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Wind Power Density Projections for the Indian Offshore Region: Annual and Seasonal Changes

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Abstract

Offshore wind energy offers a sustainable solution for India's transition from fossil fuels. Understanding how wind resources may vary under future climate conditions is essential for effective planning and development. This study assesses projected offshore wind power density (WPD) in the Indian offshore region using daily wind speeds from 13 CMIP6 global climate models under SSP2-4.5 and SSP5-8.5 scenarios. Quantile mapping bias-correction, using ERA5 reanalysis as the reference, was applied to improve model performance, and multi-model ensemble results were analysed for historical (1990–2014) and future periods. The findings reveal distinct spatial and seasonal variability in future WPD. A dipole-like pattern persists, with WPD reductions in the northwest Arabian Sea and moderate increases along the southwest coast of India, particularly during the monsoon season. Under SSP5-8.5, non-monsoon seasons show widespread declines by 2100. These results highlight the importance of incorporating climate-responsive planning and robust bias-correction practices to ensure sustainable offshore wind development in India.

Keywords

CMIP6, Quantile mapping, WPD, ERA5, Indian offshore region

Introduction

The urgent need to transition from carbon-intensive energy systems to sustainable alternatives is driven by climate change and growing energy demands. In India, a developing economy with ambitious renewable energy targets, offshore wind energy presents a promising solution due to its scalability and minimal land-use conflicts. Countries such as the United Kingdom, China, and Denmark have already made substantial investments in offshore wind infrastructure, demonstrating their economic viability and role in achieving net-zero targets (GWEC, 2024)Indian offshore region, encompassing coastal waters along Gujarat and Tamil Nadu, exhibits high wind power density (WPD), often exceeding 400–500 W/m^2 at 100–120 m hub heights, particularly during the southwest monsoon(B. A. A. Srinivas et al., 2022) However, challenges such as

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seasonal wind variability, complex marine bathymetry, high installation costs, and grid integration hurdles necessitate robust resource assessments to ensure viable wind farm deployment.

Globally, offshore wind has gained traction, with installed capacity reaching 64 GW in 2023, led by countries like Denmark, China, and the United Kingdom (GWEC, 2024). In India, preliminary studies using reanalysis datasets like ERA5 have identified high wind speeds in coastal zones, particularly off Gujarat and Tamil Nadu (Nagababu et al., 2017). These studies, however, often rely on historical data and assume stable climate conditions, overlooking the impacts of climate change on future wind resources. Shifts in atmospheric circulation, monsoon intensity, and oceanic thermal gradients, driven by global warming, could significantly alter wind patterns critical for offshore energy production (Dahiya et al., 2024). For example, warming sea surface temperatures in the Indian Ocean may weaken monsoon winds, affecting WPD in key seasons.

To address these uncertainties, global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) provide high-resolution projections under Shared Socioeconomic Pathways (SSPs), such as SSP245 (moderate emissions) and SSP585 (high emissions) (Eyring et al., 2016). However, raw GCM outputs often exhibit biases due to coarse spatial resolution and simplified atmospheric processes, necessitating statistical correction for regional applications. Recent offshore wind assessments in India using CMIP6 models and quantile mapping confirm its effectiveness in reducing bias in historical data and analyzing future trends at specific coastal sites (Wadalkar & Deo, 2024). Nevertheless, its application across the full Indian offshore region remains limited. Moreover, comprehensive assessments of wind power density (WPD) covering long-term climate projections and seasonal variability are scarce. This gap presents a critical challenge for developing climate-resilient offshore wind energy strategies.

This study addresses these gaps by evaluating WPD in the Indian offshore region using bias-corrected CMIP6 data. It focuses on annual and seasonal changes across historical (1990–2014) and future periods (2026–2050, 2051–2075, 2076–2100) under SSP245 and SSP585 scenarios. By employing a multi-model ensemble approach, the study ensures robust projections, offering actionable insights for sustainable offshore wind energy planning and policy formulation in India.

Methodology

The present study evaluates projected changes in WPD in the Indian offshore region, using daily near-surface wind speed data from 13 Coupled Model Intercomparison Project Phase 6 (CMIP6) GCMs selected based on their availability, spatial resolution, and proven applicability in wind resource studies. The models include: ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, and NorESM2-MM. Each model was individually processed and later combined using a multi-model ensemble mean (MME) approach to minimize uncertainties arising from inter-model differences. The historical period considered spans from 1990 to 2014, while three future time slices—2026–2050, 2051–2075, and 2076–2100—were analyzed under two greenhouse gas emission scenarios: SSP2–4.5 and SSP5–8.5.

Raw GCM outputs typically contain systematic biases due to coarse spatial resolution, simplification of atmospheric processes, and inherent model assumptions. Hence, it is crucial to apply bias correction before using such data for regional-scale assessments. In this study, ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) is used as a reference dataset due to its high spatiotemporal resolution and reliability in offshore environments (Hersbach et al., 2020). All datasets (GCMs and ERA5) were interpolated onto a uniform 0.25° × 0.25° grid using bilinear interpolation to ensure consistency. The wind speed magnitude at each grid point was calculated using the Euclidean norm from the eastward (u) and northward (v) wind components.

To correct model biases, a quantile mapping (QM) technique was applied, which adjusts the cumulative distribution function (CDF) of model outputs to match that of the observed (ERA5) data. At each grid point, daily wind speeds from the historical GCM and ERA5 datasets were fitted with Weibull distributions, which are commonly used to represent wind speed variability due to their flexibility and accuracy. The bias-corrected wind speed was computed using Eq. (1) (B. A. Srinivas et al., 2022)

$$WS_{corrected} = F_{ERA5}^{-1}\left(F_{GCM}(WS_{GCM})\right) \quad (1)$$

where F_{ERA5}^{-1} and F_{GCM} denote the inverse and direct CDFs of the ERA5 and GCM datasets, respectively. This transformation was subsequently applied to the GCM-projected wind speeds for future periods.

WPD was calculated using Eq. (2):

$$WPD = \frac{1}{2}\rho WS^3 \quad (2)$$

where air density ρ is assumed to be 1.225 kg/m^3, and WS is the daily wind speed in meters per second. Although offshore density varies with temperature, humidity, and pressure, the seasonal variability in the Indian region typically results in density fluctuations of only ±3–5% (literature values). Considering WPD proports to WS^3, such variability would lead to a maximum deviation of approximately ±9–15% in WPD estimates, which is within acceptable limits for large-scale climatological assessments. Thus, the constant-density assumption remains valid for comparative analysis.

A multi-model ensemble (MME) was generated by averaging the outputs of 13 CMIP6 GCMs, both without bias correction (WOBC) and with bias correction (BC), for each time period and scenario. Annual and seasonal WPD changes were analysed, with percentage change maps illustrating trends across the Indian offshore region. The percentage change was calculated using Eq. (3)

$$\%\Delta WPD = \left(\frac{WPD_{future} - WPD_{historical}}{WPD_{historical}}\right) \times 100 \quad (3)$$

Results and Discussion

Annual WPD Projections: Near, Mid and Far Future

Figure 1 depicts the projected percentage change in mean annual WPD over the Indian offshore region for three future periods—2026–2050, 2051–2075, and 2076–2100—relative to the historical baseline (1990–2014). The projected changes range from about −30% to +40%. The results clearly indicate spatial heterogeneity in future wind resource availability. Under both SSP2-4.5 and SSP5-8.5, the near-future changes remain modest, with most of the region lying between −10% and +10%. However, a contrasting spatial pattern becomes more evident and intensifies toward the end of the century. The northwestern shelf off Gujarat and the northern Arabian Sea show reductions of around 10–20%, while the southeastern offshore corridor from the southern tip of India into the Bay of Bengal exhibits increases of nearly 10–40%.

The WOBC output generally shows stronger positive anomalies offshore. This is mainly due to the tendency of GCMs to overestimate wind speeds over the open ocean, where the representation of surface drag and coastal boundary-layer processes is simplified. As WPD is highly sensitive to high wind speeds (WS^3), such overestimation leads to inflated WPD projections. After applying bias correction, the spatial structure remains largely unchanged, but the magnitude of change becomes more realistic. Typically, the northwestern region shows decreases of about 10–20%, while the southeastern region records increases of about 10–30% in the far future under SSP5-8.5. Bias correction reduces the excessive frequency of high-wind events in the model output, particularly in offshore deep-water areas, and therefore provides more reliable projections for offshore wind development planning.

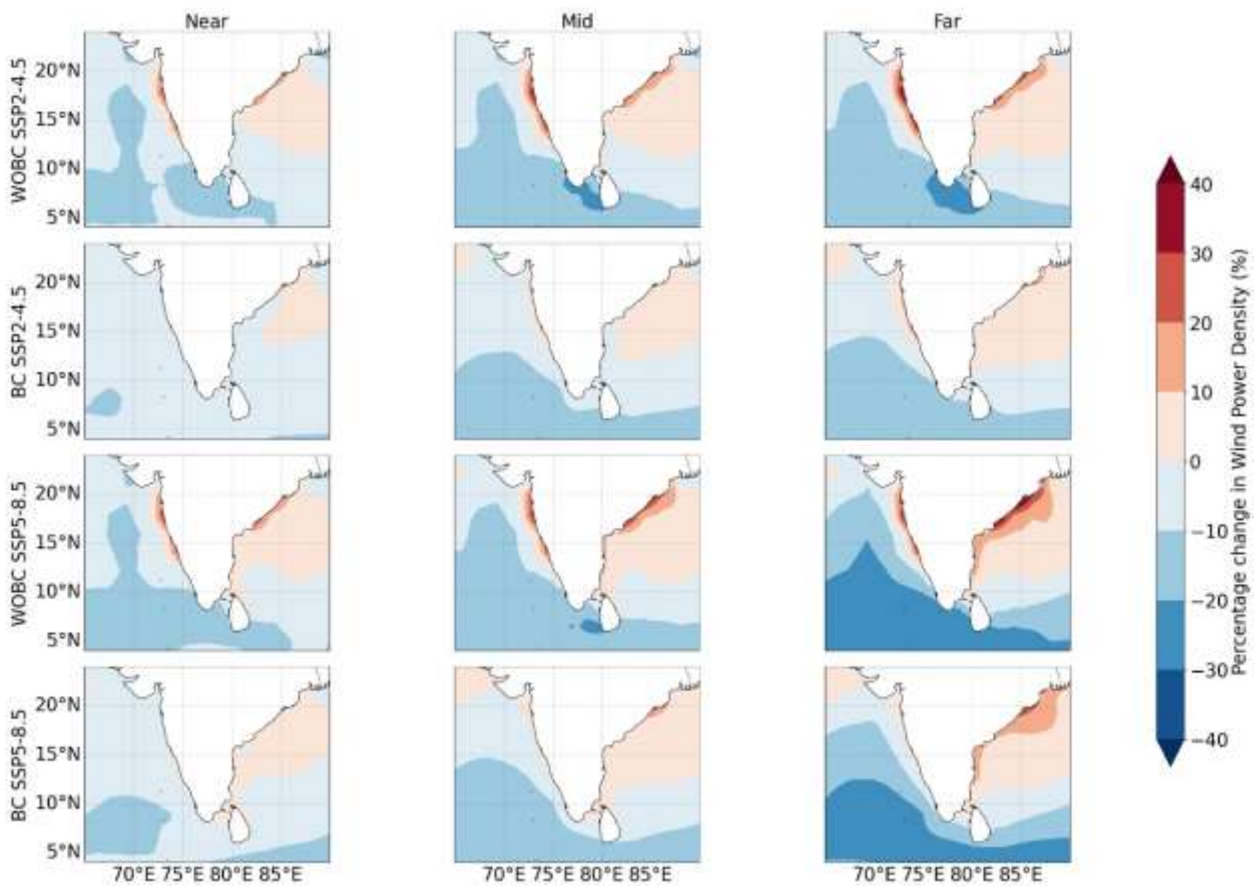

Fig. 1. Spatial maps of percentage change in mean annual WPD for 2026–2050, 2051–2075, and 2076–2100 relative to 1990–2014. Rows display WOBC and BC ensemble results under SSP2-4.5 and SSP5-8.5 scenarios

Seasonal WPD projections: Far future (2076-2100)

Seasonal WPD variations are assessed using four meteorological seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–August), and post-monsoon (September–November). These seasons represent distinct wind regimes over the Indian Ocean and are important for evaluating the year-round suitability of offshore wind development.

Figure 2 presents the seasonal percentage change in mean WPD for the far-future period (2076–2100) under SSP2-4.5 and SSP5-8.5 for both WOBC and BC ensembles. Strong seasonal contrasts are evident. Winter and pre-monsoon seasons are dominated by widespread reductions across the Arabian Sea and parts of the Bay of Bengal, mostly between −10% and −30%, indicating weaker background winds outside the monsoon months. Bias correction moderates these declines and produces smoother spatial gradients, improving the realism of weak-wind projections. In contrast, the monsoon season shows a narrow enhancement band along the southwest coast of India, driven by intensified coastal jet activity in the raw model output. These positive anomalies reach about +60% to +80% in WOBC but reduce to around +20% to +40% in BC, indicating a more credible strengthening of monsoon-driven winds. During the post-monsoon season, a transitional behaviour is observed, with limited coastal increases and mild negative changes offshore as the monsoon weakens.

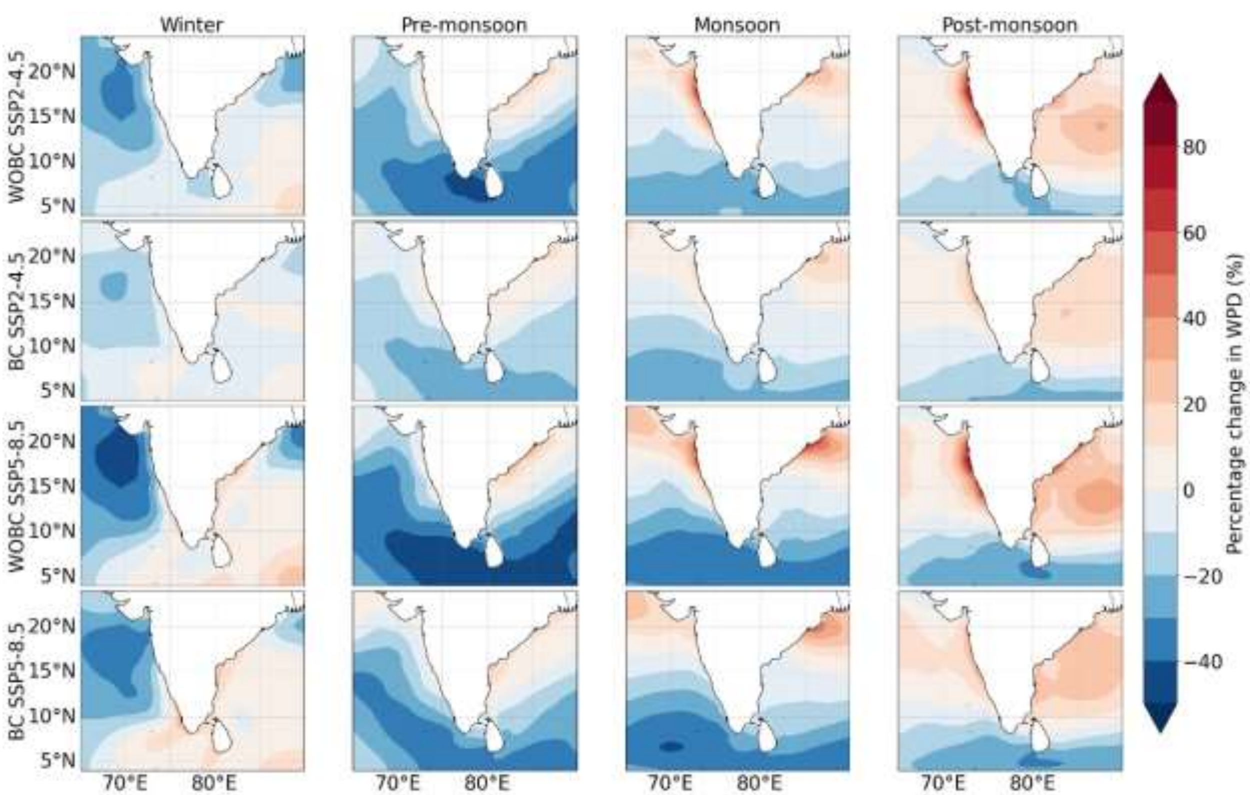

Fig. 2. Seasonal percentage change in mean WPD for the far future (2076–2100) relative to 1990–2014. Results shown for WOBC and BC ensembles under SSP245 and SSP585.

These results collectively indicate that climate change may sharpen intra-annual variability in offshore wind resources. Winter and pre-monsoon seasons are expected to become less favourable, particularly along the northwest shelf off Gujarat, whereas the southeastern offshore corridor retains strong potential mainly during monsoon months. Bias correction effectively reduces unrealistic amplification of high-wind conditions in WOBC and preserves the essential seasonal signal, thereby improving confidence in future wind resource assessments. Overall, the monsoon season remains the most promising period for offshore wind extraction toward the end of the century, while non-monsoon seasons, especially under SSP5-8.5, show declining suitability for offshore wind development in India.

Conclusion

The present study provides a comprehensive assessment of projected annual and seasonal changes in offshore WPD around India using a multi-model ensemble of CMIP6 GCMs, evaluated under SSP2-4.5 and SSP5-8.5 emission scenarios with and without bias correction. The results show distinct spatial and seasonal variations in future wind energy availability. Bias correction substantially reduces the overestimation of WPD in WOBC outputs, particularly in offshore regions where strong winds are common. Under SSP2-4.5, mild to moderate improvements are projected in selected southern offshore zones, while large portions of the Arabian Sea experience reductions, mostly between −10% and −30% by the end of the century. SSP5-8.5 reveals stronger declines in annual and seasonal WPD, particularly in winter and pre-monsoon periods, whereas the monsoon season continues to show localised enhancements of about +20% to +40% along the southwest coast due to the persistence of monsoon wind systems.

These outcomes highlight the growing intra-annual variability of future offshore wind resources under climate change. While the monsoon season remains the most favourable period for power generation, non-monsoon seasons show reduced suitability, especially under the SSP5-8.5 pathway. The significant differences between WOBC and BC projections emphasise the necessity of bias correction to avoid erroneous assessment of wind energy potential. Therefore, future offshore wind planning in India should incorporate climate change considerations, advanced statistical correction methods, and high-resolution regional modelling to ensure robust decision-making. Strengthening climate-resilient energy strategies and prioritising low-emission development pathways will be crucial to sustain long-term offshore wind competitiveness.

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