Assessing Added Value of Dynamical Downscaling for Wind Speed Over South Asia: A Distribution Added Value Approach

Muhammad Abid Khan, Koji Dairaku, and Saurabh Kelkar

Abstract

High-resolution regional climate model simulations have become increasingly prevalent due to advances in computational resources. In this study, we examine the added value of wind speed simulations of two regional climate models (RCA4, REMO2009) forced by MPI's Earth System Model (MPI-ESM-LR) over South Asia. The simulation data is acquired from the Coordinated Regional Climate Downscaling Experiment (CORDEX-SA) for the period from 1974 to 2004. To quantify the added value, we adopt the recently developed Distribution Added Value (DAV) metric, which allows a direct comparison of probability density functions (PDFs) for wind speed between the high-resolution regional model runs and the HadISD observational data. We calculate the DAV for both full PDFs and the upper-tail PDFs (P95) at the annual and seasonal levels (autumn, spring, summer, and winter). For the RCA4 model, our analysis reveals substantial added value, with DAV values ranging from 8.4 to 11.5% for the full PDF and from 4.7 to 12.1% for the upper-tail PDF (P95). Conversely, the REMO2009 model shows negative DAV values, indicating limited improvement in reproducing wind speed patterns, with values ranging from −9.9 to −10.8% for the full PDF and from −13.5 to −17.9% for the upper-tail PDF (P95). The ensemble mean shows DAV values from −2.4 to −2.1% for the full PDF and from 0.6 to 1.8% for the upper-tail PDF (P95). Our findings indicate that the RCA4 model demonstrates significant added value in reproducing wind speed characteristics over South Asia, particularly in extreme events. On the other hand, the REMO2009 model reveals limited improvement in capturing wind speed patterns, while the ensemble mean exhibits moderate added value. Overall, our study highlights the advantages of utilizing high-resolution wind speed downscaling, as demonstrated by the positive DAV values in RCA4, offering valuable insights for climate modeling and impact assessments in South Asia.

Keywords

Added value · Climate modeling · Wind speed · CORDEX-SA · Probability density functions (PDFs)

1 Introduction

Among the most critical challenges of the twenty-first century is climate change, primarily caused by human activities. As public awareness of climate change has increased as well as the Intergovernmental Panel on Climate Change (IPCC) guidance, global climate models (GCMs) have been developed so that past, present, and future climate conditions can be assessed. However, these models have limitations when it comes to the assessment of local-scale conditions, which is despite their ability to capture large-scale atmospheric and oceanic circulations. To address these limitations, small-scale processes need to be parameterized to fill the gap in their representation caused by the low spatial resolution of GCMs (Careto et al. 2022).

To resolve these limitations and gain a better understanding of climate in different parts of the world, researchers have used statistical and dynamic downscaling techniques. The development of regional climate models (RCMs) has been an essential tool in this process. Several significant advances have been made in RCM technology in recent years, which enables

M. A. Khan (✉) · K. Dairaku · S. Kelkar
Department of Engineering Mechanics and Energy, Graduate School of Science and Technology, University of Tsukuba, Ibaraki, Japan
e-mail: khan.muhammad.sa@alumni.tsukuba.ac.jp

M. A. Khan
Center for Environmental Remote Sensing, Chiba University, Chiba 263-8522, Japan

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them to generate physically consistent circulation patterns at regional and local levels, with resolutions ranging from tenths of kilometers to scales that enable convection to occur at these locations. Higher-resolution models must be compared to their lower-resolution counterparts, as well as observations, so as to establish their "added value," or ability to represent individual variables and processes better (Soares and Cardoso 2017; Khan et al. 2018; Khan and Dairaku 2024).

Despite being promising, the use of high-resolution RCMs is not without its challenges, primarily in terms of the availability of appropriate computing resources. A notable finding of high-resolution simulations is that they do not consistently reveal added value, placing a high emphasis on rigorous assessment methods. Using the Coordinated Regional Climate Downscaling Experiment for South Asia (CORDEX-SA), this study builds upon recent advances in climate modeling to examine the added value of downscaling of daily wind speeds to higher resolution. With a dataset spanning three decades, this research employs two regional climate models, RCA4 and REMO2009, driven by MPI's Earth System Model (MPI-ESM-LR), and assesses their performance against observational data from HadISD.

As a complement to quantitatively evaluate the quality of high-resolution simulations in comparison to probability density functions (PDFs) derived from observational data, our study utilizes a novel metric called Distribution Added Value (DAV). Specifically in the present study, a DAV measurement is made for both the full PDFs and upper-tail PDFs (P95) at both seasonal and annual levels (autumn, spring, summer, and winter) so that DAV values can be calculated. This study's objective is to demonstrate the effectiveness of high-resolution wind speed downscaling and its ability to capture the unique climatic characteristics of South Asia through the application of this robust methodology. Here, this frame of research highlights the importance of regional climate models for local-scale climate understanding, discussing the advantages and challenges of using high-resolution simulations and describing the present study's focus on South Asia, wind speed, and DAV. Next, the paper is unfolded into five sections. Sections 2, 3, 4, and 5 are data and methods, results, discussion, and conclusions, respectively.

2 Data and Methods

2.1 Observation Data

This study utilizes observational data from the Hadley Centre Integrated Surface Dataset (HadISD) which is maintained and distributed by the United Kingdom Met Office Hadley Centre. As one of the most comprehensive datasets for surface climate variables, HadISD is known for its extensive coverage and meticulous calibration, ensuring quality control procedures such as duplicate checks, distributional gap checks, and identification of outlier values are applied to ensure data accuracy and reliability. HadISD provides detailed climate information around the world, including sub-daily wind speed data (sub-daily data aggregated to daily means), which is integral to the present analysis. The database encompasses 8,139 stations globally, with a significant concentration in South Asia covering the period from 1931 to 2020. A key reference for the dataset can be found in Molina et al. (2022). Orography for the South Asia domain and meteorological locations are presented in Fig. 1.

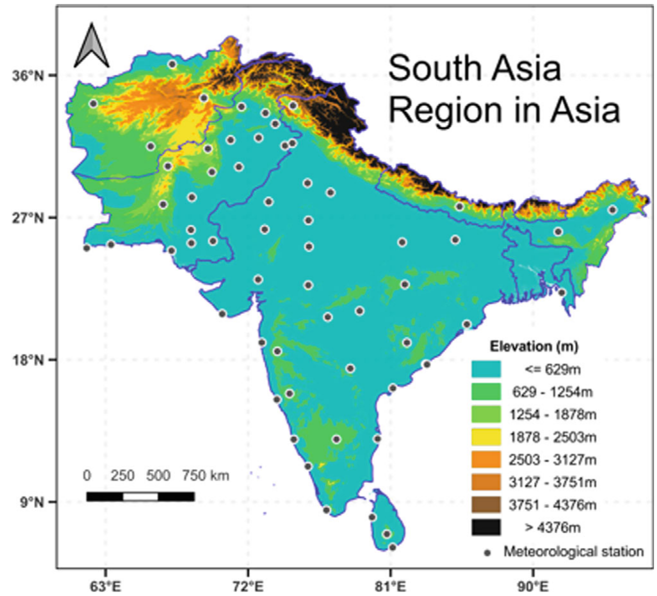

Fig. 1 Topographic map of South Asia and HadISD meteorological available wind station (Khan et al. 2025)

2.2 Simulation Data

Climate simulations at high resolution are conducted using CORDEX-SA, the Coordinated Regional Climate Downscaling Experiment for South Asia. Globally, CORDEX provides detailed climate data for a wide range of land regions worldwide, providing an important resource for research on climate change's impacts and adaptation strategies. CORDEX-SA specifically focuses on South Asia and provides valuable data due to its availability of high-resolution simulations. Climate simulations at high resolution are conducted using CORDEX-SA, the Coordinated Regional Climate Downscaling Experiment for South Asia. Globally, CORDEX provides detailed climate data for a wide range of land regions worldwide, providing an important resource for research on climate change's impacts and adaptation strategies. CORDEX-SA specifically focuses on South Asia and provides valuable data due to its availability of high-resolution simulations.

The downscaling of wind speeds over the South Asian region is carried out using two state-of-the-art regional climate models ("RCMs"), namely the RCA4 and REMO2009. A leading global climate model, MPI-ESM-LR, provides boundary conditions for these RCM simulations, which are determined using simulations from the Earth System Model at the Max Planck Institute. Models that represent regional climate phenomena using RCA4 are well known. In South Asia, wind patterns and seasonal variations are well captured by its fine spatial resolution. It simulates regional climate with precision like REMO2009, another high-resolution RCM. In this examination, historical simulations cover the period from 1974 to 2004. To ensure consistent comparisons, evaluate within a common spatial domain covering the South Asia domain. This approach involves the nearest neighbor grid point of all simulation model data relative to every weather station utilized.

2.3 Methodology

As the foundation of the evaluation process, this study uses the Distribution Added Value (DAV) metric, recently introduced by Soares and Cardoso (2017) as the cornerstone. The DAV method provides a direct method for determining whether higher-resolution models are more accurate or less accurate when compared to their lower-resolution counterparts, based on probability density functions (PDFs) and observational data as a reference. To measure the concordance between two distinct PDFs, this metric uses the PDF skill score proposed by Perkins. Afterward, the DAV metric computation is demonstrated by the below equation.

$$\mathrm{DAV} = \frac{\sum_1^n \min(Z_{hr}, Z_{ref}) - \sum_1^n \min(Z_{lr}, Z_{ref})}{\sum_1^n \min(Z_{lr}, Z_{\mathrm{ref}})} \times 100,$$

whereas Z_{hr}, Z_{lr}, and Z_{ref} denote the higher, lower resolution of simulation models, and reference data PDF, respectively. For the fraction values multiplied by 100. As the results will present, the positive and negative values represent the added and lost values, separately. To evaluate the model's performance across all distributions of wind speeds, DAV is calculated for full PDFs. The upper-tail PDFs are also calculated with DAV, specifically focusing on extreme wind events (P95). A lot of applications, such as risk assessment and infrastructure planning, rely on models to capture extreme wind conditions. This work spans multiple temporal scales, including annual and seasonal (autumn, spring, summer, and winter) assessments. By examining how the models perform across diverse climates, a comprehensive evaluation is assured.

This section presents the data and methods that support the assessment of the accuracy of RCMs in representing South Asia's wind speed to examine the strengths and limitations of advanced RCMs in capturing the complex winds in this region by combining quality observational data with advanced RCMs and the DAV metric.

3 Results

3.1 PDF: Annual and Seasonal Analysis

This study uses a novel metric called Distribution Added Value (DAV) to quantify the quality of high-resolution simulations forced by a coarser resolution model compared to probability density functions (PDFs) derived from observational data. By following the Weibull distribution wind speed, PDF diagram is skewed. PDF graphs are shown for annual and seasonal as well as extreme event values in Fig. 2c–g. Overall experiment trends delineated the overestimation and underestimation, caused by terrain height of the model grid box.

3.2 DAV Analysis for Annual and Seasonal

For the Full PDF and P95 analysis, the author assessed the performance of two RCM models driven by GCM. The DAV calculations, expressed as percentages, provide insights into the added value of higher-resolution simulations compared to their lower-resolution counterparts. Also, P95 provides insights into the performance of the models in capturing extreme wind speed events, which are crucial for understanding extreme weather phenomena in Fig. 2 (a = full PDF, b = P95). Using the DAV metric highlights the varying performance of high-resolution regional climate models. While MPI-RCA exhibited notable gains, particularly in capturing the Full PDF and extreme wind speed events during specific seasons, MPI-REMO faced challenges, especially in replicating extreme events during winter. There was no significant added value or substantial losses for the multi-model ensemble (MME), which also demonstrated a balanced performance.

4 Discussion

There are several important insights that have emerged from our study in South Asia examining the performance of high-resolution regional climate models using the DAV metric to reproduce daily wind speed distributions. It is evident from the abundance of positive DAV values observed in MPI-RCA4 during summer and autumn that the model is capable

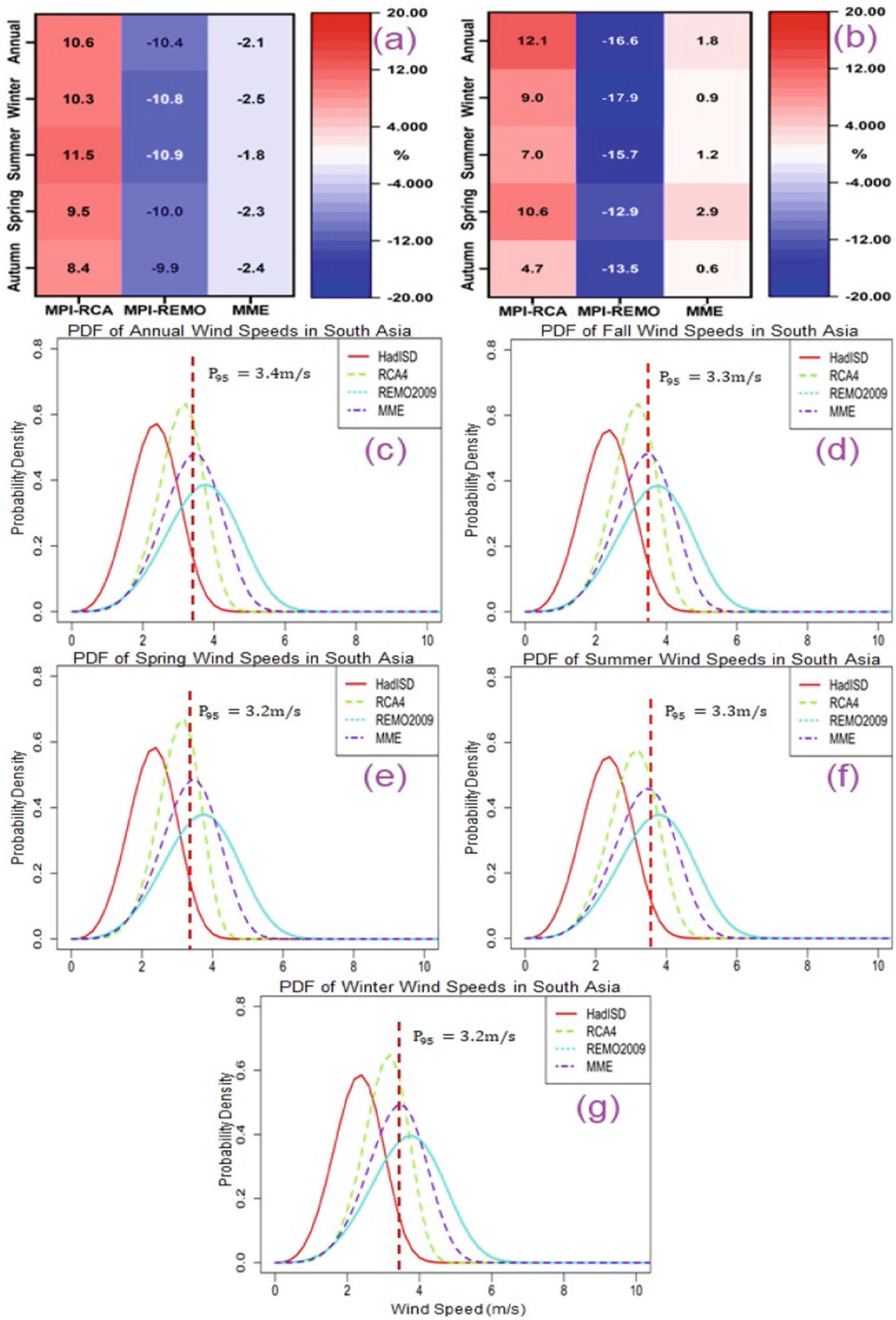

Fig. 2 Using the hindcast CORDEX-SA RCMs simulations for the 1974–2004 period with the HadISD dataset as a reference, the annual and seasonal DAVs of South Asia are shown in **a** the full PDF and **b** P95 for extreme events. Also, **c**–**g** are present for PDF for annual, fall, spring, summer, winter, respectively

of reproducing wind speed characteristics in these seasons, both for full PDF as well as upper-tail PDF. As a result of these findings, South Asia's climate patterns and extreme wind events during summer and autumn can be understood better. Conversely, MPI-REMO2009 exhibited challenges in replicating wind speed distributions, including annual and seasonal, as evidenced by consistently negative DAV values. Observations from prior works (Careto et al. 2022; Soares and Cardoso 2017; Khan and Dairaku 2024; Khan et al. 2024; Molina et al. 2022) are supported by the findings of this research. Further refinement and tuning of this model are necessary for it to capture the nuances of South Asian climatology more accurately. The performance of the MME, while not demonstrating significant added value, suggests a balanced performance across seasons, with no substantial losses. If the trade-off between computational resources and model performance is taken into consideration, this ensemble may be a dependable choice. These results emphasize the importance of annual and seasonal variability in model assessment, as models may exhibit varying performance across different seasons. Further, regional climate models need to be improved at capturing extreme weather phenomena due to varying performance in capturing extreme wind speed events.

5 Conclusions

In conclusion, our study provides valuable insights into the performance of high-resolution regional climate models in replicating daily wind speed distributions in South Asia. MPI-RCA4 demonstrated notable gains during summer and autumn, while MPI-REMO2009 faced challenges, particularly in winter. The multi-model ensemble offered a balanced performance. These findings contribute to our understanding of the capabilities and limitations of high-resolution simulations in capturing the intricate features of wind speed distribution in the context of South Asian climatology. Further model refinements and attention to seasonal variability are recommended to enhance the accuracy of regional climate models in this region.

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