managing weather-related risks.

3.4 Observed trends at 10 m above ground level (AGL) wind across South Asia (1973–2005)

This section analyzes long-term trends and variability at 10 m AGL to identify significant patterns and changes in regional wind climatology over time. In a comprehensive analysis of the data, the author found that South Asia experienced a noticeable decrease in the annual mean wind speed, with an average yearly reduction of 0.010 m/s year^{-1} ($p<0.001$), with a 95% confidence interval ranging (from -0.013 to -0.008 m/s year^{-1}) across the region during the study period. The p-value for statistical accuracy indicates that this negative trend is statistically significant. Accordingly, the R^2 (coefficient of determination) is 0.7297, which suggests that a linear trend can explain approximately 73% of the variance in wind speed data. These findings are robust statistically and have an R^2, indicating their reliability. Figure 8 presents these results based on the observation datasets (HadISD) at a 90 percent threshold across all stations from 1973 to 2005. A significant trend has highlighted substantial changes in the region's wind patterns. Wind speed trends exhibit considerable regional differences. There has been a substantial and consistent decrease in wind speed throughout the area because of this widespread pattern.

According to the 90% threshold, South Asia was represented by 36 stations, 34 (34 out of 36 stations; 94.44%) of which showed a decreasing trend in 10-m wind speed (graph presented in Figure S1) while there was some indication of a trend upward at some stations (2 out of 36 stations; 8.33%). For instance, two stations defied this trend with an increase in wind speed which were 41571-CHA (Chaklala) and 41764-HYD (Hyderabad Airport). Chaklala (41571-CHA) exhibited a significant rise of 0.055 m/s year^{-1}, while Hyderabad (41764-HYD) experienced an even more substantial increase of 0.132 m/s year^{-1}. Based on these findings, there appears to be localized variation in wind behavior within this region. Meanwhile, 17 stations displayed non-significant trends ($p>0.05$), indicating no statistical significance in changes in wind speed at these locations. These stations are included in Table 4 and suggest relatively stable wind patterns. According to our research, most South Asian stations exhibit decreasing trends in wind speed. This study adds to the growing evidence that terrestrial stilling (decline in land surface wind speed globally since the 1960s, known as global terrestrial stilling) (Zeng et al. 2018) is of worldwide importance, as well as to the growing body of research at this point. In addition to providing valuable insights into regional climatic changes, this work also contributes to a broader understanding of climate dynamics, which is supported by the consistent trends shown in (Miao et al. 2020; Fan et al. 2021).

There were notable wind speed trends observed at the remaining stations in South Asia as indicated by the three stars (***) in Table 4. A significance level (alpha) of $p<0.05$ was used to determine these trends using Mann–Kendall (M–K) nonparametric analysis. Observed wind speed changes across the region are robust and consistent, as

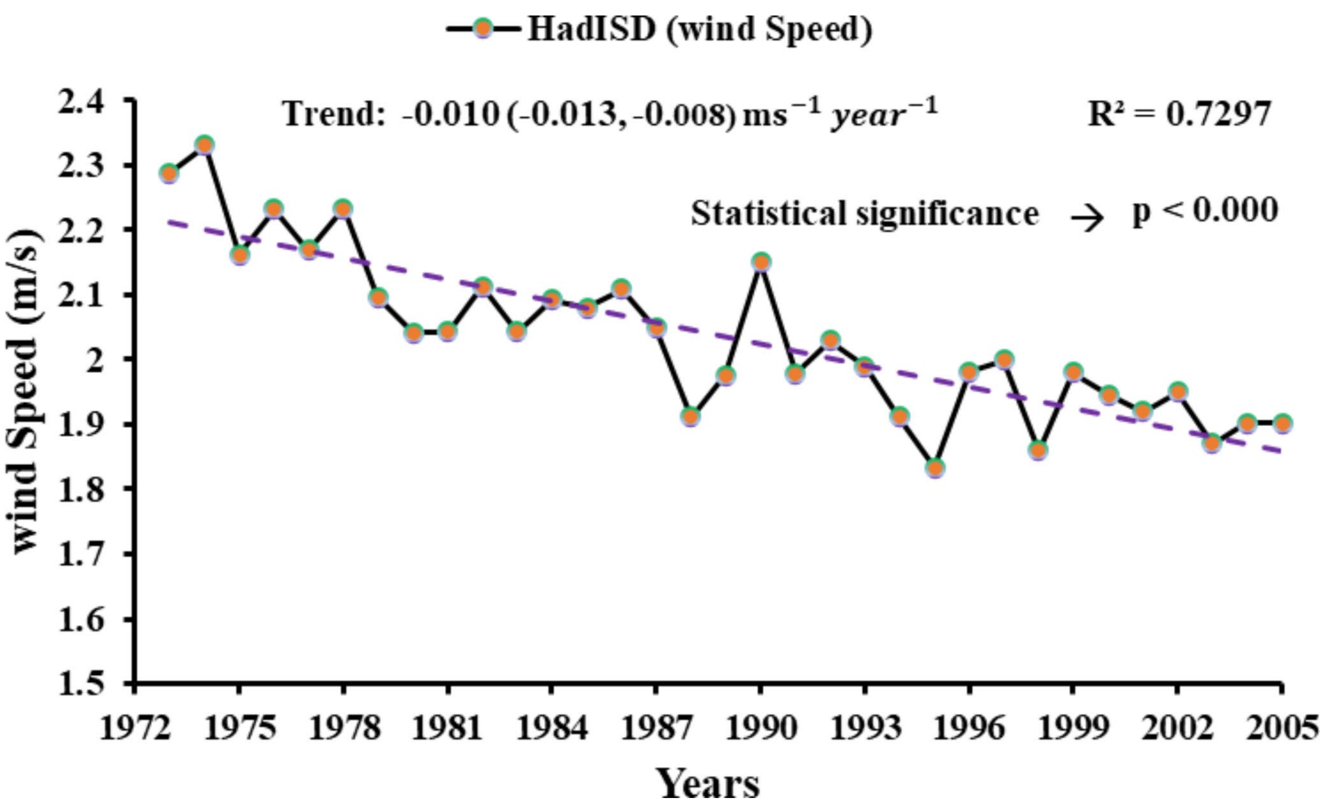

Fig. 8 Observed all stations mean at 90% threshold trends of the 10-m above ground level wind speed in South Asia, showing the time series of observed annual mean wind speed. The intersection of the trends is the turning point

Table 4 Summarizes the observed trends in 10 m wind speed (1973–2005) in the Subcontinent region, determined using the Mann–Kendall test nonparametric test with statistical significance

Research domain			Climatological mean during 1973–2005 (m/s)	Std. deviation	*p*-value	The trend in wind speed from 1973 to 2005 (measured in m/s year^{-1}) with its 95% confidence levels			Significance level
Acronym	WMO-station ID	Station name				Value	Lower bound	Upper bound	
SA-36	SOUTH ASIA (No. of stations = 36)		2.03	0.12	6.4E-08	-0.010	-0.013	-0.008	(↓)***
43424-PUT	434240-99999	PUTTALAM	2.54	0.81	3.4E-07	-0.071	-0.098	-0.049	(↓)***
41571-CHA	415710-99999	CHAKLALA	1.73	0.69	3.4E-07	0.055	0.039	0.076	(↑)***
41640-LAH	416400-99999	LAHORE CITY	1.01	0.48	4.3E-01	-0.004	-0.011	0.005	↔
41675-MUL	416750-99999	MULTAN INTL	1.37	0.28	9.6E-01	-0.001	-0.015	0.013	↔
41715-JAC	417150-99999	JACOBABAD	1.66	0.39	2.1E-04	-0.025	-0.037	-0.012	(↓)***
41764-HYD	417640-99999	HYDERABAD AIRPORT	4.05	1.67	1.3E-05	0.132	0.078	0.168	(↑)***
41780-JIN	417800-99999	JINNAH INTL	3.10	0.65	5.3E-02	0.027	-0.001	0.051	↔
42027-SRI	420270-99999	SRINAGAR	0.49	0.17	8.9E-01	0.001	-0.004	0.008	↔
42131-HIS	421310-99999	HISSAR	0.91	0.24	1.4E-09	-0.024	-0.027	-0.020	(↓)***
42165-BIK	421650-99999	BIKANER	1.34	0.32	7.0E-01	0.003	-0.013	0.019	↔
42182-SAF	421820-99999	SAFDARJUNG	1.61	0.41	4.0E-05	-0.030	-0.039	-0.020	(↓)***
42314-DIB	423140-99999	DIBRUGARH	1.48	0.19	9.1E-01	0.000	-0.007	0.009	↔
42339-JOD	423390-99999	JODHPUR	2.25	0.92	9.0E-09	-0.084	-0.098	-0.067	(↓)***
42348-JAI	423480-99999	JAIPUR	1.58	0.35	9.4E-01	0.000	-0.009	0.014	↔
42410-GUW	424100-99999	GUWAHATI INTL	1.11	0.35	6.9E-04	-0.023	-0.033	-0.013	(↓)***
42452-KOT	424520-99999	KOTA	1.98	0.41	1.8E-05	-0.031	-0.039	-0.019	(↓)***
42492-PAT	424920-99999	PATNA	1.48	0.28	7.9E-01	0.001	-0.014	0.010	↔
42647-AHM	426470-99999	AHMEDABAD	2.23	0.32	7.8E-05	-0.016	-0.024	-0.010	(↓)***
42754-DEV	427540-99999	DEVI AHILYABAI HOLKAR	4.15	0.62	3.4E-02	-0.024	-0.050	-0.002	↔
42779-PEN	427790-99999	PENDRA ROAD	0.83	0.30	7.6E-08	-0.023	-0.029	-0.018	(↓)***
28670-DR	428670-99999	DR AMBEDKAR INTL	2.01	0.30	2.7E-01	-0.007	-0.017	0.007	↔
42909-VER	429090-99999	VERAVAL	4.30	0.39	8.5E-02	-0.013	-0.027	0.003	↔
42933-AKO	429330-99999	AKOLA	1.59	0.53	3.4E-07	-0.046	-0.059	-0.033	(↓)***
42971-BHU	429710-99999	BHUBANESHWAR	3.34	0.49	2.7E-04	-0.036	-0.050	-0.018	(↓)***
43003-CHH	430030-99999	CHHATRAPATI SHIVAJI INTL	2.18	0.29	2.3E-01	-0.009	-0.021	0.005	↔
43041-JAG	430410-99999	JAGDALPUR	0.73	0.20	2.0E-05	-0.015	-0.021	-0.008	(↓)***
43063-PUN	430630-99999	PUNE	1.25	0.28	5.4E-08	-0.020	-0.027	-0.014	(↓)***
43128-BEG	431280-99999	BEGUMPET AIRPORT	2.97	0.53	2.2E-08	-0.048	-0.062	-0.031	(↓)***
43185-MAC	431850-99999	MACHILIPATNAM /FRANCHPET	2.13	0.74	6.1E-01	-0.007	-0.053	0.024	↔
43192-GOA	431920-99999	GOA/PANJIM	2.41	0.49	4.0E-07	-0.038	-0.052	-0.026	(↓)***
43198-BEL	431980-99999	BELGAUM	2.73	0.44	6.3E-01	0.004	-0.016	0.025	↔
43279-CHE	432790-99999	CHENNAI INTL	2.50	0.25	6.8E-01	-0.002	-0.012	0.007	↔
43284-MAN	432840-99999	MANGALORE	2.59	0.22	1.3E-01	-0.006	-0.012	0.003	↔
43295-BAN	432950-99999	BANGALORE	1.88	0.27	6.5E-06	-0.019	-0.027	-0.011	(↓)***
43314-KOZ	433140-99999	KOZHIKODE	2.18	0.36	4.5E-01	-0.005	-0.022	0.012	↔
43371-THI	433710-99999	THIRUVANAN THAPURAM	1.62	0.40	3.5E-05	-0.030	-0.041	-0.019	(↓)***

demonstrated by these findings. These findings align with global trends of declining wind speeds in certain regions, as evidenced in previous studies (Zeng et al. 2018; Ramon et al. 2019; Dong et al. 2020; Miao et al. 2020; Fan et al. 2021; Deng et al. 2021; Zha et al. 2021; Dunn et al. 2022). The present study results align with the findings of (Fan et al. 2021), for instance, North America, Europe, and East Asia reported decreasing trends in wind speed, while South

America, Southeast Asia, Africa, and Australia reported increasing trends. Additionally, Miao et al. (2020) also highlighted a decrease in the wind speeds over land in several parts of the world, particularly in northern mid-latitudes, which was consistent with our observation of a similar decline in wind speeds over land in South Asia.

3.5 Trends in reanalysis of wind speeds from 1973 to 2005

The observed time series of annual mean wind speed is compared with that from three reanalysis products to reveal the inter-annual variability of 10-m wind speed from 1973 to 2005. Understanding wind speed variations requires identifying the factors influencing them, such as atmospheric conditions and geographical features. These factors are critical for renewable energy generation and climate change research applications. Both observed and reanalysis data show fluctuations in wind speed, as presented in Fig. 9. South Asian wind speed anomalies are reasonably described by JRA55, the most consistent reanalysis product with the observed data compared to the other products. Researchers and policymakers seeking accurate historical wind speed data in this region can benefit from JRA55, as it seems to align with observations in this region and could serve as a valuable resource. While the other utilized reanalysis products like NCEP/NCAR and ERA5, which display variations in wind speed, they are not as effective as JRA55 at capturing the actual variations in wind speed observed in those products. This determination according to Sects. 3.2 and 3.3, particularly Figs. 5 and 6, Table 3, and illustrated in Fig. 9, highlights JRA55's high accuracy in representing wind speed characteristics. However, JRA55 significantly deviates from observed wind for particular periods, highlighting this product's limitations. This suggests that in South Asia, these datasets do not fully reflect historical wind patterns, so caution should be exercised when analyzing historical wind speeds. An interesting perspective is provided by the MRE, which combines the strengths and weaknesses of the individual reanalysis products. MRE provides a general view of the uncertainty and variability of wind speed in South Asia, which could be considered alongside JRA55 when assessing wind speed variations. In this way, the strengths of both datasets are leveraged to ensure a balanced assessment. Overall, Fig. 9 shows the annual trend in wind speed anomaly. A further examination of the regional mean trend in the figure finds that JRA55 and ERA5 generally possess the smallest standardized anomaly relative to observed wind speed. From 1993 to 1997, JRA55 exhibited the most significant deviation from observations. Accordingly, although JRA55 is often accurate, it has limitations. At the same time, NCEP/NCAR deviates significantly from the observation in the Subcontinent region.

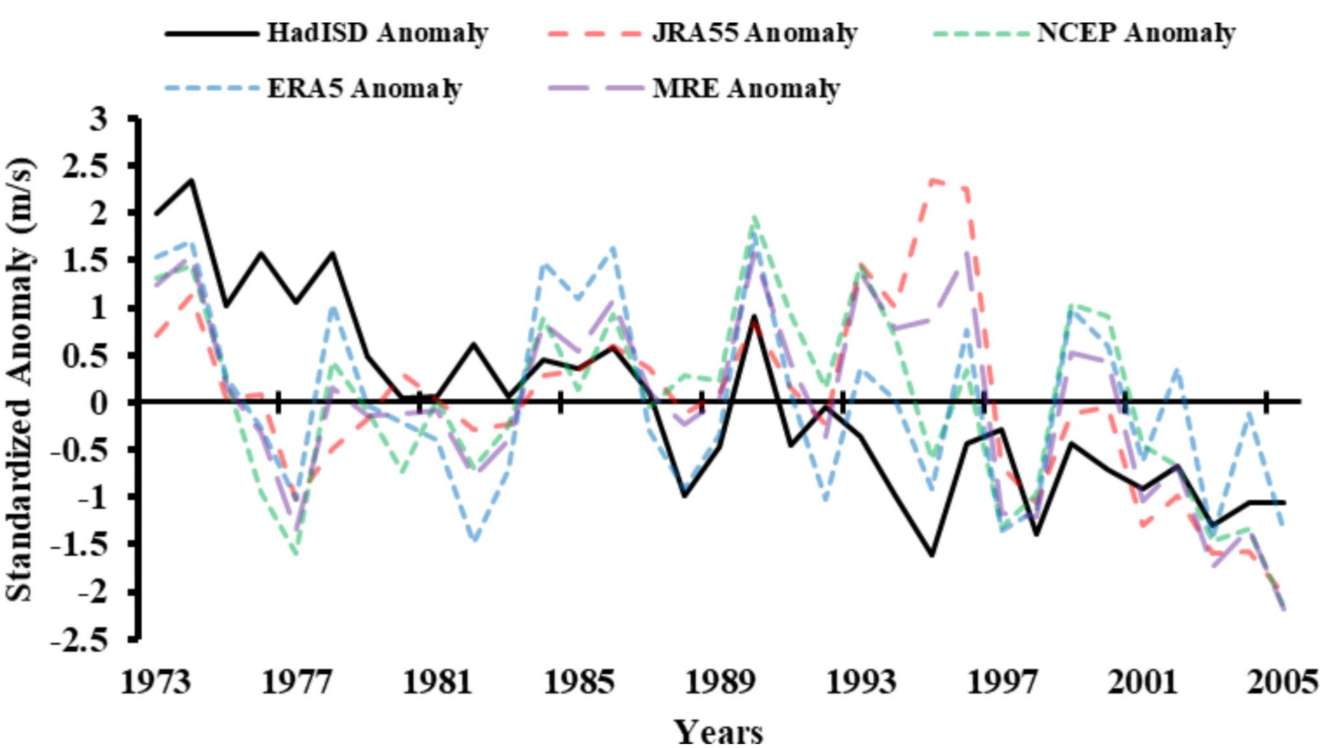

Fig. 9 Standardized anomalies of wind speed in the three global reanalysis products, MRE, and the observations in the subcontinent region

3.6 Interannual wind speed and wind power density at 100 m altitude

Wind power density is crucial for evaluating the feasibility and potential of a wind energy project. For 90% of threshold selected locations, wind speeds at 100 m heights are determined using Eq. (9). Equation (11) was subsequently used to calculate the wind power density.

Based on observations (HadISD), three reanalysis datasets, and a multi-reanalysis ensemble, Fig. 10 illustrates the time series of regional mean (a) wind speeds and (b) wind power density at 90% of the threshold. The results suggest that most datasets capture interannual fluctuations by showing similar cyclical patterns and turning points. Moreover, most of the datasets indicate a decline between 1973 and 2005, although the magnitude of the declines is variable between the datasets. Observational and reanalysis data reveal significant differences. According to HadISD, the lowest wind speeds are generally under 4 m/s with correspondingly low WPD values of under 40 W/m^2. However, reanalysis products, particularly NCEP/NCAR, indicate higher values, with wind speeds between 5–5.5 m/s and WPDs often exceeding 80 W/m^2.

As compared to the observations JRA55 shows similar aligned wind speed and power density trends. While the magnitudes of ERA5 trends differ slightly from the observation dataset, trends are consistent with observations. Contrary to the observed data, NCEP/NCAR wind speed and WPD show a less pronounced decline over time. While it is true that MRE is not comparable to HadISD, MRE generally provides a balanced representation between individual reanalysis products. Further consideration is that the observed wind speeds and wind power densities in ERA5, MRE, and NCAR are higher than those in the observation datasets, which indicates that the reanalysis products have biases, as shown in Table 3 and Fig. 5.

The wind power density is classified according to Elliot et al. (1991) international standard (Table 2) at 90% of the

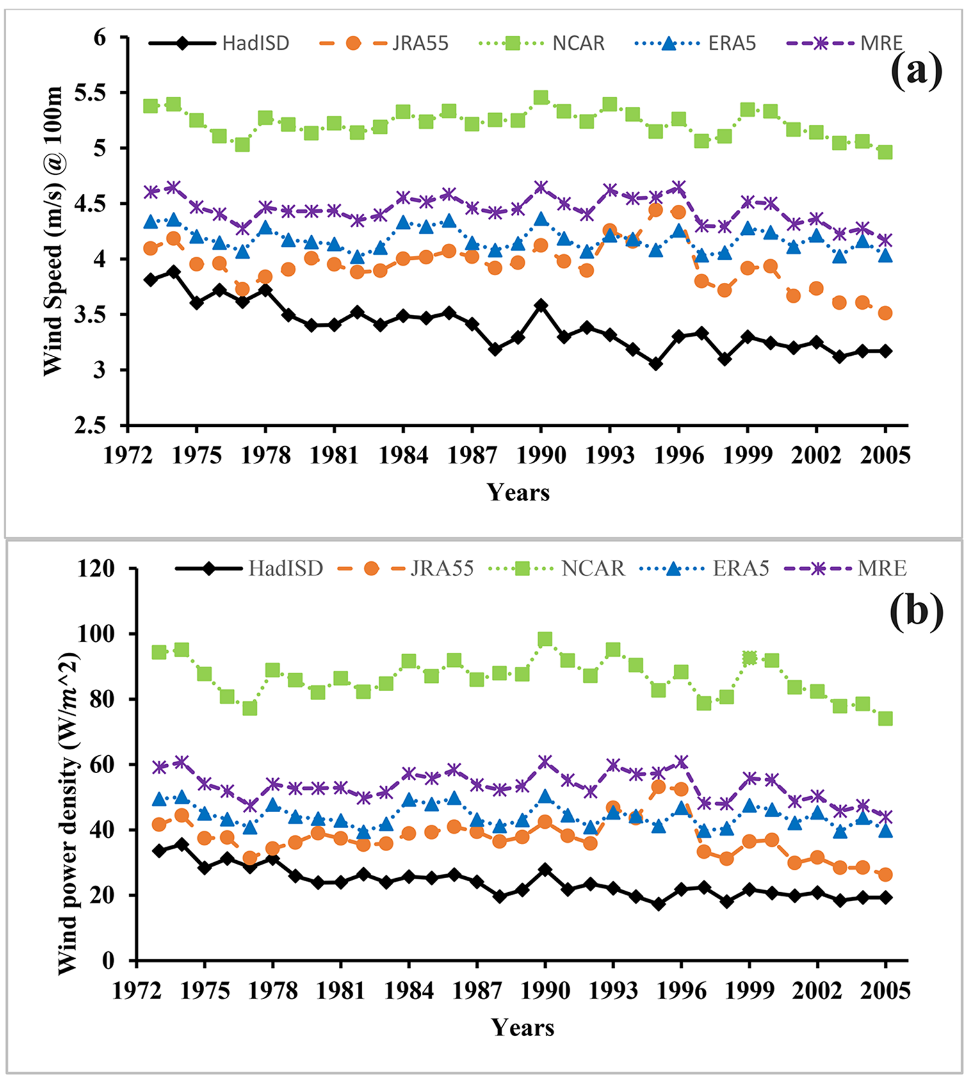

Fig. 10 Determination of the annual mean **a** wind speed as well as **b** wind power density at 100 m above ground level (AGL) historically at 90% threshold all stations average for the period 1973–2005. It includes multi-datasets such as observational datasets (HadISD), reanalysis products (JRA55, NCAR, and ERA5), and MRE

threshold at individual stations for the wind energy potential in the South Asia region and motioned in Fig. 11. It is observed that the 41764-HYD (Hyderabad Airport) location has a maximum wind power density value of 462.22 W/m^2 at 100 m altitude. Thus, this location's wind energy potential is Excellent, as it belongs to wind power class 7. Further, based on the results output it is noticed that some locations present a Moderate class 3 wind power density e.g., 42754-DEV (Devi Ahilyabai Holkar) and 42909-VER (Veraval) regions possess values of 244.51 W/m^2 and 239.04 W/m^2, respectively.

In addition, the findings of this research also demonstrate Marginal (Class 2) WPD for multiple sites during the study period such as 43424-PUT (Puttalam), 41715-JAC (Jacobabad), and 42971-BHU (Bhubaneshwar), which indicates the values of 212.32 W/m^2, 168.61 W/m^2, and 150.25 W/m^2, individually. Moreover, it is observed that the rest of the regions have low wind power density, which represents the values of the dynamic in Table 5 at 100 m altitude. In this regard, these areas may be considered "Poor" classified. However, these locations may be suitable for the use of commercial wind turbines with lower capacities.

Moreover, the coastal regions of the subcontinent demonstrate notable variations in WPD, as presented in Fig. 11 and Table 5. The WPD in these areas predominantly falls within the range of Poor (0–100 W/m^2) to Marginal (100–200 W/m^2) and Moderate (200–300 W/m^2) wind power classes. While some stations demonstrate promising wind characteristics, the overall potential remains modest. For example, stations such as 41759-PAS (Pasni) have limited data coverage, contrast coastal stations with more considerable datasets exhibit consistent wind speed patterns and wind energy potential. These outcomes emphasize the significance of targeted assessments in coastal stations to identify suitable areas for wind energy development.

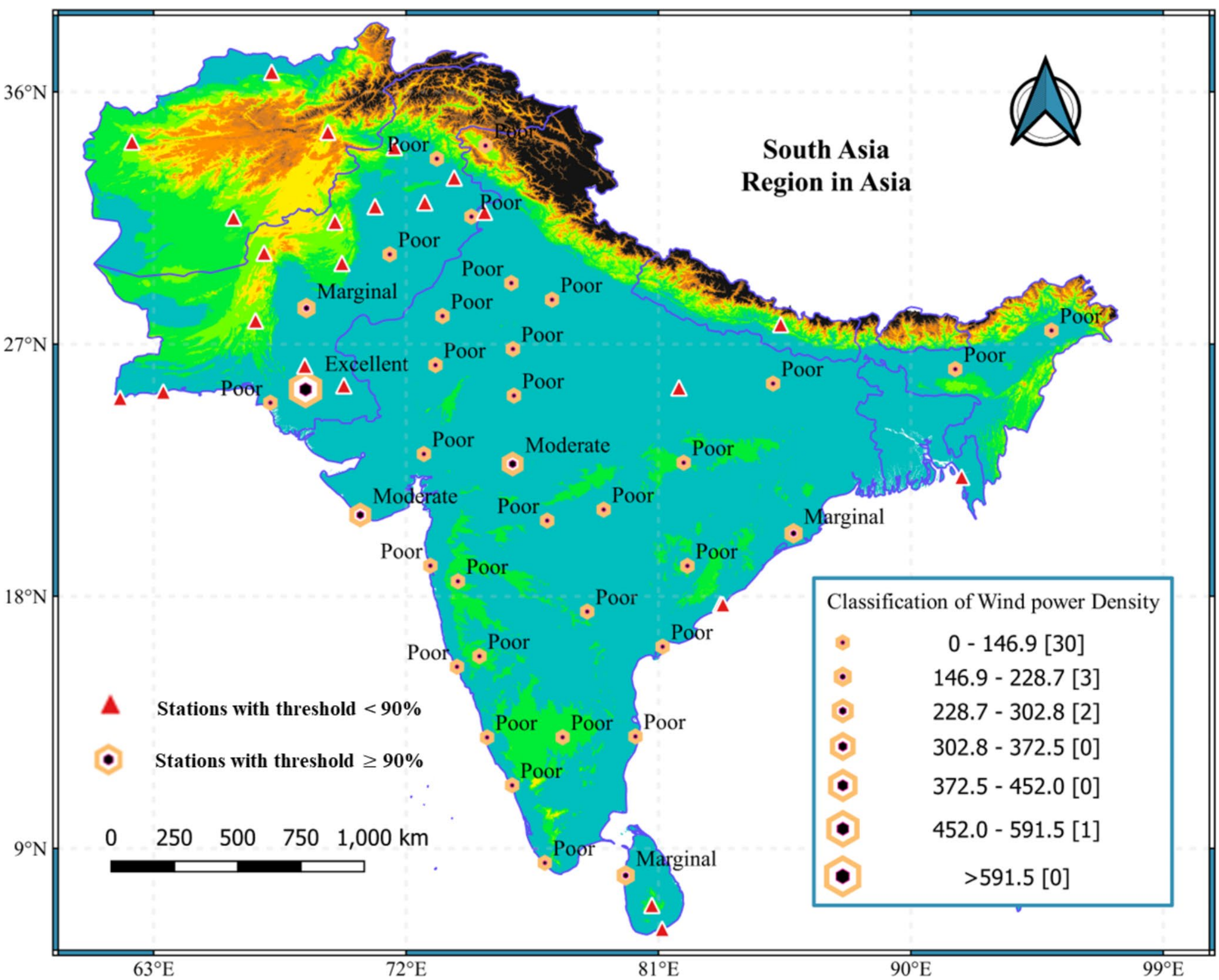

Fig. 11 Classification of the wind power density (WPD) based on the observation dataset (HadISD) at 100 m above ground level (AGL) historically (1973–2005) at 90% threshold regions examined as specified by the international standard of classes shown in Table 2

Table 5 Classification of the wind power density (WPD) at 100 m altitude historically (1973–2005) based on 90% threshold data availability regions examined. The classification of wind power resources follows the international standard of classes shown in Table 2

Acronym	WMO station ID	Station name	WPD@100 m (W/m^2)	Classification
43424-PUT	434240-99999	PUTTALAM	212.32	Marginal
41571-CHA	415710-99999	CHAKLALA	83.49	Poor
41640-LAH	416400-99999	LAHORE CITY	60.47	Poor
41675-MUL	416750-99999	MULTAN INTL	54.23	Poor
41715-JAC	417150-99999	JACOBABAD	168.61	Marginal
41764-HYD	417640-99999	HYDERABAD AIRPORT	462.22	Excellent
41780-JIN	417800-99999	JINNAH INTL	106.98	Poor
42027-SRI	420270-99999	SRINAGAR	8.41	Poor
42131-HIS	421310-99999	HISSAR	8.18	Poor
42165-BIK	421650-99999	BIKANER	26.43	Poor
42182-SAF	421820-99999	SAFDARJUNG	20.81	Poor
42314-DIB	423140-99999	DIBRUGARH	76.63	Poor
42339-JOD	423390-99999	JODHPUR	91.78	Poor
42348-JAI	423480-99999	JAIPUR	20.15	Poor
42410-GUW	424100-99999	GUWAHATI INTL	9.77	Poor
42452-KOT	424520-99999	KOTA	91.10	Poor
42492-PAT	424920-99999	PATNA	22.47	Poor
42647-AHM	426470-99999	AHMEDABAD	36.39	Poor
42754-DEV	427540-99999	DEVI AHILYABAI HOLKAR	244.51	Moderate
42779-PEN	427790-99999	PENDRA ROAD	56.37	Poor
28670-DR	28670-99999	DR AMBEDKAR INTL	31.81	Poor
42909-VER	429090-99999	VERAVAL	239.04	Moderate
42933-AKO	429330-99999	AKOLA	30.18	Poor
42971-BHU	429710-99999	BHUBANESHWAR	150.25	Marginal
43003-CHH	430030-99999	CHHATRAPATI SHIVAJI INTL	34.43	Poor
43041-JAG	430410-99999	JAGDALPUR	14.19	Poor
43063-PUN	430630-99999	PUNE	13.27	Poor
43128-BEG	431280-99999	BEGUMPET AIRPORT	93.61	Poor
43185-MAC	431850-99999	MACHILIPATNAM/FRANCHPET	100.75	Poor
43192-GOA	431920-99999	GOA/PANJIM	50.40	Poor
43198-BEL	431980-99999	BELGAUM	77.07	Poor
43279-CHE	432790-99999	CHENNAI INTL	43.51	Poor
43284-MAN	432840-99999	MANGALORE	47.22	Poor
43295-BAN	432950-99999	BANGALORE	26.32	Poor
43314-KOZ	433140-99999	KOZHIKODE	46.76	Poor
43371-THI	433710-99999	THIRUVANANTHAPURAM	29.64	Poor

These trends and statistical significance levels (Table 4) are reflected in the classification of each station based on WPD (Fig. 11), which affects their classification based on wind power density.

4 Discussion

The present research provides insight regarding wind speed trends and variability in South Asia. For a variety of purposes, such as assessing a particular region's wind energy resources, climate researchers and wind energy users utilize reanalysis datasets. At different thresholds of data availability, this study conducted an in-depth analysis of reanalysis products for the subcontinent region, including ERA5, JRA55, NCEP/NCAR, and MRE, to gain valuable insight into whether these datasets have the best quality and reliability. Moreover, classifying wind power potential based on the international standard (Elliot et al. 1991) at the regional level is an important aspect of this research.

Due to the variability in the level of data availability among South Asian weather stations, the evaluation of the reliability of the weather station data is one of the most critical aspects of this study. This study identifies several stations with high percentages of missing data for wind speed values, which include station 41759-PAS, which has 79% of its wind speed values missing, which highlights the need for cautious consideration of data limitations during the analytical process. Among all stations analyzed, the 4275-DEV (Devi Ahilyabai Holkar station) stands out with ≈ 99.9% daily wind speed data availability, indicating exceptional reliability and efficiency in data collection. Stations like this serve as a benchmark for determining the consistency and completeness of data throughout the study area. Using stations with complete datasets is important for more reliable interpretations of wind speed patterns because data gaps at some stations can introduce bias and uncertainties. Therefore, high-quality, and long-term of observation wind speed is essential to estimating the wind power potential and long-term trends for the validation of reanalysis products. The unavailability, availability of daily wind speed data at each wind station from 1973 to 2005 (Fig. 2), and statistical estimation at various thresholds for the product evaluation (Figs. 3 and 4) are presented.

One of the key contributions of this research is a systematic method for assessing wind speed data variability at various thresholds. This study presents a systematic approach to identifying the most appropriate threshold criterion and reanalysis product for determining wind speed climatology in South Asia, contrasting with previous studies that often utilized arbitrary thresholds (Zeng et al. 2018; Fan et al. 2021; Molina et al. 2021, 2023). Utilizing this method, biases associated with incomplete data are mitigated, enhancing the reliability of the dataset. Data availability thresholds are important to consider when analyzing wind speed trend data, as they impact spatial coverage, station selection, and resulting bias. This approach provides a foundation for present research in South Asia by presenting wind speed patterns more comprehensively. Additionally, this threshold aligns with previous studies (Molina et al. 2021, 2023) that have employed similar threshold criteria (90%), enhancing comparability and consistency in the field. However, the present research method ensures that the selection process is systematic threshold criteria and has statistical, empirical evidence based on a comprehensive regional wind speed data analysis rather than arbitrary choice. This method enhances wind speed assessment reliability, reinforcing its applicability and contributing to a more standardized method in the field. As mentioned in the literature review (Fan et al. 2021) high-quality and long-term observations are necessary to examine long-term trends in wind speeds. A deficiency of observation data in the processing may have an impact on the analysis because it is utilized to verify the reanalysis products and modeling applications. Researchers and users often resort to reanalysis products whenever no observations are available in a particular region.

This study has provided insight into the performance of reanalysis products by comparing them to wind speed observations over the same region and period. It was observed that JRA55 consistently demonstrated strong correlations, low bias (Table 3, Figs. 6, 7), and similarity to observed wind speed values across various threshold values (Figs. 4, 5). Consequently, JRA55 has become ideal for assessing wind energy and climate change's impacts on wind speed in South Asia. These results reflect those of Ramon et al. (2019) and Fan et al. (2021), which were reported on a global scale. Moreover, ERA5 exhibited reasonable performance, especially at specific thresholds, but the bias values varied dynamically with different thresholds. A consistent bias is displayed by NCEP/NCAR across all thresholds of expected wind speed, indicating limitations in the ability of this product to represent observed wind speed data across the region. Although the JRA55 reanalysis product demonstrated superior performance in statistical analyses compared to other products concerning observations, MRE considered exploring the potential for reducing uncertainties by integrating multiple reanalysis products. Though MRE datasets do not outperform JRA55 in bias, it highlights the importance of cross-referencing numerous products to understand wind speed dynamics comprehensively. Whereas the ERA5 product also demonstrated promising results, it is crucial to note that NCEP/NCAR overestimated wind speed significantly enough to consider when evaluating the potential for wind energy yields (Fan et al. 2021). These findings are of utmost importance, as they empower wind energy developers and policymakers to harness the region's wind resources more effectively and create economic growth in the South Asia region.

Reanalysis products (NCEP/NCAR, JRA55, ERA5) exhibit diverse performance characteristics due to the complex interplay of fundamental equations, grid cell resolutions, and observation processing methods. In this study, the descriptions of these products are detailed in Sect. 2.2, and understanding and selecting the most suitable product is crucial. Generally, the ERA5 product provides more accurate wind speed estimates due to its higher spatial resolution and advanced data assimilation techniques. JRA55 also demonstrates robust performance, largely due to its comprehensive assimilation of observational data, despite its somewhat coarser resolution compared to ERA5. While NCEP/NCAR's long-term datasets are valuable, their lower resolution and simpler assimilation methods often lead to lower statistical performance (Table 3, Fig. 4, 5, 6 and 7). Given these performance variations, selecting an appropriate reanalysis product based on specific research needs and regional characteristics is significant.

To assess whether reanalysis products indicate a similar trend in wind speeds compared to observational data. The trends and their corresponding 95% confidence levels were determined using the Mann–Kendall (M–K) nonparametric test, with a significant level (alpha) set at 0.05. The overall trend of wind speed is downward (negative trend) during the current period 1973–2005. HadISD, ERA5, JRA55, NCEP/NCAR, and MRE trends are -0.010, -0.002, -0.005, -0.002, and -0.003 m/s per decade, respectively. The JRA55 trend is closer to the observations compared to the other reanalysis products. These results reflect those of Fan et al. (2021), who also found that JRA55 can represent the phenomenon of global terrestrial stilling (Zeng et al. 2018). Further, the results align with those of Ramon et al. (2019) who reported that JRA55 presents strong natural observation trends compared to the other reanalysis products such as ERA-Interim, ERA5, MERRA2 (Modern-Era Retrospective Analysis for Research and Applications), and NCEP/NCAR. Despite its widespread use, the MERRA-2 product was excluded from present study since its scope was limited to evaluating specific datasets that align directly with the objectives and methodologies of the project. Several literature reports have shown that JRA55's findings, known for their reliability, can capture a significant downward trend. For instance, Torralba et al. (2017) reported on global seasonal wind speed trends; Zhou et al. (2021) said that JRA55 captures substantial downward trends in most regions (global-scale evaluation) due to the assimilation of land surface winds. Further, Miao et al. (2020) reproduce the best-representing surface wind speeds in Asia and Europe. In addition, Dong et al. (2020) expressed the best job for the escarpment in the Antarctic region. Zhang and Wang (2020) possess the highest correlations with the observations and capture the terrestrial stilling over the China domain, while Shen et al. (2022) reported finding that JRA55 can capture the terrestrial stilling over eastern China and the Tibetan Plateau. The consistent performance of JRA55 in wind speed and potential evaluations is a testament to the value of this research. It suggests that other reanalysis products may not accurately capture variations in regional wind speeds. This underscores the importance of present work in selecting appropriate reanalysis products for accurate wind energy assessments in South Asia.

Prior studies by Dong et al. (2020) reported that the best performance is observed in the ERA5 and JRA55 in the plateau and escarpment regions of South Asia, respectively. Moreover, Fan et al. (2021) and Vautard et al. (2010) observed that NCEP/NCAR could not represent the observational wind speed trend over the land (that is phenomena in the global terrestrial stilling). These stations' results are in line with those of previous studies, but some wind stations are unable to demonstrate. For instance, the 43128-BEG (Bangalore) wind station region in the plateau presents a low (high) bias for ERA5 compared to other products. In the case of JRA55, 43284-MAN (Mangalore) station tends to be low bias with the present results whereas 43371-THI (Thiruvananthapuram) has a high bias compared to other reanalysis datasets. For more details, all wind station results at the 90% threshold are presented in Figs. 6 and 7.

The reasons for inconsistencies between reanalysis products and observations are due to several potential causes (Fan et al. 2021). One reason is differences in the types of assimilation data used by different reanalysis products. The second reason is errors in the observations themselves. The third is differences in the physical assumptions and parameterizations used in the models. By extrapolating from the lowest model level to 10 m in the boundary layer scheme, wind speeds are parameterized after considering land surface characteristics and stability. This results in inconsistent trends in the reanalysis of wind speeds due to different methods of vertical extrapolation. The aerodynamic roughness length of ERA5 is adjusted based on orographic drag by using the modified Monin–Obukhov scheme. With a given cover type and fixed aerodynamic roughness length over time, NCEP interpolates the wind speed from the lowest model level to 10 m. JRA55 uses a univariate two-dimensional optimal interpolation method to extrapolate the wind speed of the land surface model (lowest level model) to 10 m based on neutral stability. The extrapolated wind speeds may be significantly reduced due to the lower level being set too high in the forest-covered areas, as noted by Torralba et al. (2017). Wind speed trends may be affected by these different methods of data processing. The fourth is the uncertainties of different reanalysis products. Lastly, large inconsistencies in the land surface wind speed trends between reanalysis products and observations, regardless of whether overall trends or piecewise trends are considered.

Assimilation of observation datasets from ships, buoys, radiosondes, aircraft records, and satellites to the reanalysis is frequent practice. Land surface observations are included in the NCEP/NCAR and JRA55 systems as well. According to Zhang and Wang (2020) and Torralba et al. (2017), the JRA55 reanalysis is the only one that incorporates land surface wind speeds in their systems of assimilation, which holds significant implications for the field of atmospheric science. Torralba et al. (2017) found that grids with vegetation cover usually have a negative bias and are corrected in wind speeds at the lowest model level, further enhancing the importance of the JRA55 reanalysis. Therefore, JRA55 outperforms the other reanalysis chosen for intercomparison in this study due to its assimilation of land surface wind speed observations. It is therefore the differences between the reanalysis that will result in differences in the representability of any meteorological variable due to the difference in resolution, data assimilation, and model physics. In the results section of this research, a comparative analysis of reanalysis products is presented, providing valuable insight into their reliability and accuracy performance relative to observations of wind data. Figures 4, 5 and 6 highlight that JRA55 demonstrates the closest alignment with observed variations, indicating its superior accuracy. This is further reinforced by Table 3, which quantifies statistical evaluation among various reanalysis products and highlights JRA55's performance. These results unequivocally establish JRA55 as the most reliable for capturing wind speed variability in South Asia. Despite the broader view of uncertainty in wind speed provided by the MRE, JRA55 emerges as the most accurate product. The results underscore the critical perspective that underlines the importance of selecting the most precise reanalysis data when studying wind speed and climate in the South Asia region, instilling confidence in the reliability of JRA55.

As previously reported evidence (Zeng et al. 2018; Fan et al. 2021; Zha et al. 2021; Dunn et al. 2022; Utrabo-Carazo et al. 2022), this comprehensive study of wind speed trends analysis in South Asia from 1973 to 2005 is aligned with the global phenomenon of terrestrial stilling that is occurring in other regions. This phenomenon has critical implications for various fields. For instance, hydrology affects water resource management. Further, wind energy influences site selection and energy yield predictions. Also, environmental impact assessments alter the understanding of wind-related ecological changes. Although some localized variations are observed, such as the notable increases at stations 41571-CHA (Chaklala) and 41764-HYD (Hyderabad Airport), highlighting that wind speed patterns on the subcontinent are complex, this is illustrated by the fact that there are some localized variations. There is a critical need for accurate and reliable wind speed data in the region as it has important implications for wind energy generation and climate studies. As previously reported (Khan et al. 2019), this study's results are consistent with the region's current evidence conditions despite the use of different weather stations.

The classification of wind power potential at the regional level was another crucial aspect of the research, which laid the foundations for future research. The present study addressed this gap by categorizing wind power potential for specific locations, in contrast to previous studies (Torralba et al. 2017; Ramon et al. 2019; Miao et al. 2020; Fan et al. 2021; Libanda and Paeth 2023) that often focus on the overall wind speed trends without considering regional variations. This study found that the wind station (41764-HYD; Hyderabad Airport) has a maximum WPD of 462.22 W/m^2 at 100 m above ground level (AGL) in the subcontinent region, which indicates Excellent class 7. This wind station 41764-HYD, located in Sindh province within Pakistan's wind corridor, demonstrates an exceptional wind resource. There is also substantial evidence that the region has a proven capacity for generating wind power, with existing wind turbines stations harnessing this renewable energy source (Khan et al. 2019, 2020). Furthermore, it is observed that two wind stations (42909-VER; Veraval, 42754-DEV; Devi Ahilyabai Holkar) are in class 3 due to the Moderate wind energy potential whereas 43424-PUT (Puttalam), 41715-JAC (Jacobabad), and 42971-BHU (Bhubaneshwar) wind stations are in class 2 due to the produce Marginal wind power potential. Some wind stations are in class 1 which presents Poor classifications while these wind locations are acceptable with lower capacity by using commercial wind turbines. This research work supports evidence from previous observations by (Khan et al. 2019; Khan and Dairaku 2024). For investors and decision-makers interested in wind power, this classification provides valuable information enabling them to differentiate between regions with high potential and those with Moderate or low potential.

While this study meticulously presents comprehensive systematic data threshold criteria and wind power potential, it is important to acknowledge that it also has some limitations:

First, the development of threshold criteria for data availability has been systematically derived and is inherently subject to trade-offs. When the threshold increases, the study area is less covered spatially, while the data quality, accuracy, and reliability are compromised if the threshold decreases. Even though this systematic approach has greater robustness than previous arbitrary thresholds, potential biases remain. This is a factor that researchers should be mindful of. Second, relying on reanalysis products introduces variability in the results due to differences in basic complex equations, grid cell resolutions, and observation processing algorithms. Despite being evaluated using statistical analysis, they have inherent limitations that can impact wind trends and wind power density estimation.

Third, Extrapolating winds at 100 m AGL based on the Power law method presents uncertainties and may not fully address the atmospheric stability regimes. This extrapolation inaccuracy may further affect the classification of wind stations based on wind power density despite its insightfulness. Fourth, by focusing on South Asia, the study confirms previous findings that wind speeds are decreasing. However, regional variations and local factors not included in the reanalysis products might contribute to these findings. Future research recommendations include exploring alternative reanalysis products, refining extrapolation methods, and considering local meteorological influences to improve wind speed and power density assessment.

5 Conclusions

The present research aimed to examine a comprehensive assessment of wind speed trends and variability in South Asia, focusing on the reliability and accuracy of reanalysis products. Using a systematic approach to data threshold selection enhances the quality and representativeness of the dataset, filling a critical gap in previous research. Furthermore, this study addressed the classification of wind energy potential at the regional scale based on the international standard which fulfills the study gap in South Asia. This study has revealed several key findings:

Data reliability: A careful consideration of data limitations is essential in South Asia, due to the variability in data availability among weather stations. It is possible to introduce bias and uncertainties into the analysis of wind speed data when there is a high percentage of missing values at certain stations. For instance, station 41759-PAS displays 79% highest missed values compared to other wind stations' locations, in other words, 21% of valid values are available. High-quality and long-term observations are necessary for the analysis of long-term trends in wind speeds. As observation data are used to verify reanalysis products and models, thus a deficiency may affect the analysis. Users and researchers prefer reanalysis products whenever observations are not available.

Systematic data thresholds: A comprehensive representation of wind speed patterns in South Asia is achieved by systematically evaluating data availability at multiple thresholds, namely 80%, 85%, 90%, and 99%. When analyzing wind speed trends, it is essential to choose a data availability threshold based on the systematic evaluation of the trade-off between completeness and spatial coverage of the data. In this case, increasing the threshold provides greater accuracy but limits the coverage area, whereas lowering it extends the coverage area but consequently leads to reduced accuracy. Data quality and completeness were balanced by selecting a 90% threshold. Maintaining this threshold, enough data was available for each selected station throughout the study period. A 90% threshold is more reliable in the results while data gaps are minimized.

Reanalysis product performance: JRA55 consistently exhibits strong agreement with observed wind speed variations compared to other reanalysis products at all systemic thresholds. For instance, at a 90% threshold, JRA55 displays the preference with the 0.33 m/s, 0.99 m/s, 0.94 m/s, 0.58, 0.38 values of Mean Bias, RMSE, Standard Deviation, Correlation Coefficient, and Coefficient of Determination, respectively. South Asia is well captured by JRA55 when it comes to terrestrial stilling. This reliability has established JRA55 as a preferred choice for wind energy resources and research on regional climates in South Asia. In contrast, despite its reasonableness, ERA5 displays deviations depending on data availability thresholds. NCEP/NCAR, on the other hand, demonstrates lower accuracy in representing observed wind speed data, indicating the limitations of this product. Despite its comprehensiveness, JRA55's reliability is higher than the MRE. When it comes to projecting long-term wind speed averages, JRA55 provides valuable analysis for wind energy developers and policymakers in South Asia. Its assimilation of near-surface wind speed observations and its strong agreement with observed wind speed variations make it a reliable choice. Moreover, JRA55's unique characteristics give it an added value over other reanalysis products. These results demonstrate that JRA55 can be utilized further in the wind power industry for wind resource evaluation and perform downscaling experiments for regional climate modeling to present the high-resolution dataset over South Asia. Meanwhile, findings depict that the regional land surface speed variation is uncertain to reproduce using the products regarding wind speed trends. This may result from different scales, atmospheric model quality, data assimilation methods, observations data availability, and accuracy. In addition, the technology for measuring wind speed is also continually emerging.

Wind speed trends: The observed annual mean wind speed over land areas declined across South Asia ($p < 0.001$) during the study period (1973–2005), which aligns with the global terrestrial stilling phenomenon. The average observed decline in wind speed trend value is 0.010 m/s year^{-1} in the present study. Nevertheless, some localized variations reverse this trend emphasizing the dynamic nature of wind patterns and the importance of region-specific analyses. For instance, 41571-CHA ($p < 0.001$), and 41764HYD ($p < 0.001$), wind stations increase the wind speed compared to other stations by 0.055 m/s year^{-1}, and 0.132 m/s year^{-1}, respectively. This trend has significant implications, considering that wind energy development, regional climate modeling, and understanding of atmospheric dynamics in climate change are becoming more critical in the Subcontinent region.

Wind power classified: This study identified wind energy potential for each region and classified it at 100 m AGL level to facilitate informed decision-making in this area of wind energy research. The authors achieve this by using a regional scale classification of wind energy potential. Findings from localized regions such as 41764-HYD have a maximum wind power density value of 462.22 W/m^2, offering Excellent class power seven prospects for developing wind energy as well as providing investment opportunities. Further, it is noticed that two wind stations (42909-VER, 42754-DEV) present Moderate wind energy potential which suggests class power 3, power range are 239.04 W/m^2 and 244.51 W/m^2. Meanwhile, it is found that three wind stations (43424-PUT; 212.32W/m^2, 41715-JAC; 168.61W/m^2, and 42971-BHU; 150.25 W/m^2) exhibit Marginal class power 2. Moreover, it is observed that wind stations have low wind power density, many of which fall into the Class 1 (Poor) classification range (8.18 to 106.98 W/m^2). However, these locations may be suitable for the use of commercial wind turbines with lower capacities.

Acknowledge the limitations: This study has certain limitations that need to be acknowledged. A higher threshold reduces the number of stations, thus limiting the spatial coverage and excluding most research areas. The reanalysis products used in this study come with inherent uncertainties resulting from model inadequacies and their assimilation of wind speed observations. Extrapolating wind speeds at 100m AGL was a necessary step due to the lack of available observations. However, this process is imprecise, as power laws, which were used for the extrapolation, struggle to account for atmospheric stability regimes. Moreover, a constant wind profile exponent α may not be adequate to represent the localized effects of surface roughness for areas with highly variable topography, although this method works quite well-practical for regional-scale studies. It would be useful to conduct further research in other regions as well, since the study only focused on South Asia, leading to a lack of a comprehensive understanding of global wind dynamics.

Consequently, these findings provide an understanding of wind energy resources and regional climate dynamics in South Asia. Reliable datasets are essential to the development of sustainable wind energy and the study of climate change in the area. Furthermore, the systematic selection of data threshold criteria presents an important contribution to the quality of datasets, thereby improving the quality of the datasets used in the study. Wind power potential classification in the localized regions in South Asia provides practical insights that support advances in regional climate research and sustainable wind development. This research can provide insights into wind energy investors, decision-makers, and climate scientists which ultimately contribute to the development of renewable energy sources and climate resilience in South Asia.

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Author contributions KHAN Muhammad Abid: Led the research and development of the manuscript as the main author, contributing to the conceptualization, methodology, software development, data curation, validation, and writing of the manuscript. Responsible for the overall structuring of the study, including performing analyses and formulating the discussion to provide meaningful interpretations. Managed the revision process and incorporated feedback into the final draft. DAIRAKU Koji: Provided critical and constructive feedback throughout the research process. Played a key role in the supervision of the study, ensuring scientific accuracy, and offering guidance on the research methodology and interpretation of results. Contributed significantly to the critical discussions that shaped the study's final form. KELKAR Saurabh: Assisted with data checking.

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Data availability The observation data are achieved by Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/index.html), Reanalysis products; ERA5 (https://cds.climate.copernicus.eu/cdsapp#!/home), NCEP/NCAR (https://www.ncei.noaa.gov/), and JRA55 (https://jra.kishou.go.jp/JRA-55/index_en.html).

Declarations

Conflict of interest The authors declare no conflict of interest.

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