

Unravelling the future role of internal variability in South Asian near-surface wind speed

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Abstract. Near-surface wind speed (NSWS) plays a critical role in water evaporation, air quality, and energy production. Despite its importance, NSWS However, changes in NSWS over South Asia, a densely populated and climate-sensitive region, remain underexplored. This study aims to understand assess and quantify the uncertainties in the NSWS projections of NSWS over South Asia, particularly in relation to with a focus on internal variability. Utilizing a 100-member large ensemble simulation from the Max Planck Institute Earth System Model, we identified the Interdecadal Pacific Oscillation (IPO) as the leading dominant climate mode of internal variability influencing South Asia affecting NSWS in the near future. Our findings reveal results show that the IPO could significantly impact future NSWS, with its positive phase being linked to strengthened of the IPO enhances regional westerly flows and increased NSWS across South Asia. Notably, the study shows that winds, leading to an increase in NSWS. Importantly, accounting for the impact influence of the IPO could reduce NSWS reduces projection uncertainty of NSWS by up to 8% in the near future and 15% in the far future. This highlights These findings highlight the key critical role of internal variability, particularly especially the IPO, in modulating regional NSWS projections. By reducing narrowing uncertainties in these projections, our findings can inform, this work supports improved planning for climate adaptation strategies for South Asia, helping optimize and wind energy assessments in the context of changing winds development in South Asia.

1—Introduction

Near-surface wind speed (NSWS), observed at approximately 10 meters above ground level, is a crucial meteorological variable. As a key driver in the hydrological cycle, NSWS directly impacts water evaporation and runoff (Roderick et al., 2007). Additionally, NSWS is essential for air quality management by influencing the dispersion of atmospheric pollutants (Jacobson and Kaufman, 2006). Its importance extends to the renewable energy sector, particularly in wind energy generation, where fluctuations in NSWS can significantly affect the energy output of both onshore and offshore wind farms, as highlighted by recent research (Pryor and Barthelmie, 2021; Shen et al., 2024). In 2020, wind energy contributed 6.1% of global electricity generation, with projections indicating an increase in its share as the adoption of renewable energy grows to meet international goals for carbon emissions reduction and climate change mitigation (Antonini and Caldeira, 2021; Council, 2023).

External forcings that can drive NSWS changes include greenhouse gas emissions (Zha et al., 2021b; Shen et al., 2022a), aerosols (Biehet et al., 2012), volcanic eruption (Shen et al., 2025b), surface roughness related to vegetation changes (Vautard et al., 2010), as well as land use and land cover change (Minola et al., 2021). Climate teleconnections such as the Atlantic Multidecadal Oscillation (AMO) (Li et al., 2024), Interdecadal Pacific Oscillation (IPO) (Shen et al., 2021a), and the North Atlantic Oscillation (Minola et al., 2016) are significant modes of internal variability. Overall, these factors can be categorized as either external forcings or internal variability drivers, and NSWS changes are driven by a combination of both (Wu et al., 2017; Zha et al., 2024).

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The pressure gradient force predominantly controls changes in mean NSWS, with large-scale atmospheric circulation patterns playing a pivotal role at regional scales (Minola et al., 2023). Variations in these patterns are largely manifestations of internal variability, though external forcings like greenhouse gases and aerosols also exert some influence (Jiang and Zhou, 2023). Understanding the degree to which NSWS changes can be attributed to internal variability is essential for assessing the role of anthropogenic influences in past changes and for making reliable projections of future trends. However, our current knowledge in this area remains limited.

Previous studies have investigated long-term NSWS changes over South Asia (Jaswal and Koppar, 2013; Saha et al., 2017; Das and Roy, 2024). For example, South Asian NSWS experienced a significant decline from 1961 to 2008 (Jaswal and Koppar, 2013), with a more pronounced decrease along the eastern coast compared to the western coast (Saha et al., 2017). However, only a few of these studies have attributed the observed changes to internal variability. Moreover, in model projections, NSWS shows considerable uncertainty in South Asia: Coupled Model Intercomparison Project phase 5 (CMIP5) models suggest an increase in NSWS on the eastern coast but a decrease on the western coast and northern regions by the end of the 21st century (Saha et al., 2017), while CMIP6 models project a decrease in NSWS over South Asia in the near future, followed by an increase (Shen et al., 2022a). These discrepancies emphasize the substantial uncertainties in projecting future NSWS changes over South Asia.

Distinguishing the effects of internal variability from external forcing in NSW changes using only observational data or a single simulation is challenging, as they provide just one realization (Shen et al., 2021b; Deng et al., 2024; Pryor et al., 2025).

To isolate the signals of internal variability, we utilize large-ensemble simulations (LEs). These simulations share identical greenhouse gas emission scenarios and boundary conditions but differ only in initial condition disturbances (Deser et al., 2020).

The multi-member ensemble mean (MMM) of the LEs represents the effects of external forcings, while differences among members reflect the impacts of internal variability (Mitchell et al., 2017; Li et al., 2019; Wu et al., 2021). In this study, we specifically use a 100-member Max Planck Institute Earth System Model (MPI-ESM), which has been compared its historical performance with observation-based data, and applied to project NSW changes (Zha et al., 2021b; Shen et al., 2022a).

Therefore, our objectives are to (i) identify the leading mode of internal variability affecting near-future NSW changes over South Asia and (ii) quantify the uncertainties of NSW projections associated with internal variability. The remainder of this paper is structured as follows: Section 2 presents data and methods; Section 3 discusses the results; and the summary and discussion are provided in Section 4. These findings offer valuable insights for better understanding regional NSW changes

from the perspective of internal variability.

2 Material and Methods

2.1 Reanalysis data

To evaluate the ability of MPI-ESM to reproduce the historical NSW trend over South Asia, we utilize several up-to-date reanalysis datasets. These include NSW data from the Japanese Meteorological Agency (~~JRA-55~~JRA55) (Kobayashi et al., 2015), which is considered the most representative of observed NSW over India (Das and Baidya Roy, 2024); the National Meteorological Information Center of the China Meteorological Administration (~~CRA-40~~)(Liu et al., 2023), which has been shown to outperform other datasets for NSW over China (Shen et al., 2022b)CRA40), which has been shown to outperform other datasets for NSW over China (Liu et al., 2023; Shen et al., 2022c); and the European Centre for Medium-Range Weather Forecasts atmospheric reanalysis fifth generation (ERA5) (Hersbach et al., 2020), a global reanalysis with the highest spatial resolution (~~Bell et al., 2021~~)(Bell et al., 2021). All reanalysis datasets cover a common period from 1970 to 2020, except for ~~CRA-40~~CRA40, which spans from 1979 to 2020. To facilitate comparison, all reanalysis datasets have been bilinearly interpolated to a uniform spatial resolution of 1.5° x 1.5°.

2.2 Large-ensemble simulations

~~The 100-member~~In this paper we selected the MPI-ESM LE primarily for its large ensemble size (100 members), which is well-suited for isolating internal variability. Other available LEs have smaller ensemble sizes (40–50 members), which may reduce their effectiveness in detecting internal variability (Milinski et al., 2020). The MPI-ESM has a horizontal spatial resolution of T63 (~1.9°) and 47 vertical layers extending up to 0.01 hPa in the atmosphere. The historical simulations of MPI-ESM span from 1850 to 2005, following the protocol established within the framework of CMIP5. The representative concentration pathway scenarios, RCP4.5 and RCP8.5, with radiative forcings increasing by 4.5 W/m² and 8.5 W/m², respectively, by 2100, are performed for the period from 2006 to 2099 (Maher et al., 2019). ~~The individual members of the~~

MPI-ESM ensemble differ only in their initial conditions (Bittner et al., 2016). While data from 2006 to 2020 are technically part of the RCP experiment, they no longer represent the future from today's perspective. Therefore, we define 2021 as the beginning of the future period, and designate 1970–2020 and 2021–2099 as the present and future periods, respectively. The individual members of the MPI-ESM ensemble differ only in their initial conditions (Bittner et al., 2016), with branching times for each member from the preindustrial control run detailed in (Maher et al., 2019). These "initial condition disturbances" refer to slight variations in the starting conditions of each member, introduced to capture a range of possible outcomes driven by internal variability (Deser et al., 2020; Phillips et al., 2014; Schneider et al., 2011).

2.3 Inter-member EOF

To identify the dominant spatial modes that account for the differences in NSW trends across ensemble members, we employ an inter-member empirical orthogonal function (EOF) (Smith and Jiang, 1990; Hannachi et al., 2007). For inter-member EOF, the member index replacing the time index in a conventional EOF analysis. In other words, the decomposition is applied to an $M \times N$ matrix, where M represents the number of ensemble members (100 in this case), and N denotes the number of grid points over the South Asia region. Each row of the matrix contains the spatial pattern of NSW trends for a single ensemble member. This analysis can help us yield the leading spatial modes that explain inter-member differences in NSW trends, along with the associated principal component (PC) scores that characterize the magnitude of each mode across ensemble members.

2.3.2.4 Isolating external and internal forcing signals

Considering the member discrepancies differences among ensemble members of the MPI-ESM arising from random internal variabilities, the internal variability can be isolated by the deviations in each member from the MMM:

$$A(i) = A_{forced} + A_{internal}(i), i = 1, 2, 3 \dots 100 \quad (1)$$

where A_{forced} is the MMM of the MPI-ESM, which denotes the response to external forcings. $A_{internal}(i)$ is the residual of the original $A(i)$ minus the external forced response. $A_{internal}(i)$ varies among different members and shows the variability associated with internal variability.

2.4.2.5 IPO and AMO definitions

The climate teleconnection index used to represent the IPO is often derived using an empirical orthogonal function (EOF) EOF method applied to sea surface temperature (SST), as outlined by Mantua and Hare (2002b). In this study, the IPO index is defined as the 9-year running mean of the principal component (PC) Mantua and Hare (2002b). In this study, the IPO index is defined as the 9-year running mean of the PC score from the EOF of detrended annual SST over the North Pacific (20°N–70°N, 120°E–100°W). Similarly, the AMO index is defined as the 10-year running mean of detrended, annually averaged SST over the North Atlantic (0°N–60°N, 80°W–0°W) (Trenberth and Shea, 2006). (Trenberth and Shea, 2006). As both the IPO and AMO indices are derived from detrended SSTs, they are inherently detrended and minimally affected by long-term global warming. For this analysis, both indices are calculated for each member in the LEs.

2.5.2.6 Quantifying the contributions of IPO/AMO to NSW

The impacts of IPO are roughly extracted by removing the NSW variations that are linearly related to the IPO index from 9-year running mean of NSW, as:

$$NSWS(i, t) = r(i)_{NSWS,IPO} \times IPO(i, t) + NSWS_{non-IPO}(i, t), i = 1, 2, 3 \dots 100 \quad (2)$$

where $r(i)_{NSWS,IPO} = \frac{\partial NSWS(i,t)}{\partial IPO(i,t)}$ is the regression coefficient of IPO index and the 9-year running mean NSWS within member i during 1974–2095. [This extended period ensures statistical robustness by including multiple IPO cycles, thus effectively isolating the persistent, long-term influence of the IPO and reducing sampling uncertainty \(Huang et al., 2020a; Jiang and Zhou, 2023\).](#) Thus, $r(i)_{NSWS,IPO} \times IPO(i, t)$ represents the IPO-related component of the NSWS over South Asia in the member i and the $NSWS_{non-IPO}(i, t)$ represents the IPO-independent NSWS component without the IPO-induced variations for each member (Fig. S1). Similar methods are also applied to study the contribution of AMO to NSWS. Following the timeframes selected in (Dreyfus et al., 2022), we set the 2021–2050 as the near-term and 2021–2095 as the full 21st century to compare the contribution of IPO across different periods. [Further details of the quantification method are provided in Figure S1.](#)

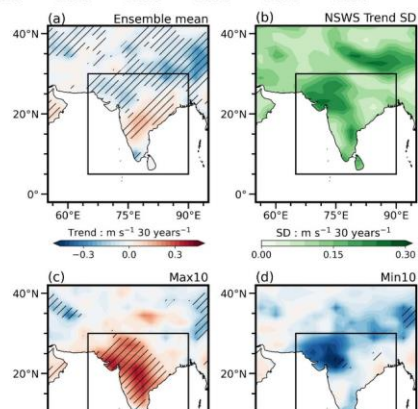
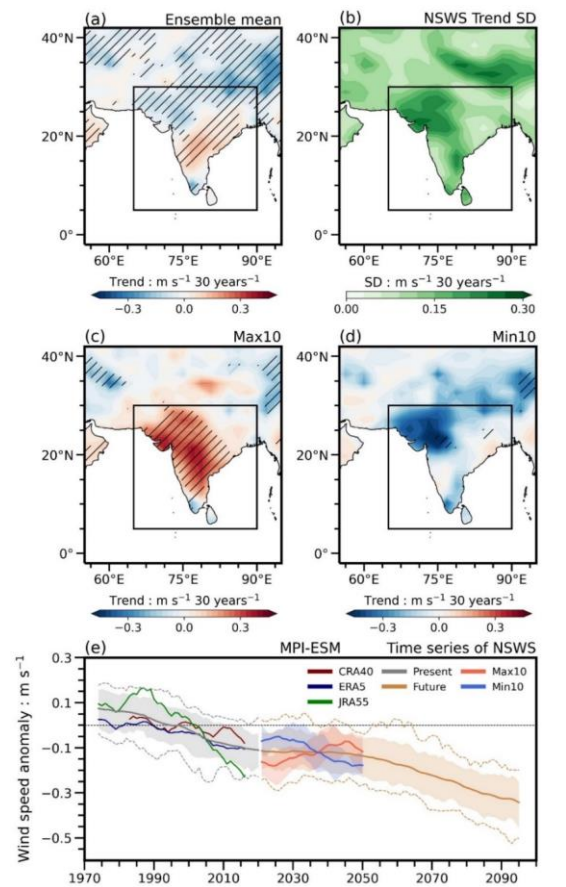


Figure 1. Temporal NSWS changes over South Asia. Annual mean near-surface wind speed (NSWS) trends under the RCP8.5 scenario for (a) the 100-member ensemble mean of MPI-ESM, (b) inter-member standard deviation, (c) the mean trend of the 10 members with the highest increase in NSWS over South Asia, and (d) the mean trend of the 10 members with the highest decline in NSWS over South Asia between 2021 and 2050. Slant hatching denotes trends that passed a significance test with $P < 0.05$. The box in (a) to (d) highlights the South Asia region (5°N–30°N, 65°E–90°E). (e) Time series of the 9-year running mean of NSWS anomalies (relative to the 1980–2010 mean). Purple, dark-blue, and green solid lines represent reanalysis data from CRA40, ERA5, and JRA55, respectively. Gray and brown solid lines represent the ensemble mean of all members of MPI-ESM for the present (1970–2014) and future (2015–2099), with light-gray and light-brown lines indicating the associated 5th and 95th percentiles. Orange and blue solid lines represent the ensemble mean of the ten simulations with maximum and minimum trends in NSWS. Dashed lines refer to the maximum and minimum ranges of MPI-ESM.

3 Results

3.1 Present and near-future South Asian NSWS

To evaluate the ability of MPI-ESM in simulating NSWS, we compared its historical simulation over 1970–2020 with three reanalysis datasets. The MPI-ESM successfully reproduces the current slowdown of the NSWS trend, as seen in all reanalysis datasets, with comparable magnitudes of interdecadal variability (Fig. 1e). Note that the 2021–2099 data are based on the RCP8.5 scenario, whereas the 2006–2020 data follow the RCP4.5 scenario, aiming to reflect real-world conditions as closely as possible. Figure S2 further presents the mean NSWS trend over South Asia for each dataset. Specifically, the historical mean NSWS trends over South Asia are estimated to be -0.049 , -0.037 , -0.064 , and -0.045 m s^{-1} per 30 years for MPI-ESM, CRA40, ERA5, and JRA55, respectively. The results suggest that the decreasing trend of NSWS is generally captured by the MMM of MPI-ESM. Similarly, most regions in the reanalysis datasets also exhibit a reduction in NSWS. The differences between MPI-ESM and the reanalysis data may arise from that the ensemble mean tends to suppress internal variability, as such variability is random across individual members and can be averaged out. These findings indicate that the MPI-ESM large ensemble reasonably reproduces the historical NSWS trend, and that internal variability plays a significant role in shaping this trend over South Asia. Moreover, Figure S3 illustrates a good agreement in the 850 hPa wind climatology during the historical period between MPI-ESM and three reanalysis datasets. The model reproduces key large-scale circulation features, such as the easterlies over the western Pacific and the westerlies over the Indian Ocean, supporting its credibility in simulating historical NSWS patterns. Under the high-emission scenario of RCP8.5, the externally forced annual NSWS in the MMM of MPI-ESM exhibits a hiatus relatively stable phase over South Asia in the near term, reflecting inter-decadal variability. Notably, significant increases in NSWS are observed over the central and eastern coasts of India, contrasted by pronounced decreases over northern regions (Fig. 1a). The large standard deviation observed in the NSWS trends among members is comparable to the long-term trend (Fig. 1b), suggesting a substantial impact of internal variability on NSWS trends. Furthermore, the Although the decreasing trend of NSWS in the MMM of MPI-ESM MPI-ESM successfully reproduces the current slowdown of the NSWS trend, as seen in all reanalysis datasets, with comparable magnitudes of interdecadal variability (Fig. 1e). Although the decreasing trend persists throughout the 21st century, significant uncertainty remains in near-term projections, as reflected by the large spread among members. The NSWS trends for this period range from -0.20 to 0.34 m s^{-1} per 30 years, with the 5th to 95th percentile spread of -0.17 to 0.11 m s^{-1} per 30 years.

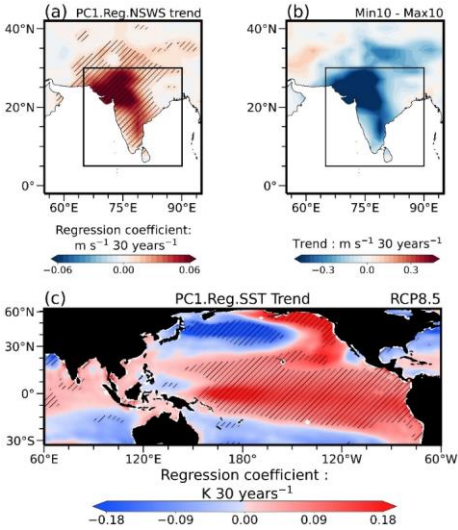
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To further quantify the impact of internal variability, we analyzed NSW trends within two extreme groups: the ten members with the largest increases in NSW (Max10) and the ten with the largest decreases (Min10). The Max10 group displays pronounced increasing trends across most of South Asia (Fig. 1c), while the Min10 group primarily exhibits significant decreasing trends over northwestern South Asia (Fig. 1d). The average trend in the Min10 and Max10 groups is -0.18 m s^{-1} per 30 years and 0.14 m s^{-1} per 30 years, respectively. The diversity in NSW changes between these two groups, despite identical external forcing, underscores highlighting the significant role of internal variability in influencing South Asian NSW.



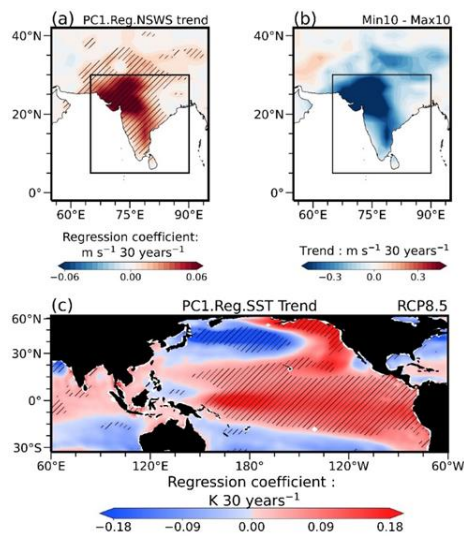


Figure 2. The leading inter-member EOF pattern of the NSWS trend over South Asia and the associated sea surface temperature trend under the RCP8.5 scenario between 2021 and 2050. (a) The first mode of an EOF analysis was that applied to the 400 members' NSWS trends over South Asia (5°N–30°N, 65°E–90°E) in MPI-ESM, with the Inter-member index replacing the time index in a conventional EOF analysis based on a $100 \times N$ matrix, where N is the number of grid points over South Asia. (see Method). (b) The group differences between the mean trend of the ten members with the highest decline in NSWS over South Asia and the ten members with the highest increase. The box in (a) and (b) highlights the South Asia region. (c) The regression pattern between the PC score of (a) and the sea surface temperature trends of corresponding members. Slashes denote regions are significant at the 95% confidence level.

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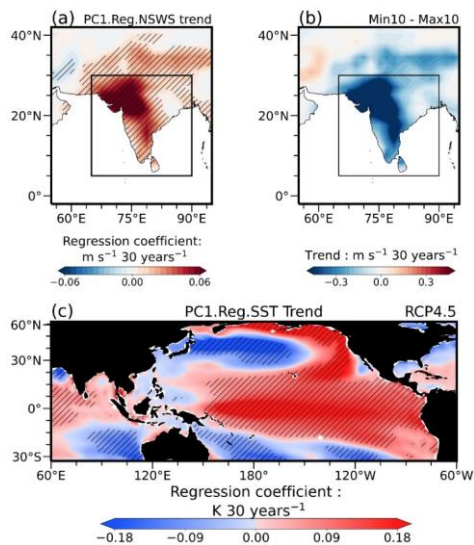
To identify the leading mode of internal variability affecting NSWS and its associated SST pattern, we performed an inter-member EOF analysis. As shown in Fig. 2a, NSWS exhibits a uniform enhancement across South Asia, accounting for 54.6% of the total variance. This spatial pattern closely resembles the trend differences observed between the Max10 and Min10 groups (Fig. 2b), indicating that the EOF analysis successfully captures the leading mode of NSWS variability among members. Internal climate variability stems from the natural fluctuations of the climate system that occur in the absence of external forcing, arising from the non-linear dynamical processes intrinsic to the climate system, the ocean, and particularly the coupled ocean-atmosphere system, with ocean-atmosphere coupling playing a crucial role (Deser et al., 2010). The regression coefficient between the leading PC of NSWS trends and the SST trends of corresponding members from 2021 to 2050 is shown in Fig. 2c. The regression analysis reveals a significant cooling trend over the North Pacific and a significant warming trend over the tropical central-eastern Pacific, resembling a classical IPO-like mode (Mantua and Hare, 2002a). This alignment highlights the IPO's role in modulating large-scale tropical atmospheric circulation, suggesting a strong link between surface and low-level tropospheric winds over South Asia. Moreover, to assess the robustness of these findings under different warming scenarios, we compared the results from the RCP4.5 scenario with those under RCP8.5, finding that the spatial patterns are quite similar (Fig. 3).

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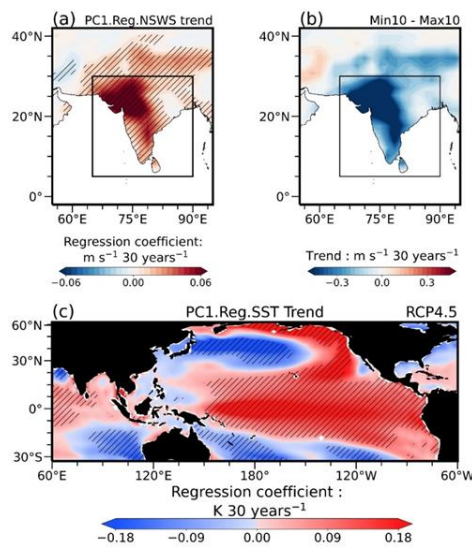
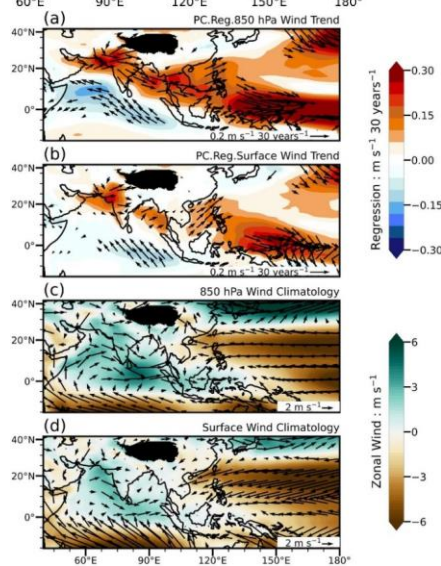
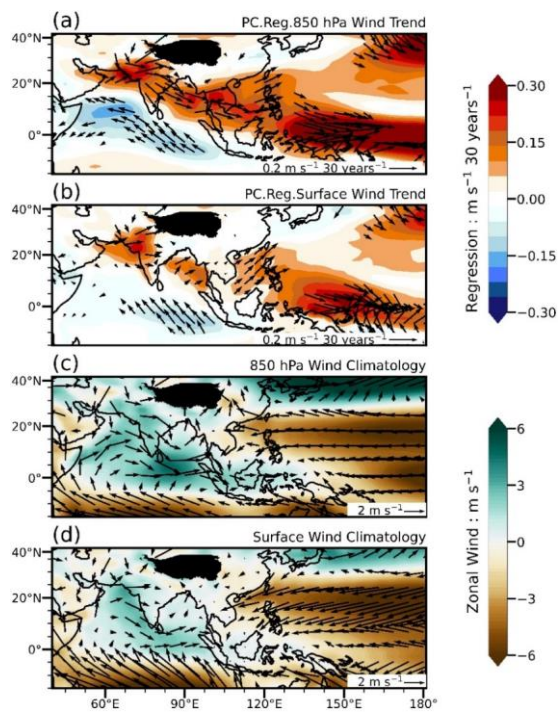


Figure 3. The leading inter-member EOF pattern of the NSWS trend over South Asia and the associated sea surface temperature trend under the RCP4.5 scenario between 2021 and 2050. (a)–(c) Same as in Figure 2, but for the representative concentration pathway 4.5 (RCP4.5).

3.2 Quantifying the contribution of IPO

Previous works have seldom [explored the connection between](#) low-level tropospheric winds [with](#) NSWS (Wu et al. 2017). [However, changes](#) in low-level tropospheric winds [can affect](#) the vertical distribution of momentum, [thereby](#) leading to changes in wind shear between different atmospheric layers ([Jacobson and Kaufman, 2006](#)). Figure 4 illustrates the regression coefficient between the leading PC of NSWS trends and the trends in winds at 850 hPa and 10m. During the positive phase of the IPO, anomalous easterly winds over the tropical Indian Ocean are observed (Fig. 4a). This anomaly in tropical oceanic low-level tropospheric winds counteracts the climatological mean state (Fig. 4b), suggesting a weakening of the Walker Circulation. The resulting anomalous descending motion triggers anticyclonic circulation to the northwest of the Maritime Continent, akin to the Gill response (Gill, 2007). The associated westerly winds, part of this anticyclone pattern near the Indian Ocean, enhance the climatological westerlies over South Asia. The MPI-ESM also provides data on surface meridional and zonal winds, allowing for exploration of the relationship between winds at 850 hPa and the surface. The spatial distributions of the regressed and climatological 10m winds (Figs. 4c and 4d) closely resemble those of the 850 hPa winds over South Asia (Figs. 4a and 4b), highlighting the consistency of atmospheric circulation changes within the region's lowest atmospheric layer.

To quantify the IPO’s effect on NSWS changes over South Asia in the near future, we isolated the IPO-related NSWS changes by removing the NSWS changes linearly related to the IPO index in each member (see Section 2.56). Histogram analysis reveals a narrowing in the distribution of NSWS trends over South Asia after removing the IPO’s effect, with the standard deviation in the members’ trends decreasing by approximately 8%, from 0.09 to 0.08 m s⁻¹ per 30 years (Fig. 5a). Although
250 modest, these reductions suggest that the uncertainty in NSWS trend projections over South Asia could be reduced by improving our ability to predict the IPO in the future. Applying this method to far-future projections for the 21st century (2021–2095) further confirms the sensitivity of these conclusions to the selected period and underscores the significance of long-term changes, which can be compared with inter-decadal variability in the near future. As expected, by eliminating the IPO’s influence, projection uncertainty is significantly reduced by 15%, nearly double the reduction observed in the near future
255 (Fig. 5b).



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Figure 4. Large-scale circulations associated with the inter-member EOF and climatological circulations under the RCP8.5 scenario between 2021 and 2050. (a) The regression pattern between the PC score and the trends of corresponding members' zonal wind (shading) and wind (vector) at 850 hPa. Shading and vectors denote significance at the 0.10 level. (b) Climatological zonal wind (shading) and wind (vector) at 850 hPa from 2021 to 2050 across all members of MPI-ESM. (c) Same as (a), but for winds near the surface. (d) Same as (b), but for winds near the surface.

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Notably, a recent study shows that over land in Asia, projection uncertainty is mostly dominated by model uncertainty, with internal variability accounting for around 20% of the total uncertainty (Zhang and Wang, 2024). This highlights the significant role of the IPO, whose contributions of 8% and 15% represent 40% and 75% of the internal variability in different future periods, respectively. This robust quantification supports the conclusion that NSWs projections are significantly affected by the IPO, with its influence growing and extending through the end of this century.

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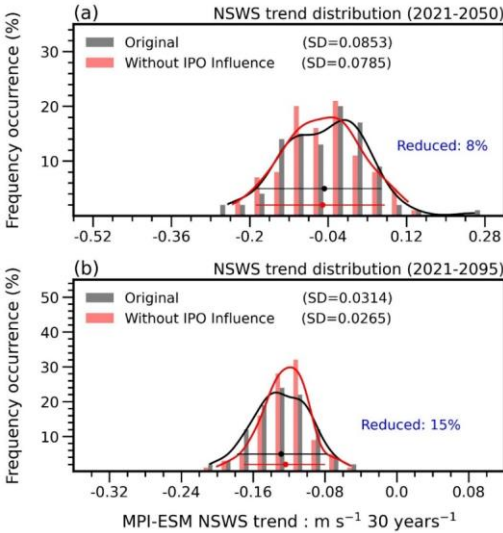
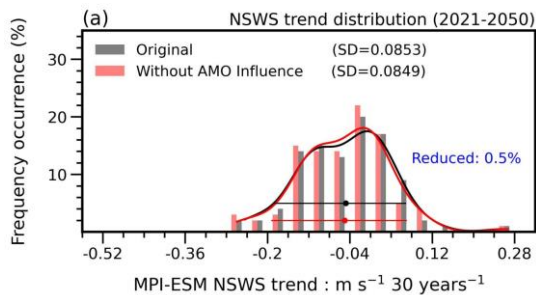


Figure 5. Histograms of the NSW trend over South Asia in the future under the RCP8.5 scenario with and without the impact of the IPO. (a) Histograms and fitted distribution lines of the area-averaged South Asian NSW trend derived from the 100 MPI-ESM ensemble members from 2021 to 2050. The gray bars and black fitted curves show the frequency of the occurrence of NSW trends, while the red bars and red fitted curves represent the frequency of NSW trends with the IPO's influence removed through linear regression against the IPO index in individual runs. (b) Same as (a), but for the period from 2021 to 2095.

4 Conclusion and Discussion

275 In this study, LEs from the MPI-ESM are used to project future changes in NSWS over South Asia. We identify the IPO as the leading mode of internal variability affecting South Asian NSWS in the near future. A positive IPO phase ~~is conducive to~~ ~~enhance~~ ~~enhances~~ westerly ~~flows~~ ~~winds~~ over South Asia, ~~leading to an increase~~ ~~resulting in~~ ~~increased~~ NSWS. Furthermore, we quantify the ~~impact~~ ~~influence~~ of the IPO, ~~finding and find~~ that ~~the~~ ~~removing its impact can reduce~~ uncertainty in NSWS projections ~~could be reduced~~ by approximately 8% in the near-term and 15% in the long-term ~~after removing the IPO's effect~~.
280 While these reductions may seem modest, they are ~~crucial~~ ~~important~~ for regional planning, ~~especially~~ ~~particularly~~ in wind-sensitive sectors such as energy production, agriculture, and disaster ~~risk~~ management.
Our findings significantly ~~enhance~~ ~~improve~~ the understanding of the ~~linkage~~ ~~relationship~~ between internal variability and regional NSWS changes. Given the substantial IPO-related uncertainty ~~in~~, future NSWS changes, ~~future research~~ ~~studies~~ should also consider other internal interdecadal climate variabilities that ~~could impact~~ ~~may affect~~ NSWS. The AMO, ~~for instance~~, is
285 another important oscillation known to influence tropical atmospheric circulation (Zhang et al., 2019). However, ~~our analysis~~ ~~using~~ a similar quantification method ~~shows~~ ~~reveals~~ that the AMO's contribution to NSWS changes is minimal, ~~underscoreing~~ ~~further highlighting~~ the ~~IPO's predominance~~ ~~dominant role of the IPO~~ in ~~influencing~~ ~~modulating~~ NSWS over South Asia in the near future (Fig. 6)-6). The limited impact of the AMO on projected NSWS may partly be due to its longer oscillation period, which ~~reduce~~ its relevance over shorter time scales and may be masked by external forcings over longer
290 periods. Additionally, the large geographic distance between the Atlantic and South Asia likely weakens the AMO's influence via teleconnection pathway, especially under strong external forcings.

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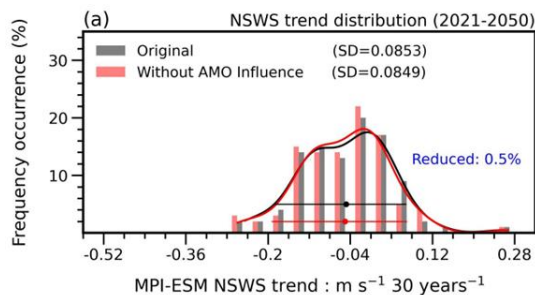


Figure 6. Histograms of the NSWS trend over South Asia under the RCP8.5 scenario with and without the impact of the AMO between 2021 and 2050. (a) Histograms and fitted distribution lines of the area-averaged South Asian NSWS trend derived from the 100 MPI-ESM ensemble members from 2021 to 2050. The gray bars and black fitted curves show the frequency of the occurrence of NSWS trends, while the red bars and red fitted curves represent the frequency of NSWS trends with the AMO's influence removed through linear regression against the AMO index in individual runs.

To date, few studies have systematically evaluated the ability of MPI-ESM, comparing to other models, to simulate the mechanisms by which the IPO influences atmospheric variables and associated SST variability in the western Pacific and Indian Oceans. Nonetheless, existing research has shown that MPI-ESM performs reasonably well in simulating key features of the Indian and East Asian summer monsoons (Guo et al., 2016). Similarly, studies by Prasanna et al. (2020) and Henley et al. (2017) indicate that CMIP5 models, including MPI-ESM, can generally reproduce the IPO and associated circulation features over South Asia. Furthermore, MPI-ESM has been applied in past studies to investigate IPO-related variability and has demonstrated some skills in capturing its key spatial and temporal characteristics (Huang et al., 2020a; Huang et al., 2020b), lending confidence to its representation of internal variability in this study. However, Henley et al. (2017) also noted that many CMIP5 models underestimate the ratio of decadal-to-total SST variance, suggesting that the IPO's actual influence on variables like NSWS may be stronger than currently simulated.

The resolution of the LE used in this study may not be high enough, limiting the climate model's ability to simulate regional details of NSWS in South Asia, where the terrain is which features complex. There is also room for improvement in this work, which remain and should be addressed in future research: (i) Future studies should incorporate additional LEs, with a sufficiently large ensemble size (Milinski et al., 2020), to enhance the robustness of these conclusions, which currently rely heavily on this model. (ii) The "hist-resIPO" experiment in CMIP6 historical simulations (Zhou et al., 2016), which includes all forcings used in CMIP6 historical simulations but restores SST to model climatology plus observed historical anomalies in the tropical IPO domain, could provide deeper insights into the dynamic mechanisms of IPO-related tropical SST's influence on regional NSWS changes. (iii) Future improvements in predicting the IPO, potentially achievable through the Decadal Climate Prediction Project (Milinski et al., 2020), to enhance the robustness of these conclusions that currently rely heavily on a single model. (ii) The "hist-resIPO" experiment in CMIP6 (Zhou et al.,

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2016), may enhance the reliability of NSWS projection over South Asia, which includes all forcings used in CMIP6 historical simulations but restores SST to model climatology plus observed historical anomalies in the tropical IPO domain, could offer deeper insights into the dynamic mechanisms through which IPO-related tropical SST's influence on regional NSWS changes. (iii) Improvements in IPO prediction, potentially achievable through the Decadal Climate Prediction Project in CMIP6, may enhance the reliability of future NSWS projections over South Asia (Zhou et al., 2016).

325 Additionally, future research should focus on extreme wind events against the backdrop of consistently decreasing average NSWS, especially with the background as year-maximum NSWS events are projected to increase in frequency in South Asia (Yu et al., 2024).

330 Although this study emphasize the role of the IPO in reducing NSWS projection uncertainty over South Asia, accurately predicting decadal IPO variations remains a major challenging (Pang et al., 2025). This limitation hampers the reliability of regional wind projections and highlights the need for improved prediction of internal climate variability. In addition, because our analysis is based on a single-model ensemble, the projection spread reflects internal variability only. Inter-model uncertainty, shown in other studies to exceed any single mode of internal variability, has yet to be assessed and should be a focus of future multi-model research. Finally, extreme wind events under a background of declining mean NSWS also merit attention, particularly as year-maximum NSWS events are projected to become more frequent in South Asia (Yu et al., 2024; Zha et al., 2023).

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Competing interests

The contact author declares that none of the authors have any competing interests.

Author contribution

All authors reviewed and revised the manuscript. C.S. and D.C planned and designed the study. C.S and H.S.Y conducted the visualization and analysis.

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Code and data availability

All datasets used in this study are publicly available. ERA5 reanalysis data is available at Hersbach et al. (2020). CRA40 reanalysis data is available at Liu et al. (2023). JRA55 reanalysis data is available at Kobayashi et al. (2015). MPI-ESM reanalysis data is available at Maher et al. (2019). The [Python](#) script used for generating and analyzing are available on request.

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