Analysis of future wind and solar potential over India using climate models

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Climate change is expected to impact future renewable energy production. Therefore, investors in this sector should understand and consider possible changes due to climate change. Here, we analyse the future wind and solar energy potential over the Indian landmass using climate model ensembles. Our analyses reveal that, in future, seasonal and annual wind speed is likely to decrease over North India and increase along South India. On the other hand, solar radiation is estimated to decrease (10–15 Wm^{-2}) over the next 50 years during all seasons. With the estimated decrease in future wind and solar potential, expanded and more efficient networks of wind and solar farms are needed to increase renewable energy production.

Keywords: Climate models, future renewable energy, solar radiation, wind and solar potential, wind speed.

THE Assessment Reports 5 and 6 (AR5 and AR6) of the Intergovernmental Panel on Climate Change (IPCC) guide our knowledge in analysing and moderating the world energy requirements from a climate change perspective[1]. According to the latest sixth assessment report (AR6) of IPCC, human influence in contributing to the warming of the global climate system is unequivocal and it is extremely likely (95%) that human influence is the dominant cause for global warming over the recent decades. The contributions from other natural causes, which include volcanoes, and variation in solar energy are minimal. The major human influence in global warming is through burning of fossil fuels[2], which leads to the release of greenhouse gases (GHGs)[3,4]. As the United Nations tries to stabilize GHG concentration in the atmosphere through numerous agreements, the shift towards renewable energy from fossil fuels is gaining more strength and this is seen as the main step towards reducing global warming. In the last two decades, renewable energy production has seen significant growth worldwide. In 2018 alone, renewable energy accounted for more than 25% of the world's energy production, which is expected to reach up to 80% by 2050 (refs 5, 6).

Renewable energy includes hydroelectric power, wind energy and solar energy as its major constituents. Geothermal energy and bioenergy also constitute a lesser amount of global renewable energy production. In India, renewable energy generation supported 23% of energy production in 2019. This is expected to increase up to 40% in 2030 (ref. 7). With proper planning and infrastructure, renewable energy can entirely support the growing energy demands in the future. Hydroelectric power over the Indian landmass shows a promising future with increased potential in climate projections[8]. The other major components of renewable energy, such as wind and solar, are sensitive to even small changes in atmospheric conditions and therefore, to climate change[9,10]. Variations of wind speed in the order of 1 m/s can change the wind energy drastically as power is proportional to the velocity cubed[11]. Any change in wind shear and direction can alter energy production significantly in the existing wind fields[12,13]. Climate change can induce interannual variations that affect wind dependence over existing and future energy grids. Climatic influence on the future wind energy potential was studied globally[14], in the European countries[15,16], North America[17] and East Asia[18,19]. India mainly receives majority of its wind energy during the southwest monsoon and solar energy during the pre-monsoon season. If the return of investments during other seasons is not profitable, the dependence on renewable energy may be reduced. Previous climatic analysis has reported that the wind potential over India is likely to be affected because of the Indian Ocean warming[20].

Climate models provide a wide array of information to analyse how renewable energy sources were available in the past and how they will be available in the future. They also use various scenarios to understand how the future will evolve. Climate models assessed as part of the IPCC, such as Coordinated Regional Climate Downscaling Experiment (CORDEX), Coupled Model Intercomparison Project phase 5 (CMIP5)[21] and phase 6 (CMIP6) are used to derive the future climatic projections over various parts of the Earth. CORDEX experiments are dynamically downscaled regional climate models which are a subset of CMIP5. Thus, CMIP5 and CORDEX are not independent. AR5 is used to study the past, present and future climate changes. IPCC has currently released AR6 to improve the climate projections in AR5. CMIP6 datasets, generated from AR6 projects, will be made official by 2022. For AR6, various coupled model projections are

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being carried out. AR6 is aimed to be an improvement for climate studies and uses a new set of shared socio-economic pathway (SSP) scenarios. Even though CMIP experiments provide a better understanding of the future global climate, experiments involving regional climate models (RCMs), such as CORDEX, are expected to provide more details on a regional scale[22–25]. CORDEX experiments are high-resolution RCMs, which better resolve the fine-scale features of a terrain and land-use/land-cover characteristics that influence the regional climate and its response to regional forcings[26]. The biases in the climate models, where few of them differ by a large margin, can be mitigated by multi-model ensembles[27].

In India, renewable energy generation is gaining more support from the Government and private investors. Cost reduction for new wind farms and solar fields has made drastic changes in the investment in recent years[28]. Studies that examine the possible changes in wind and solar potential over the Indian region are limited in the literature. As climate change is expected to impact both wind and solar potential in the future, there is a requirement for proper documentation of the results from climate model simulations. This will help the investors in this sector to carefully plan their investments, which are expected to significantly increase in the next 30–40 years in the Indian region. With this objective, the present study aims to evaluate the projected change in wind and solar energy potential over the Indian landmass using various climate models for the near future.

Data and methodology

Data

In this analysis, we have used CMIP5 and CMIP6-based climate model outputs to examine solar and wind energy potential over the Indian landmass. For solar energy analysis, we have used daily downward solar radiation, whereas for wind energy analysis we have used daily horizontal wind components at 10 m height, interpolated to 100 m using the power law.

The world climate research program (WCRP)-supported CORDEX-SA (CORDEX hereafter) provides an ensemble of RCM projections for South Asia[29,30]. All CORDEX RCMs follow a common experiment protocol, including a predefined domain at 50 km resolution, common output variables and a format that facilitates assessment of projected climate changes in South Asia. The CORDEX simulations over the South Asian region have been generated by the Indian Institute of Tropical Meteorology (IITM), Pune, by dynamical downscaling of six CMIP5 global climate model outputs using the International Centre for Theoretical Physics (ICTP) regional climate model (RegCM4) guidelines (a description is provided in the Supplementary Material A). The data are in 0.5° × 0.5° resolution, which were interpolated (using bilinear interpolation technique) to 1° × 1° (the added value of dynamical downscaling of global climate model (GCM) outputs to higher resolution will not be seen if the RCM outputs are interpolated to coarser resolution; however, we have done it for comparison consistency).

CMIP5 climate model simulations have been carried out worldwide to assess climate on a decadal to centennial scale-based on the influence of anthropogenic GHG emissions[21]. The future climate projections using CMIP5 atmosphere–ocean coupled global climate models (AOGCMs) reference concentration pathways (RCPs) are driven by the radiative forcing deduced from different scenarios of anthropogenic emissions of GHG, land-use change and industrial aerosols[31]. Climate projections externally forced with two RCP scenarios are used in this analysis: high emissions scenario (RCP8.5) and medium emissions scenario (RCP4.5). RCP8.5 imposes 8.5 Wm^{-2} of radiative forcing due to GHGs at the end of the 21st century, whereas RCP4.5 imposes 4.5 Wm^{-2} of radiative forcing. Daily outputs from the ensembles of multi-CMIP5 models were used in wind and solar potential analysis (Supplementary Material A). The robustness of the usage of CMIP5 models in climatic analysis has been examined in several previous studies[32–34].

In the IPCC AR6 (ref. 35), future projections of different scenarios also known as SSPs, are being introduced in CMIP6 (ref. 36). The SSPs define five different ways in which the world might evolve with different climate policies and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with SSPs. These include SSP1: a world of sustainability-focused growth and equality; SSP2: a 'middle of the road' world, where trends broadly follow their historical patterns; SSP3: a fragmented world of 'resurgent nationalism'; SSP4: a world of ever-increasing inequality, and SSP5: a world of rapid and unconstrained growth in economic output and energy use. SSP2 is similar to RCP4.5 and SSP5 is similar to RCP8.5 of CMIP5. Daily outputs from the ensembles of multi CMIP6 models were used in wind and solar potential analysis (Supplementary Material A).

The historical simulations of the CMIP5 framework ended in 2005, whereas CMIP6 ended in 2015. We have maintained this for comparison consistency. The analysis started in 1951 and ends in 2070 for all climate models. For comparison purposes, we have used the climatology and probability density function (PDF) employing daily wind speed from the National Centers for Environmental Prediction (NCEP) reanalysis data for the years 1951–2005 (ref. 37). The original model output of 2.5° × 2.5° resolution is interpolated to 1° × 1° grid (using bilinear interpolation technique) and the daily average wind speeds for the locations in Table 1 are extracted. For comparison of solar climatology, downward solar radiation from MERRA reanalysis data is extracted from 1979 to 2015 and averaged[38].

Table 1. Coordinates of the locations used in wind and solar potential analysis

Wind potential		Solar potential	
Location	Coordinates	Location	Coordinates
Tamil Nadu	10°–12°N, 77°–79°E	Gujarat	22°–25°N, 67.5°–70.5°E
Karnataka	14°–16°N, 75°–77°E	Western Rajasthan	25.5°–28.5°N, 69.5°–72.5°E
Andhra Pradesh	17°–19°N, 81°–83°E	Eastern Rajasthan	25.5°–28.5°N, 74.5°–77.5°E
Gujarat	21°–23°N, 70°–72°E	Maharashtra	17.5°–22.5°N, 74.7°–77.7°E
Rajasthan	26°–28°N, 72°–74°E	Madhya Pradesh	23°–26°N, 80°–83°E
Jammu and Kashmir	33°–35°N, 75°–77°E	Andhra Pradesh	12.5°–15.5°N, 76°–79°E

Methodology

In this study, we have considered CORDEX-SA, CMIP5 and CMIP6 models to analyse solar and wind potential over the Indian peninsular region. For CORDEX and CMIP5 analysis, the historical simulations comprise data from 1951 to 2005, whereas the future climate simulations are analysed from 2006 to 2070. For CMIP6 analysis, the historical simulations comprise data from 1951 to 2015, while the future model simulations are from 2016 to 2070. The models are interpolated over a constant resolution of 1° × 1° horizontal grids, and the ensemble annual and seasonal means are calculated for historical and future projections separately.

The analysis consists of two parts. One is spatial analysis over entire India and the second is location analysis of selected energy farms over different parts of the country. The energy farms are selected from regions of different states having considerable investment in the renewable energy sector. In spatial analysis, variations in the historical and future projections are studied from the ensemble of climate models annually and seasonally. The differences in wind and solar potential between future and past will show how the climate will change in the near future. Supplementary Figure F1 shows the locations of wind and solar farms across India that have been considered in this study. Location analysis will give the projections needed for future investments in these regions. For the analysis, daily climatology and PDFs of the ensemble means were compared between historical and future projections.

The differences in the future and historical ensemble means were analysed to determine the multi-model ensemble mean changes to the present climate in solar and wind speed. Seasonal analyses of the models were also done to determine the season of maximum variations. The seasons were selected based on the climate of India and are defined as follows: December to February – winter, March to May – pre-monsoon, June to September – monsoon and October and November – post-monsoon seasons. To find the reasons for variations in solar radiation, cloud fraction from the CMIP6 model was also analysed for its differences. This was done because the cloud fraction influences solar radiation more than any other parameter. To check the statistical significance of the results, *t*-test was performed over the differences in the trend from daily ensemble means and the regions with significant variations (99% confidence interval) are shown as dotted areas in the spatial figures. Statistical significance tests were conducted on the basis that the differences in the models broadly follow a normal distribution. The normality test for the differences is provided in Supplementary Material B.

The energy potential of six wind and six solar farms in India was analysed to observe how the future potential will be. A 3° × 3° grid box was extracted around these regions, and the average wind and solar radiation for each day were estimated.

For wind speed analysis, wind speed at 10 m height, which was extracted from the models, was extrapolated over the average turbine hub height at 100 m using the power law as

$$\frac{U_z}{U_{z_r}} = \left(\frac{z}{z_r}\right)^{\alpha},$$

where U_z is the wind speed at height z (100 m), U_{z_r} is the reference wind speed at height z_r (usually 10 m), and α is the power law exponent. For locations far away from the coast, α was taken as 0.2 and for ocean regions, α was taken as 0.14 (ref. 39). The value of α depends on factors such as air temperature, turbulence, elevation, season, orography, etc. Since this study has been performed to get an understanding of the future potential in a broad manner, a constant exponent is used here. As we are focused on wind potential over the Indian landmass, we have chosen α as a constant (0.2) throughout our estimation. In the literature, this type of analysis using constant α has been done before over other regions[40–42]. In this study, we do not compare current climate models, but make an effort to understand how the future solar and wind projections are represented in each of them. Also, the models may differ from each other in the projections as they have different sources and methods of simulation. In this study, we observe how the trend of wind and solar potential changes in the ensemble mean of these climate models.

Results and discussion

Projected changes in multi-model ensemble annual means

Wind: Figure 1 compares the difference between the ensemble means of wind speed from historical and future

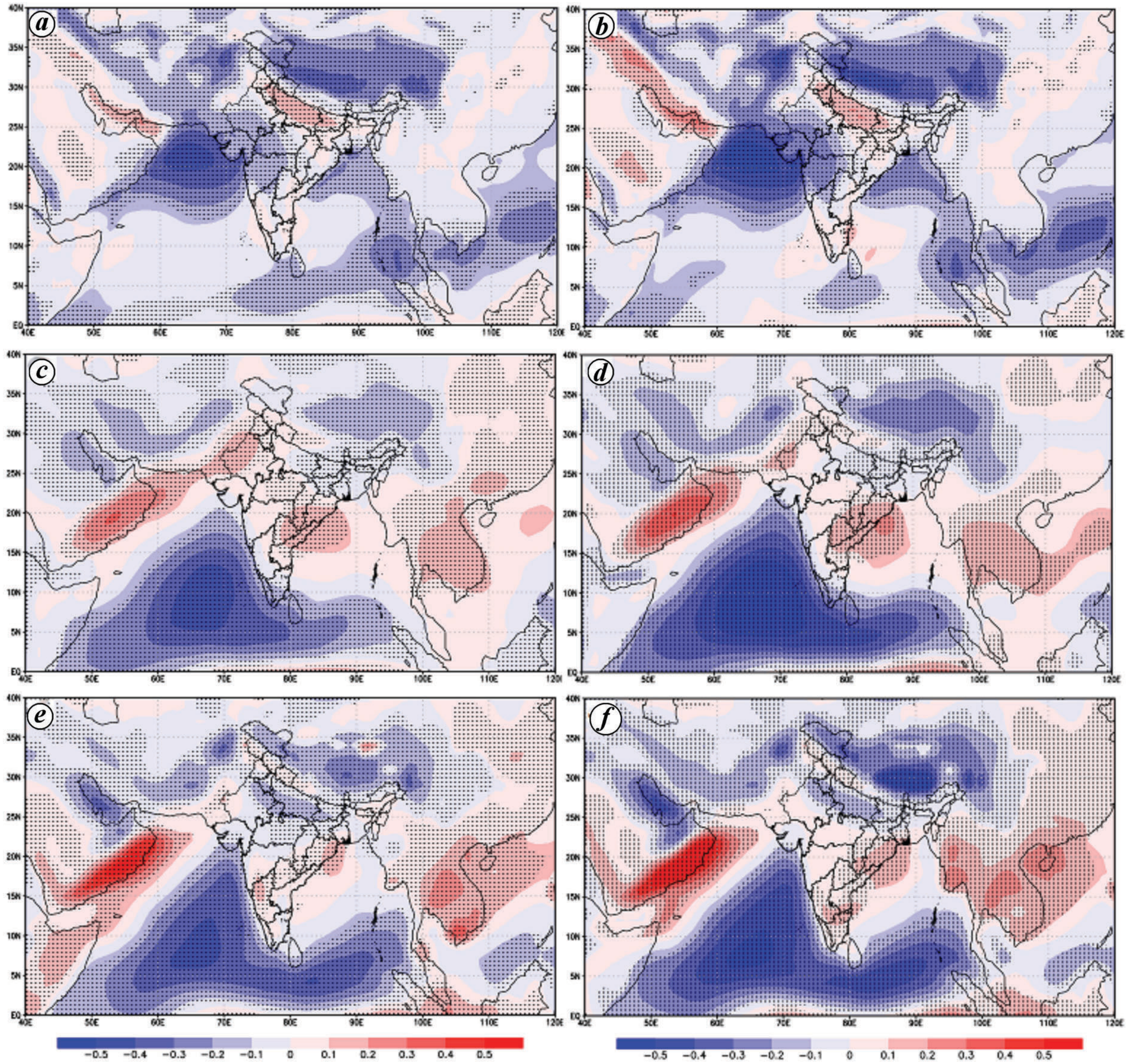

Figure 1. Difference between the ensemble means (mean of 55 years in the historical and future projections) of wind speed from (***a***) CORDEX RCP4.5 and historical, (***b***) CORDEX RCP8.5 and historical, (***c***) CMIP5 RCP4.5 and historical, (***d***) CMIP5 RCP8.5 and Historical, (***e***) CMIP6 SSP2-4.5 and historical and (***f***) CMIP6 SSP5-8.5 and historical. Dots represent regions with 99% significance.

projections from a multi-model mean of climate models. In the CORDEX simulations, wind speed in the future projections is found to increase in the Gangetic plains and decrease along the western coast of India. The eastern and southeastern parts of India show little change, whereas the eastern offshore regions show a reduction in wind speed. The differences are enhanced with the RCP 8.5 ensemble (Figure 1 *b*). In the CMIP5 simulations, northwest India shows an increase in wind speed while the western coast shows a decrease in wind speed. All the models reveal that wind speed in the west coast offshore regions will decrease in the future, but the CMIP simulations show that the inland wind speed over south-central India will slightly increase. The Gangetic Plains show an increase in wind speed in CORDEX simulations, while they show a decrease in both the CMIP ensembles. Along northwest India, near Rajasthan, we observed an increase in wind speed in the CMIP simulations. Majority of the climate experiments indicate that the wind fields over southern and northwestern India will increase in the future, whereas the offshore winds near western India will decrease. The difference between different decades and historical means from the CMIP6 experiments are shown in Supplementary Material C. The analysis shows that the variations get stronger with time,

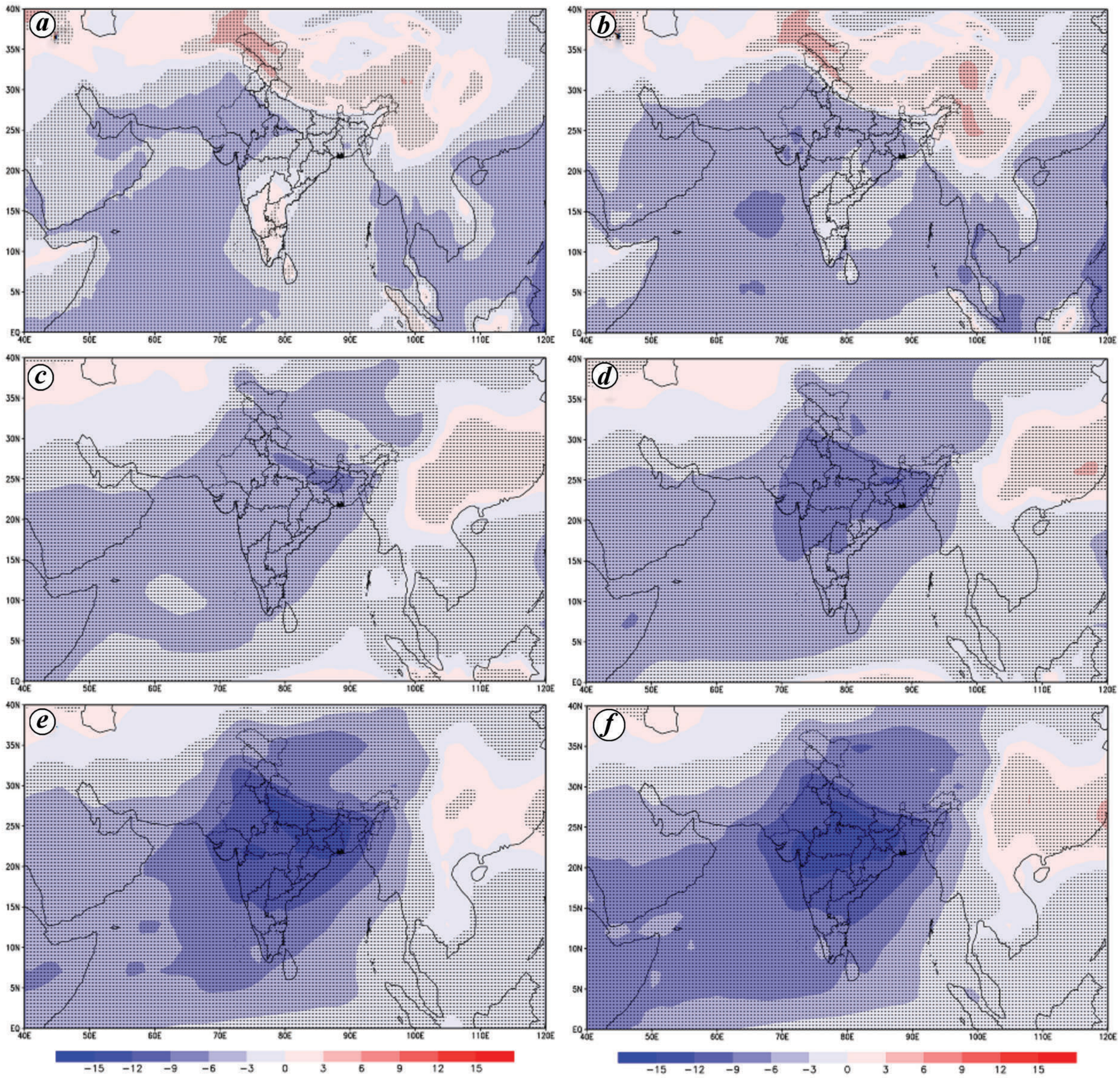

Figure 2. Difference between the ensemble means of solar radiation from (***a***) CORDEX RCP4.5 and historical, (***b***) CORDEX RCP8.5 and historical, (***c***) CMIP5 RCP4.5 and historical, (***d***) CMIP5 RCP8.5 and historical, (***e***) CMIP6 SSP2-4.5 and historical, and (***f***) CMIP6 SSP5-8.5 and historical. Dots represent regions with 99% significance.

but signatures of variations are present in the near future as well. The differences become stronger from 2030 onwards and follow the trend shown in Figure 1.

Solar: Figure 2 compares the difference between the ensemble means of solar radiation from the historical and future projections from different models. Figure 2 *a* shows the difference between RCP4.5 and historical from CORDEX simulations. It reveals that solar radiation along the western and northwestern bay will reduce in this scenario from the historical mean. This is further emphasized in Figure 2 *b*, where RCP8.5 is compared with historical simulations. Along southern India, we notice few changes in CORDEX simulations. The CMIP5 analysis shows major changes occurring along central India with prominent changes in the foothills of the Himalayas (northeastern India; Figure 2 *c* and *d*). The differences from the RCP8.5 ensemble have stronger signals in this region than RCP4.5. The CMIP6 ensemble analysis also shows similar results. The main regions of change are central India and the foothills of the Himalayas. The reduction is maximum in the CMIP6 ensemble mean for future predictions (>8 Wm^{-2}). All the ensemble analyses for future projections estimate that solar radiation over the Indian subcontinent will reduce in the immediate future. Similar to decadal wind speed analysis, we have added decadal solar differences from CMIP6 experiments (see Supplementary Material C as well). Supplementary Material C (Figures C3 and C4) show that

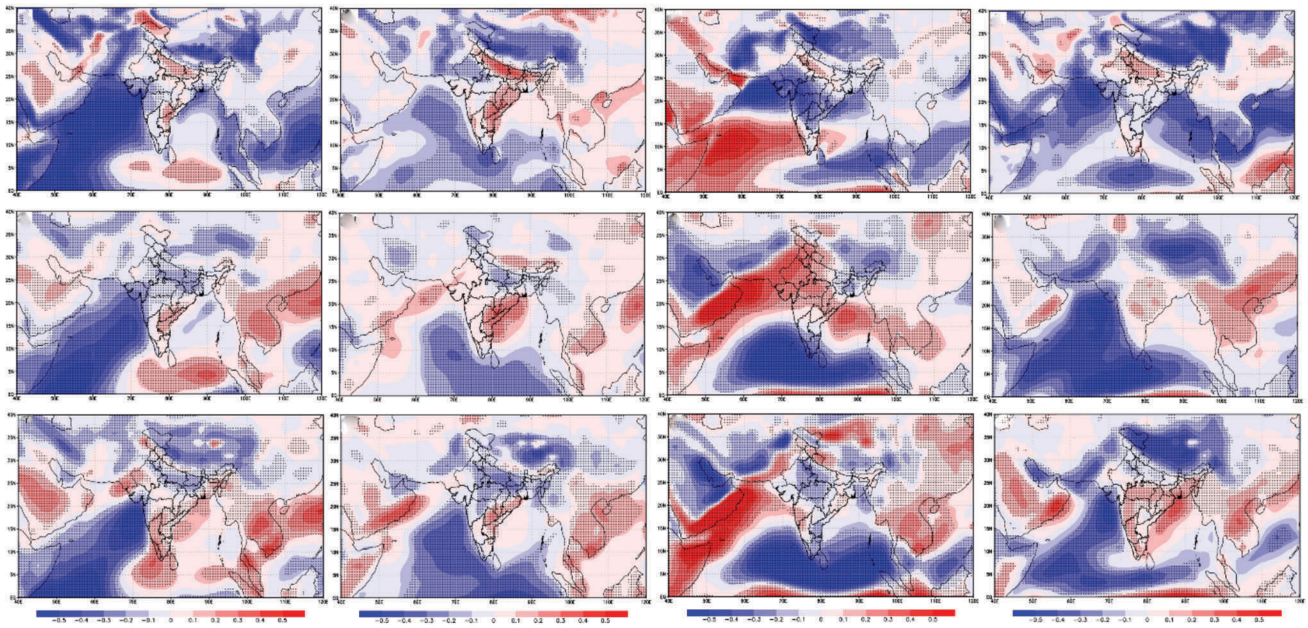

Figure 3. Difference between seasonal ensemble means of wind speed between RCP4.5 and historical data. Top row is from CORDEX, middle row from CMIP5 and bottom row from CMIP6 models. First column is from winter, second column from pre-monsoon season, third column is from monsoon season and fourth column from post-monsoon season. Dots represent regions with 99% significance.

solar radiation will be the lowest in the future decades, and improve along the central and south-central India in future (2040–70). Solar radiation and wind speed are not uniform throughout the year, and thus their potential also varies with changing seasons. Hence, seasonal variations in these future projections were analysed. A similar analysis over the entire Earth for wind and solar potential is shown in Supplementary Material D.

Seasonal variations in projected multi-model ensemble mean changes

Wind: The wind speed over India shows a bimodal variation with a maximum during winter months and another maximum during monsoon months. Summer and post-monsoon seasons record some of the lowest winds over the subcontinent. The differences between seasonal ensembles of wind speed from historical and RCPs were compared for CORDEX, CMIP5 and CMIP6 (Figure 3 and Supplementary Figure F2). In CORDEX simulations, future wind speed increases along the Gangetic plains during all seasons. The wind speed along central and western India decreases in the monsoon months, whereas along southeastern India, it is estimated to increase in the future winter and pre-monsoon months. In CMIP ensembles, future wind speed increases moderately along central India during the pre-monsoon months. Drastic changes are predicted along western offshore India during the post-monsoon and winter seasons. Southern India shows higher wind speed in the future predictions for most seasons, except for the monsoon period. During most seasons, there is an increase in wind speed along southeastern India, whereas the Gangetic plains show a decrease in wind speed compared to historical simulations. The CMIP analysis reveals that wind farms along southern, southeastern and northwestern India will be more beneficial compared to those from other regions. RCP8.5 differences show that future wind speed along southern India will increase, whereas in northern India, it will decrease or show a slight increase during all seasons.

Solar: The Indian subcontinent receives maximum solar radiation during the pre-monsoon months and minimum during the winter months. The seasonal ensemble means of solar radiation for different future scenarios were compared with historical simulations from CORDEX, CMIP5 and CMIP6 (Figure 4 and Supplementary Figure F3). The seasonal comparisons showed maximum variation during the monsoon months along central and northeastern India. During the pre-monsoon season, CORDEX simulations showed an increase in solar radiation along southern India, whereas the rest of the country did not show any significant variations. Except for the pre-monsoon months, northwestern India, where the maximum number of solar farms are located, showed reduced future projections of solar radiation throughout the year. The only regions which showed an increase in future solar projections were Ladakh, Himachal Pradesh and Uttarakhand. In Figure 4 *e–h* and Supplementary Figure F3 *e–h*, the seasonal ensemble mean from CMIP5 are compared between historical and future projections. Maximum variations were observed in

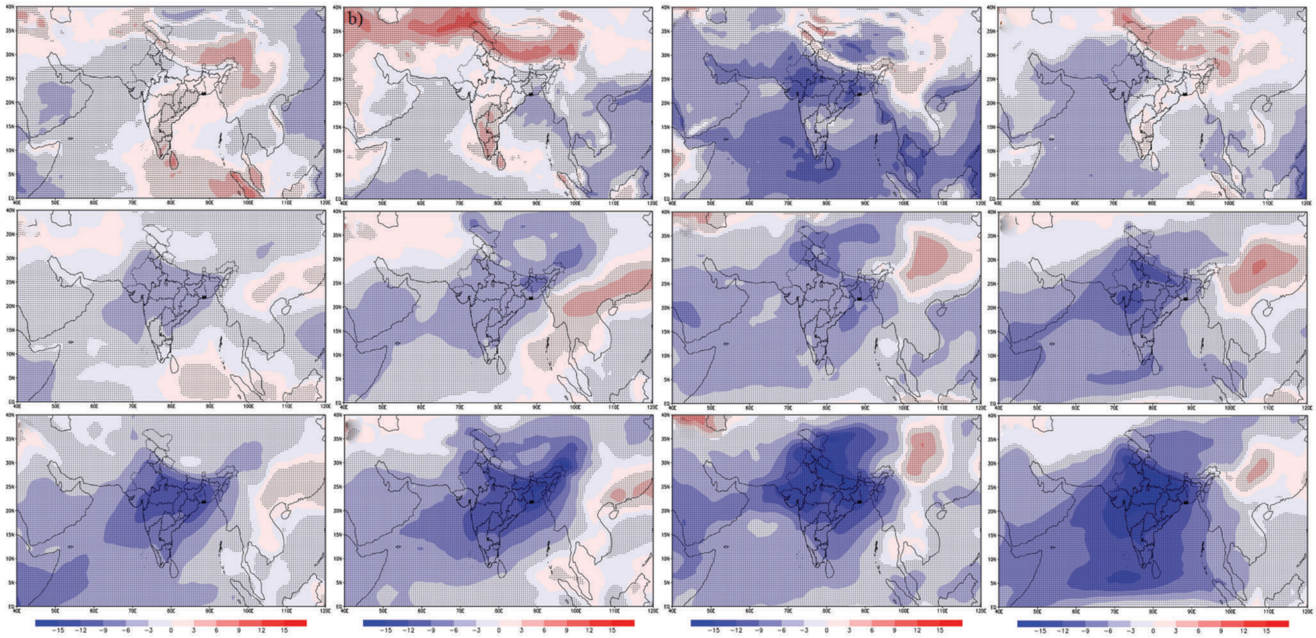

Figure 4. Same as Figure 3, but for solar radiation.

the post-monsoon season along central India. Both RCPs showed that the future solar radiation would reduce all over the country. Western India showed less variations during the prominent solar potential months of pre-monsoon, while eastern India showed reduction in solar radiation throughout the year. Figure 4 *i–l*, Supplementary Figure F3 *i–l* compare the seasonal ensembles from CMIP6 historical and future projections.

In CMIP6 simulations, the future solar radiation was lower than the historical values for almost all the months all over India. The maximum reduction in solar radiation was seen during the post-monsoon season, where the entire future projections over India have been affected. The CMIP6 ensemble means also show an east–west divide in the pre-monsoon season, with eastern India being the most affected, as in the CMIP5 simulations.

Projected changes in daily climatology at selected locations

Wind: The daily climatological wind speeds of various locations over India from historical and different RCPs were compared with NCEP climatology (Figure 5). Most of the locations showed bimodal variations in wind speed. The CORDEX projection recorded lower wind speed when compared to the CMIP projections. The monsoonal wind speeds over Tamil Nadu, Karnataka and Gujarat were higher in the NCEP data, which has also been recorded in the ensembles of CORDEX and CMIP. Over Rajasthan, the CMIP models predicted higher wind speeds than those recorded in the NCEP and CORDEX simulations. Over Andhra Pradesh and Jammu and Kashmir the wind speeds were low, but the ensembles were able to capture the variations in the simulations. The climatological analysis from all the models showed that the future projections had lower or equal wind speeds in the monsoon months when compared to the corresponding historical simulations.

Solar: The daily climatological solar radiation of various locations over India from historical and different RCPs was compared with MERRA climatology (Figure 6). From the climatological data, solar radiation remained above 200 Wm^{-2} for most of the years. It increased from winter to the beginning of the monsoon season. During the monsoon season, solar radiation decreased over all the locations. This is mostly due to the cloud formations associated with summer monsoon. After the monsoon season, solar radiation was found to increase during the post-monsoon season and attain an average value during winter season. In comparison, CORDEX outputs were closer to the MERRA data than the CMIP experiments. The CMIP experiments overestimated the summer solar radiation over most of the locations. In all climatological data, the trend and values of historical experiments were followed closely by the future experiments showing that the future will not have a large climatic shift in solar radiation.

Climatological distributions at selected locations

Wind: The PDF comparison between historical and future RCPs for daily mean wind speed over the locations in Table 1

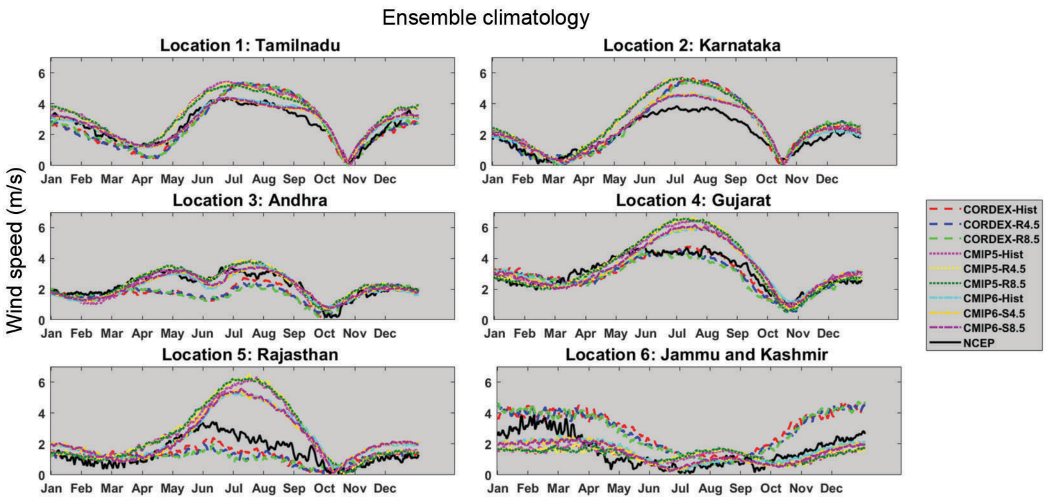

Figure 5. Daily climatology of wind speed from all historical and future projection ensembles of CORDEX and CMIP models compared with NCEP over the locations mentioned in Table 1.

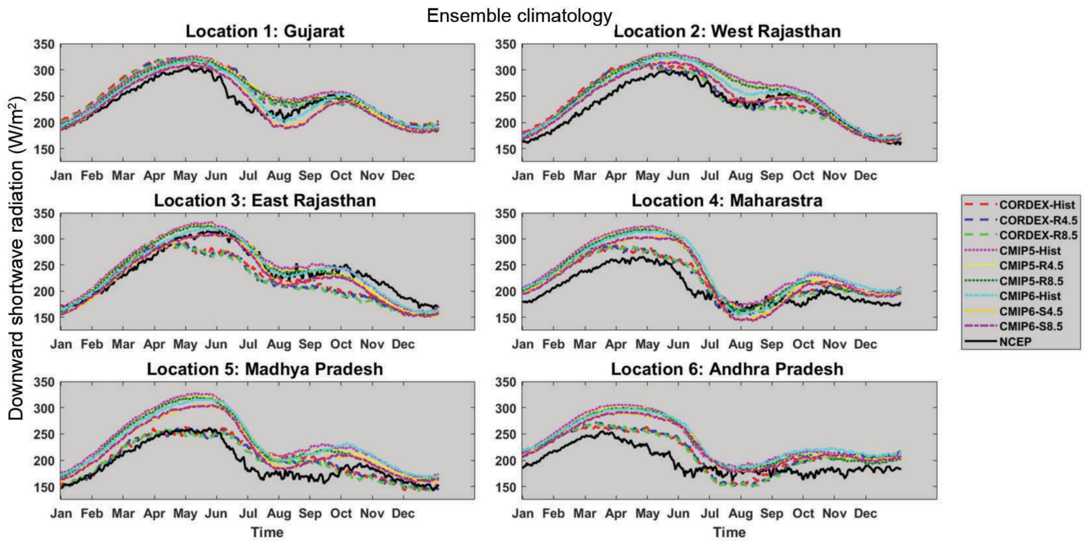

Figure 6. Same as Figure 5, but for solar radiation over locations in Table 1.

is given in Supplementary Figure F4 for the CORDEX, CMIP5 and CMIP6 simulations. The PDF spread from individual models is provided in Supplementary Material E. It can be noted that the CORDEX simulations have similar spread among themselves, whereas in the CMIP experiment, some of the models have different spread, which varies between different locations. In order to incorporate the effect of all the spreads, we have used ensemble means for the analysis. This ensemble reduces the extremities caused by different models and the differences from historical simulations are kept in check. In location 1 over Tamil Nadu, we found that CMIP5 showed a decrease in wind speed at higher velocities, while CMIP6 simulations indicated that higher velocities would increase substantially. In location 2, over Karnataka, CORDEX and CMIP5 experiments did not show any notable variation, but CMIP6 simulations showed a decrease in the frequency of lower and higher velocities and an increase in median wind speed. In location 3 over Andhra Pradesh, there was a slight increase in the frequency of higher velocities and a decrease in lower velocities in the CMIP5 and CMIP6 simulations. In location 4 over Gujarat, the frequency of wind <6 ms^{-1} increased while higher velocities showed a decreasing trend in all the simulations. The PDF in location 5 over Rajasthan did not have any noticeable change in the future projections compared to historical simulations in all ensembles. In location 6, over Jammu and Kashmir, we observed an increase in the frequency of lower velocities, while the higher velocities showed a decreasing trend. This reveals that, over most parts of India, wind power in the future is likely to be less than that in the present.

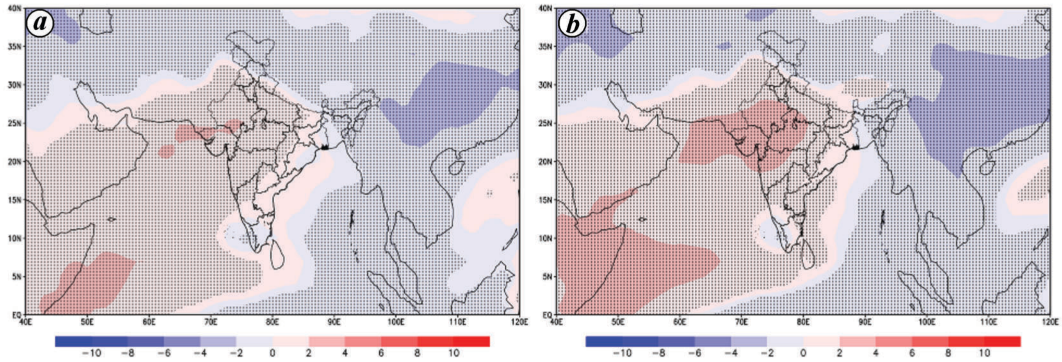

Figure 7. Difference between ensemble means of total cloud cover from CMIP6: (***a***) SSP2-4.5 and historical and (***b***) SSP5-8.5 and historical. Dots represent regions with 99% significance.

Solar: The PDF comparison between historical and future RCPs for daily mean solar radiation over the locations in Table 1 is given in Supplementary Figure F5 for the CORDEX, CMIP5 and CMIP6 simulations. The PDF spread from individual models is provided in Supplementary Material E. In this analysis, all the ensemble models predict that the future solar radiation will be lower than that observed in the historical simulations for all the locations. The reduction in solar radiation between historical and RCPs was less in CORDEX but more in the CMIP6 ensembles. In CORDEX, the deviations were not substantial but the solar potential was found to decrease. In CMIP5 and CMIP6, the shift in PDF was substantial in the range 10–15 Wm^{-2} over all the locations. The CMIP6 analysis revealed a substantial reduction in solar radiation. To verify this, we have considered cloud fraction estimates from the same models.

Total cloud cover

Similar to solar radiation, we plotted the ensemble means of historical and future projections of total cloud cover using the CMIP6 simulations. Figure 7 shows the difference between historical total cloud cover and SSPs. Supplementary Figure F6 shows the seasonal variation of the ensemble differences. The daily climatology and PDF of total cloud cover are given in Supplementary Figure F7 for all the locations used for solar potential analysis. The ensemble difference showed that the future projections of cloud cover are higher than those from the historical simulations over central and northwestern India. The seasonal analysis showed that this increase in cloud cover mostly occurred during the monsoon and winter months. The increase in cloud cover was enhanced in the SSP5-8.5 models when compared to SSP2-4.5. This is correlated to the lower solar radiation recorded in the CMIP5 SSP5-8.5 ensemble (Figure 2). The climatological analysis also suggested that the monsoon months in the future will have slightly higher cloud fractions. The shift towards the right side in the PDF analysis in Supplementary Figure F7 also supports the same.

Limitations of the present study

- The CMIP experiments are run with a coarser horizontal resolution on a global scale to gather a broader understanding of climate change. CORDEX experiments are conducted at a higher resolution to analyse the regional level impact of climate change. The skill of regional climate simulations from CORDEX experiments against their forcing GCMs has been evaluated before[43]. In this evaluation, deterioration of signals in the downscaled products that are actually present in the forcing data was noted. It was speculated that this could be due to poor representation of ocean–atmosphere interaction. Such a misrepresentation of air–sea fluxes in the model can definitely lead to different results while downscaling the GCM simulations. The improvement of the CORDEX models over CMIP5 models is also analysed in recent studies[44,45]. These studies indicate that the choice of driving GCMs affects the outcome. Moreover, studies on CORDEX and CMIP5 data show that the configuration and physics employed in each of the models are not similar[46–51]. This difference can indeed influence the output and give different results.
- Ensemble members can have differences because of the methods and approaches involved. Hence, to neutralize the extreme predictions, ensemble mean is used. With the inclusion of more models for the ensemble mean, the influences of outliers can be further reduced.

Conclusion

The future potential of wind and solar energy over the Indian subcontinent is analysed using ensembles of climate models. The climate simulations for the past 55 years and future projections for 55 years are considered from six CORDEX-SA, 13 CMIP5 and 13 CMIP6 models for the analysis. The future projections include RCP4.5 and RCP8.5 in the CORDEX-SA and CMIP5 models, and SSP2-4.5

and SSP5-8.5 in the CMIP6 models. The analysis reveals that over most of the Indian landmass, solar potential will decrease in the near future. In the CMIP experiments, wind potential over the onshore regions shows an increasing trend, while offshore regions show a decreasing trend for the non-monsoon months. The southern coast of Odisha and the southern Indian states of Andhra Pradesh and Tamil Nadu show promising potential for wind energy in the climate change scenario. The seasonal analysis indicates that the southern and northwestern regions of the country will have higher wind speed in the winter and monsoon months when the wind potential is maximum. Solar projections for the future indicate that solar radiation will decrease during all seasons over most of the active solar farming regions. For future investments in the solar power sector, central and south-central India must be considered during pre-monsoon months, as the potential loss is minimum in these regions. Regional analysis of wind potential indicates that the frequency of high energy-producing wind speeds will decrease, whereas low energy-producing wind speeds are likely to increase in the future. In the solar potential regional analysis, future projections predict a shift in the frequency of solar radiation in the negative direction, implying that solar energy production will decrease in the immediate future. This can be attributed to the increase in total cloud cover. The present study shows that the renewable energy fields of solar and wind potential in India are likely to face a negative trend in the future. This can be overcome by including more farms and using highly efficient power generators than those available at present.

1. Intergovernmental Panel on Climate Change, IPCC Fifth Assessment Report (AR5) Observed Climate Change Impacts Database, Version 2.01. Palisades, NY, Socioeconomic Data and Applications Center, NASA, USA, 2017; https://doi.org/10.7927/H4FT8J0X (accessed on 10 December 2019).
2. Rodhe, H., A comparison of the contribution of various gases to the greenhouse effect. *Science*, 1990, **248**(4960), 1217–1219.
3. Lashof, D. and Ahuja, D., Relative contributions of greenhouse gas emissions to global warming. *Nature*, 1990, **344**, 529–531; https://doi.org/10.1038/344529a0.
4. Ruddiman, W. F., The anthropogenic greenhouse era began thousands of years ago. *Climatic Change*, 2003, **61**(3), 261–293.
5. Gielen, D. *et al.*, Global Energy transformation: A roadmap to 2050; Hydrogen Knowledge Centre, Derby, UK, 2019; https://www.h2knowledgecentre.com/content/researchpaper1605 (accessed on 1 November 2020).
6. REN21, Asia and the Pacific Renewable Energy Status Report, REN21 Secretariat, Paris, 2019, ISBN: 978-3-9818911-8-8; http://dx.doi.org/10.22617/SPR200173-2.
7. Kumar, J. C. R. and Majid, M. A., Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and investment opportunities. *Energ. Sustain Soc.*, 2020, **10**, 2; https://doi.org/10.1186/s13705-019-0232-1.
8. Ali, S. A. *et al.*, Projected increase in hydropower production in India under climate change. *Sci. Rep.*, 2018, **8**, 12450; https://doi.org/10.1038/s41598-018-30489-4.
9. Pryor, S. C. and Barthelmie, R. J., Assessing the vulnerability of wind energy to climate change and extreme events. *Climatic Change*, 2013, **121**, 79–91; https://doi.org/10.1007/s10584-013-0889-y.
10. Quaschning, V. V., *Renewable Energy and Climate Change*, John Wiley, 2019, ISBN: 978-1-119-51486-2.
11. Brower, M., Wind Resource Assessment: A Practical Guide to Developing a Wind Project, Wiley, Hoboken, NJ, USA, 2012, ISBN: 978-1-118-02232-0.
12. Pedersen, T. F., On wind turbine power performance measurements at inclined airflow. *Wind Energy*, 2004, **7**, 163–176; https://doi.org/10.1002/we.112.
13. Wagner, R., Courtney, M., Larsen, T. and Paulsen, U., Simulation of shear and turbulence impact on wind turbine performance Tech. Rep. Risø-R-1722 (EN), Risø National Laboratory, Roskilde, 2010.
14. Karnauskas, K. B., Lundquist, J. K. and Zhang, L., Southward shift of the global wind energy resource under high carbon dioxide emissions. *Nature Geosci.*, 2018, **11**, 38–43; https://doi.org/10.1038/s41561-017-0029-9.
15. Carvalho, D., Rocha, A., Gomez-Gesteira, M. and Santos, C. S., Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. *Renew. Energy*, 2017, **101**, 29–40; https://doi.org/10.1016/j.renene.2016.08.036.
16. Hosking, J. S., MacLeod, D., Phillips, T., Holmes, C., Watson, P., Shuckburgh, E. and Mitchell, D., Changes in European wind energy generation potential within a 1.5°C warmer world. *Environ. Res. Lett.*, 2018, **13**(5), 054032.
17. Kulkarni, S. and Huang, H. P., Changes in surface wind speed over North America from CMIP5 model projections and implications for wind energy. *Adv. Meteorol.*, 2014, 292768, 10; https://doi.org/10.1155/2014/292768.
18. Chen, L., Pryor, S. C. and Li, D. L., Assessing the performance of Intergovernmental Panel on Climate Change AR5 climate models in simulating and projecting wind speeds over China. *J. Geophys. Res.: Atmosp.*, 2012, **117**, D24102; http://doi.org/10.1029/2012JD017533.
19. Li, D., Feng, J., Dosio, A., Qi, J., Xu, Z. and Yin, B., Historical evaluation and future projections of 100-m wind energy potentials over CORDEX-East Asia. *J. Geophys. Res. Atmosp.*, 2020, **125**, e2020JD032874; https://doi.org/10.1029/2020JD032874.
20. Gao, M., Ding, Y., Song, S., Lu, X., Chen, X. and McElroy, M. B., Secular decrease of wind power potential in India associated with warming in the Indian Ocean. *Sci. Adv.*, 2018, **4**(12), eaat5256; https://doi.org/10.1126/sciadv.aat5256.
21. Taylor, K. E., Stouffer, R. J. and Meehl, G. A., An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.*, 2012, **93**(4), 485–498; https://doi.org/10.1175/BAMS-D-11-00094.1.
22. Alvarez, I. and Lorenzo, M. N., Changes in offshore wind power potential over the Mediterranean Sea using CORDEX projections. *Reg. Environ. Change*, 2019, **19**, 79–88; https://doi.org/10.1007/s10113-018-1379-6.
23. Barstad, I., Sorteberg, A. and Mesquita, M. D. S., Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover. *Renew. Energy*, 2012, **44**, 398–405; https://doi.org/10.1016/j.renene.2012.02.008.
24. Li, D., Geyer, B. and Bisling, P., A model-based climatology analysis of wind power resources at 100-m height over the Bohai Sea and the Yellow Sea. *Appl. Energy*, 2016, **179**, 575–589; https://doi.org/10.1016/j.apenergy.2016.07.010.
25. Kulkarni, S., Deo, M. C. and Ghosh, S., Performance of the CORDEX regional climate models in simulating offshore wind and wind potential. *Theor. Appl. Climatol.*, 2019, **135**, 1449–1464; https://doi.org/10.1007/s00704-018-2401-0.
26. Gutowski Jr, W. J. *et al.*, The ongoing need for high-resolution regional climate models: process understanding and stakeholder information. *Bull. Am. Meteorol. Soc.*, 2020, **101**(5), E664–E683; https://doi.org/10.1175/BAMS-D-19-0113.1.
27. Tobin, I. *et al.*, Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections.

Climatic Change, 2015, **128**(1–2), 99–112; https://doi.org/10.1007/s10584-014-1291-0.
28. Sholapurkar, R. B. and Mahajan, Y. S., Review of wind energy development and policy in India. *Energy Technol. Policy*, 2015, **2**(1), 122–132; https://doi.org/10.1080/23317000.2015.1101627.
29. Giorgi, F. and Gutowski, W. J., Regional dynamical downscaling and the CORDEX initiative. *Annu. Rev. Environ. Resour*., 2015, **40**, 467–490; https://doi.org/10.1146/annurev-environ-102014-021217.
30. Pattnayak, K. C., Panda, S. K., Saraswat, V. and Dash, S. K., Assessment of two versions of regional climate model in simulating the Indian summer monsoon over South Asia CORDEX domain. *Climate Dyn*., 2018, **50**(7–8), 3049–3061; https://doi.org/10.1007/s00382-017-3792-9.
31. Moss, R. *et al.*, The next generation of scenarios for climate change research and assessment. *Nature*, 2010, **463**, 747–756; https://doi.org/10.1038/nature08823.
32. Bracegirdle, T. J. *et al.*, Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing response, and state dependence. *J. Geophys. Res. Atmosp.*, 2013, **118**(2), 547–562; https://doi.org/10.1002/jgrd.50153.
33. Knutti, R. and Sedláček, J., Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, 2013, **3**, 369–373; https://doi.org/10.1038/nclimate1716.
34. Morim, J. *et al.*, Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, 2019, **9**, 711–718; https://doi.org/10.1038/s41558-019-0542-5.
35. Masson-Delmotte, V. *et al.* (eds), Climate Change 2021: The Physical Science Basis; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2021; https://www.ipcc.ch/report/ar6/wg1/ (accessed on 20 February 2022).
36. O'Neill, B. C. *et al.*, The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environ. Change*, 2017, **42**, 169–180; https://doi.org/10.1016/j.gloenvcha.2015.01.004.
37. Kalnay, E. *et al.*, The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.*, 1996, **77**(3), 437–472.
38. Rienecker, M. M. *et al.*, MERRA: NASA's modern-era retrospective analysis for research and applications. *J. Climate*, 2011, **24**, 3624–3648; https://doi.org/10.1175/JCLI-D-11-00015.1.
39. International Electrotechnical Commission, Wind turbines – Part 1: design requirements. IEC 61400–1, Geneva, Switzerland: International Electrotechnical Commission, 2005, p. 179.
40. Hueging, H., Born, K., Haas, R., Jacob, D. and Pinto, J. G., Regional changes in wind energy potential over Europe using regional climate model ensemble projections. *J. Appl. Meteorol. Climatol.*, 2013, **52**(4), 903–917; https://doi.org/10.1175/JAMC-D-12-086.1
41. Moemken, J., Reyers, M., Buldmann, B. and Pinto, J. G., Decadal predictability of regional scale wind speed and wind energy potentials over Central Europe. *Tellus A*, 2016, **68**(1), 29199; https://doi.org/10.3402/tellusa.v68.29199.
42. Moemken, J., Reyers, M., Feldmann, H. and Pinto, J. G., Future changes of wind speed and wind energy potentials in EURO-CORDEX ensemble simulations. *J. Geophys. Res. Atmosph.*, 2018, **123**, 6373–6389; https://doi.org/10.1029/2018JD028473.
43. Singh, S., Ghosh, S., Sahana, A. S., Vittal, H. and Karmakar, S., Do dynamic regional models add value to the global model projections of Indian monsoon? *Climate Dyn.*, 2017, **48**(3), 1375–1397.
44. Choudhary, A., Dimri, A. P. and Paeth, H., Added value of CORDEX-SA experiments in simulating summer monsoon precipitation over India. *Int. J. Climatol.*, 2019, **39**(4), 2156–2172.
45. Sanjay, J., Ramarao, M. V. S., Mujumdar, M. and Krishnan R., Regional climate change scenarios. In *Observed Climate Variability and Change Over the Indian Region* (eds Rajeevan, M. and Nayak, S.), Springer Geology, Springer, Singapore, 2017; https://doi.org/10.1007/978-981-10-2531-0_16.
46. Vishnu, S., Sanjay, J. and Krishnan, R., Assessment of climatological tropical cyclone activity over the north Indian Ocean in the CORDEX-South Asia regional climate models. *Climate Dyn.*, 2019, **53**, 5101–5118; https://doi.org/10.1007/s00382-019-04852-8.
47. Kumar, P. *et al*., Regional earth system modelling framework for CORDEX-SA: an integrated model assessment for Indian summer monsoon rainfall. *Climate Dyn.*, 2022; https://doi.org/10.1007/s00382-022-06217-0.
48. Boucher, O. *et al.*, Presentation and evaluation of the IPSL-CM6A-LR climate model. *J. Adv. Model. Earth Syst.*, 2020, **12**, e2019MS002010; https://doi.org/10.1029/2019MS002010.
49. Dunne, J. P. *et al*., The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): overall coupled model description and simulation characteristics. *J. Adv. Model. Earth Syst.*, 2020, **12**, e2019MS002015; https://doi.org/10.1029/2019MS002015.
50. Chylek, P. *et al*., Observed and model simulated 20th century Arctic temperature variability: Canadian earth system model CanESM2. *Atmosp. Chem. Phys. Discuss.*, 2011, **11**(8), 22893–22907.
51. Voldoire, A. *et al*., The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dyn.*, 2013, **40**, 2091–2121; https://doi.org/10.1007/s00382-011-1259-y.

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