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Droughts in Wind and Solar Power: Assessing Climate Model Simulations for a Net-Zero Energy Future

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Key Points:

- Wind and solar power droughts are linked to high/low pressure systems
- The simulated power droughts during historical periods are more sensitive to model bias than to model resolution
- Future simulations of these power droughts vary between low- and high-resolution simulations, and across various regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Understanding and predicting "droughts" in wind and solar power availability can help the electric grid operator planning and operation toward deep renewable penetration. We assess climate models' ability to simulate these droughts at different horizontal resolutions, ∼100 and ∼25 km, over Western North America and Texas. We find that these power droughts are associated with the high/low pressure systems. The simulated wind and solar power variabilities and their corresponding droughts during historical periods are more sensitive to the model bias than to the model resolution. Future climate simulations reveal varied future change of these droughts across different regions. Although model resolution does not affect the simulation of historical droughts, it does impact the simulated future changes. This suggests that regional response to future warming can vary considerably in high- and low-resolution models. These insights have important implications for adapting power system planning and operations to the changing climate.

Plain Language Summary

A carbon neutral future depends upon deep decarbonization of the electricity sector. As we move toward a future where we use cleaner energy sources, like wind and solar, it is important to ensure that the electric grid stays reliable. Scientists have been studying how climate change affects the weather, but we know less about how climate change affects periods when there is not enough wind or sunlight to generate renewable energy—known as "power droughts." And to plan for the future, we need to study power droughts in global climate models. We analyze the climate models to assess how good they are at predicting when these energy shortages might happen in two regions of the United States. We found that adjusting the models to better match real-world conditions improved how well they predicted the frequency of these power droughts. Refining model horizontal resolution from 100 to 25 km, did not impact the simulation of historical power droughts. Our results also show that in the future, the frequency of these power droughts will vary in a region-dependent manner. Such information can help us plan for a future that is increasingly dependent on more sustainable energy sources.

1. Introduction

Wind and solar power are the key drivers of electricity decarbonization. While the global energy infrastructure is still in the early stage of a transition away from the fossil fuels toward the energy sources with near-zero greenhouse gas emissions, projections and proposals indicate electricity supply relying on wind and solar power will continue to expand in the near-term (Jacobson et al., 2017; Sepulveda et al., 2018; Williams et al., 2012).

Despite their growing importance, wind and solar energy are subject to inherent limitations, which include intrinsic variability, substantial land requirements, technical difficulties in grid integration, and others (Albertus et al., 2020; Gowrisankaran et al., 2016; Jurasz et al., 2020; Sepulveda et al., 2018; Shaner et al., 2018; Tong et al., 2020; Ueckerdt et al., 2013). These limitations make it challenging to guarantee a stable and reliable supply of electricity from wind and solar energy to the power grid. As the world transitions to a net-zero energy future, handling the reliability of wind and solar energy sources and guaranteeing a continuous supply of renewable energy have become increasingly critical.

Extreme weather events have had a demonstrated impact on electricity grids historically. For example, the extreme cold event in 2021 winter, which was associated with a persistent trough over the central United States, led to power outages that lasted several days in Texas (Busby et al., 2021). Heatwaves occurring over the Western North America in 2021 stressed the power grid by raising the energy demand. Recent studies (Brown et al., 2021; Jurasz et al., 2021; Millstein et al., 2019; Rife et al., 2016; Rinaldi et al., 2021) further point out that the extremely low wind and solar power resource availability, that is, wind and solar power droughts, are closely linked to synoptic weather patterns. A better understanding of the links between the availability of wind and solar energy resources and the weather patterns can help inform the development of effective strategies for managing their intrinsic variability.

There have been many studies of global climate model (GCM) simulation of weather extremes and their projected future changes. However, the GCM simulations of wind and solar power droughts and their future changes have not received similar attention. Weather forecast models, which typically have high spatial resolutions, are capable of forecasting the renewable power drought events at short timescales. But GCMs are typically run at coarse spatial resolution and also suffer from significant model bias. Thus, it is crucial to assess the capability of GCMs in predicting wind and solar power droughts.

Climate change is expected to exert substantial impacts on electricity demand and generation during the transition into the net-zero (Meckling et al., 2017). Previous studies (Craig et al., 2019; Karnauskas et al., 2018; Losada Carreño et al., 2020; Petri & Caldeira, 2015) have assessed the potential impact of climate change on energy demand, the wind and solar power resources and their generations using GCM future climate simulations. Overall, it is projected that wind resources will decrease on average throughout the United States by 2050, with some regions expected to experience an increase (Haupt et al., 2016; Johnson & Erhardt, 2016; Karnauskas et al., 2018; Pryor et al., 2020). There is less agreement about the future changes in solar resources, but it is generally agreed that the future change in solar resources varies geographically (Crook et al., 2011; Haupt et al., 2016; Wild et al., 2015, 2017). Solar resources are predicted to decrease over California, but increase over the southern United States (Crook et al., 2011; Wild et al., 2015, 2017).

Although many previous studies have assessed global warming's impact on wind and solar resources, limited studies (e.g., Kapica et al., 2024; Otero et al., 2022) have focused on wind and solar power droughts. Otero et al. (2022) illustrate that the European countries are frequently impacted by moderate renewable energy droughts especially during winter. And Kapica et al. (2024) assess the climate changes' impact, highlighting the potential rise in wind droughts in Central Europe. Understanding power droughts is important for guaranteeing a stable and reliable supply of electricity relying on wind and solar resources. As climate change leads to more frequent and severe extreme weather events, it is interesting and important to project changes in wind and solar droughts under a warming climate, as they are closely linked with certain weather patterns believed to be impacted by global warming.

In this study, we aim to evaluate GCMs' ability to predict wind and solar power droughts, to understand the dominant weather patterns associated with these events, and to explore how their occurrences are expected to change in the future. Our study focuses on two target regions, the Western North American (WNA) region (WNA; 30°N–55°N, 135°W–105°W; shown as Figures 2a–2c orange box) and the Texas (TX) region (30°N–55°N, 107°W–93°W; shown as Figures 2d–2f orange box), both of which are susceptible to extreme heat waves that can stress the power grid.

2. Data and Methods

2.1. Observational Data

This study utilizes the latest European Center for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA5) (Hersbach et al., 2020), which offers variables with 0.25° spatial resolution from January 1950 to present, as the reference data for studying the observed wind and solar power droughts. ERA5 incorporates a 4-dimensional variational assimilation approach that combines abundant satellite and in situ observations with the ECMWF weather forecast model. Wind and solar power, as well as their drought events, are computed using both 6-hourly and 1-hourly data sets. Results obtained are consistent with the previous study Brown et al. (2021), and are not sensitive use of 6-hourly or 1-hourly products. Since GCM simulations are typically archived at 6-hr intervals, this validates results using 6-hourly data sets for studying wind and solar power droughts.

2.2. Climate Model Simulations

Sets of climate simulations from the Community Earth System Model (CESM) version 1.3 (Meehl et al., 2019) are used in this study. A detailed description of the model configuration is presented in Chang et al. (2020). The model simulations include both historical and future transient climate runs and use historical radiative forcing

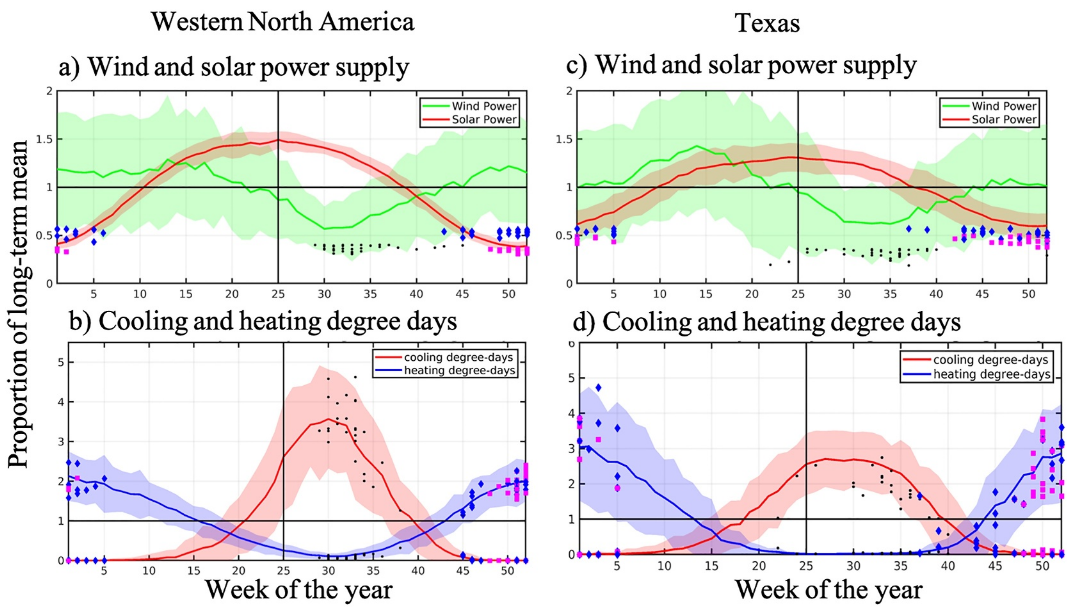

Figure 1. Observed (a, c) wind and solar power supply and (b, d) heating and cooling degree days over (a, b) Western North America (WNA) and (c, d) Texas regions derived from ERA5. 1 percentile droughts weeks are highlighted. In panels (a, c), black dots highlight the weeks of wind power droughts; Magenta squares refer to the weeks of solar power droughts, and blue diamonds are during the weeks of compound wind and solar power droughts. While in panels (b, d), they indicate the heating and cooling degree days when the corresponding droughts occur.

from 1850 to 2005 and the very high-emission Representative Concentration Pathway 8.5 (RCP8.5) scenario for the future period 2006–2100, respectively. Our results for the future changes should therefore be considered more as an upper-bound on possible climate change, rather than as a plausible or likely future.

The GCM runs were carried out at different horizontal resolutions, while utilizing the same forcing data sets. The high-resolution (HR) runs employ a nominal horizontal resolution of 0.25° for the atmosphere and land models, and a nominal 0.1° for the ocean and sea-ice models. In contrast, the low-resolution (LR) runs use a nominal horizontal resolution of 1° for all the model components.

2.3. Computing Wind and Solar Energy Resource Availability

This study emphasizes the physical understanding of wind and solar power potential, its relationship to weather patterns, and the projected future changes. Thus, complicated factors related to the practical sociological, technological or political constraints, which are subject to much uncertainty, are ignored when computing the renewable power potential. Following Brown et al., 2021, we focus on the weekly timescales, which are most relevant for power system planning (Albertus et al., 2020), and the spatial scales of the existing large power grids.

2.3.1. Calculations of Wind and Solar Power Resources and Electric Demand

Calculating wind and solar power directly from climate model outputs is a challenge due to the disconnect between data saved for climate simulation and the information needed for energy systems (Craig et al., 2022). Wind power is calculated from the wind speed at 100 m above the surface U_{100}. This variable is not typically saved as model output for climate simulations, although it is available for ERA5. Therefore, the simulated U_{100} was derived from the neutral wind speed at 10 m and atmospheric bottom layer wind speed using the logarithmic law of the wall. Wind power is then calculated based on the wind power curve for wind turbines (Brown et al., 2021). (This extrapolation procedure was validated by comparing the U_{100} computed in this manner using ERA5 with the corresponding U_{100} directly provided by ERA5).

For solar resource calculations, hourly downward incident surface solar radiation is adjusted based on radiation and temperature to account for the fact that photovoltaic performance is affected by both variables. Brown et al. (2021) provides a detailed description of this calculation.

To determine electric demand of the entire regional grid, daily mean temperature departures from 18°C are used, where positive departures indicate *cooling degree days* and negative departures indicate *heating degree days*. These residential heating or cooling degree days are commonly served as an indicator for the energy demand (Brown et al., 2021; Petri & Caldeira, 2015).

2.3.2. Definition of Wind and Solar Power Droughts

The power droughts are defined as the extreme low values in power generation availability. We first calculate the averaged wind or solar power resources over a given week for the entire target domain. Here, the solar resource is determined by both radiation and temperature, indicating the solar photovoltaic generation potential. Then we identify a drought as a week where the wind or solar power (or their compound) resource falls within the first percentile of all weeks across the entire historical period (1950–2004) for each respective product. This definition primarily encompasses weeks with exceptionally calm winds or persistent cloud cover, which result in inadequate power generation. It also considers weeks with extremely high levels of wind penetration, during which turbines are unable to generate wind power, though such events are rare. The compound wind and solar droughts are identified as the first percentile weeks of the sum of the normalized wind and solar resources, following Brown et al. (2021). And both historical and future droughts are defined using consistent thresholds derived from the first percentile of historical weeks.

3. Climate Model Simulated Wind and Solar Power

3.1. Observed Results Over WNA and Texas

Figure 1 shows the observed wind and solar power resources and cooling/heating degree days from ERA5 over the WNA and Texas. As described above, the heating and cooling degree days are commonly used to interpret the power demand. In Figure 1, the available wind and solar resources and the power demand are presented as a proportion of the long-term area mean to highlight the temporal distribution of the resources and demand rather than the absolute value, which depends on the technological assumptions. The solar power resource displays a strong seasonal cycle over WNA (Texas) region, with a range of ~40%–160% (60%–130%) of its annual mean, peaking in summer and dipping in winter (Figures 1a and 1c). In contrast, wind power displays a seasonal cycle with a range of ~60%–120% (60%–140%) of its annual mean, dual peaks in spring and mid-winter and dipping in late summer, respectively. The seasonal cycle in wind power is weaker than in the solar power, and is approximately anticorrelated with the seasonal cycle in solar power, with its phase lagging that of solar power by about 5 weeks. Overall, the variability in solar power is primarily dominated by the seasonal cycle, while the variability in wind power exhibits more month-to-month variability.

This indicates that solar power droughts are more likely during winter, while wind power droughts can occur at any time of the year, but are most likely in the late summer in July and August when the mean values are the smallest due to the seasonal variation. In the context of power demand, solar droughts tend to occur during high values of heating degree days while the wind droughts tend to occur during high values of cooling degree days. The WNA and Texas regions show similar climatology variations in wind and solar power resources and power demand, but the power droughts in Texas are more scattered throughout the year than in WNA. Compound drought events are more likely to occur during the winter season (heating degree days).

Figure 2 illustrates the weather patterns responsible for the wind and solar droughts over WNA and Texas. Solar droughts occur in both regions due to a low-pressure system in the west and a high-pressure system in the east, causing strong winds blowing from the ocean to the land, resulting in cloudy skies (reduced outgoing longwave radiation; Figure S1 in Supporting Information S1). Wind droughts, on the other hand, are marked by a high-pressure system situated in the north of the region of interest and calm weather characterized with small wind anomalies in the south. The difference between WNA and Texas is that the high-pressure system with calm weather in the center overlaps with the north part of WNA but is located outside Texas. Clustering analyses (Figures S2 and S3 in Supporting Information S1), using the method proposed by Kohonen (1995), further confirm that these composited weather patterns prevail when the wind and solar droughts occur (see Supplementary Information S1).

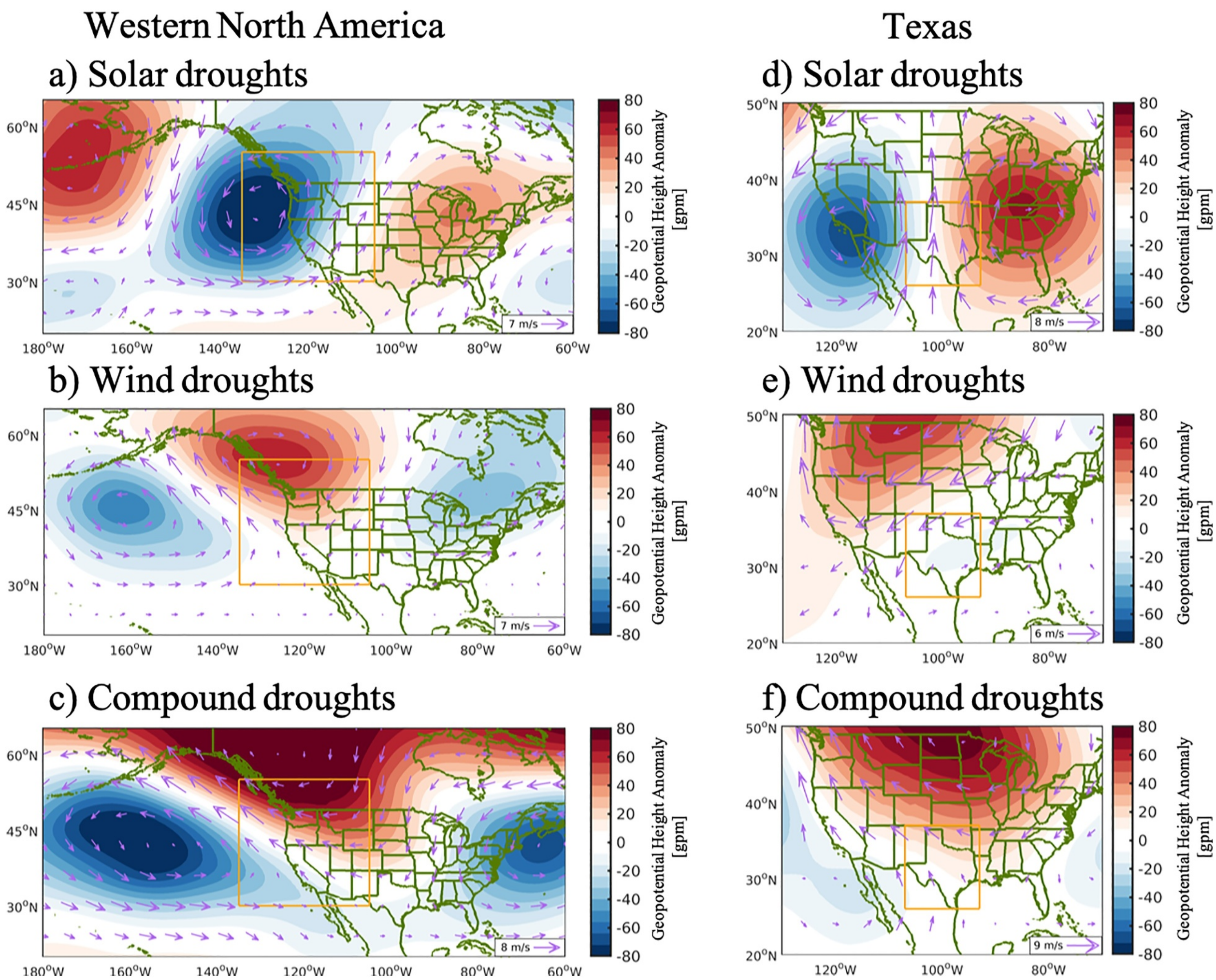

Figure 2. Composite maps of geopotential height anomalies at 500 hPa (color; unit: gpm), and wind anomalies at 500 hPa (purple vector; unit: m/s) when (a, d) solar, (b, e) wind and (c, f) compound power droughts occur over (a–c) Western North America (WNA) region and (d, e, f) Texas Region from ERA5. The orange boxes show the target regions. Surface winds exhibit similar patterns to these of 500 hPa winds (not shown).

3.2. Model Simulated Results

Next, we evaluate the capability of climate models in simulating wind and solar power resources and their associated droughts at both LR and HR configurations, as illustrated in Figure 3. Our initial focus is on the WNA region. In comparison to the observed power resource availability computed from ERA5 (Figure 1), both CESM1.3 HR and LR are capable of accurately simulating solar power variability and its corresponding droughts: A prevailing seasonal cycle in solar power, characterized by high value during summer and low value during winter, is observable, and all solar droughts occur during the winter season. However, the models fail to reproduce the seasonal cycle of wind power resource accurately. According to the observations, wind power has two peaks, one in the spring and another in early winter, with values ∼130% of its long-term area-mean. While, in the simulations, wind power has a single peak at the end of the calendar year with a value ∼150% of its long-term area-mean. The simulated wind power seasonal cycle (Figure 3) displays smooth low values during week of 25–37, whereas observations indicate that the low values are more concentrated during late summer, particularly near week 30 (Figures 1a and 1c). Consequently, the simulated wind power droughts are more spread out in simulations than in observations: the wind power droughts only occurred in late summer (week of 29–38) in observations, but can occur from late spring to early winter (week of 18–45) in simulations.

Two possible reasons for the poor simulation of wind power droughts are biases in the simulated climate and inadequate model resolution. Although an extensive analysis reveals that enhancing model resolution can

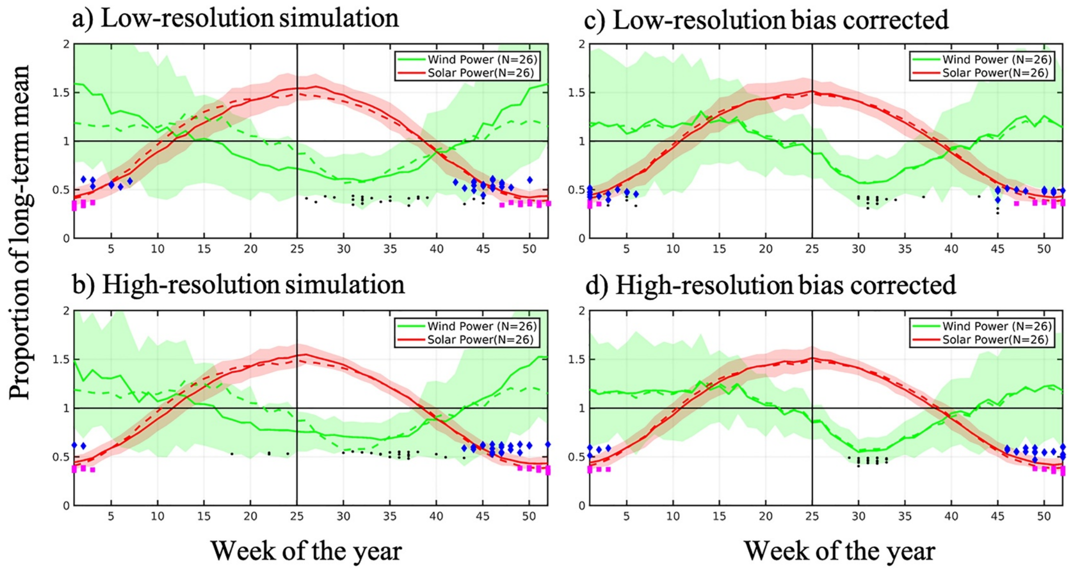

Figure 3. Simulated wind and solar power supply (solid lines) from CESM1.3 (a) Low resolution (LR) simulation; (b) High resolution (HR) simulation; (c) LR bias corrected outputs; (d) HR bias corrected outputs over Western North America region. The observed mean wind and solar power supply curves from ERA5 (same as Figure 1a) are indicated by dashed green and red lines. All other details are consistent with Figure 1a.

improve simulations of exceptionally strong 6-hourly 100 m winds (Figure S4 in Supporting Information S1), such events, which may render wind turbines incapable of generating wind power and potentially trigger power droughts, are rare, their impacts on the overall drought occurrence at weekly timescales are small. As we seen in Figure 3b, increasing the model resolution from LR to HR does not improve the accuracy of the simulated wind power droughts. Therefore, we applied a bias correction to the model simulations. We adhere to the approach outlined in Brown et al. (2021) focusing on the weekly timescale and the spatial scales of the existing large power grids. Initially, we computed the weekly- and area-mean of both observed X_{obs} and modeled data $X_{simulated}$. Then the bias X_{bias} is obtained for each model by subtracting the modeled climatology of mean wind and solar power values $\overline{X_{simulated}}$ from the observed mean values $\overline{X_{obs}}$: $X_{bias} = \overline{X_{simulated}} - \overline{X_{obs}}$. Subsequently, the corrected simulated wind and solar power $X_{corrected}$ is obtained by removing the linear bias for each model: $X_{corrected} = X_{simulated} - X_{bias}$. This correction was applied to averaged data, ensuring that $X_{simulated}$ values, which do not contain zeros, were adjusted to better match observed averages. As seen in Figures 3c and 3d, bias correction significantly improved the results: The seasonal cycle of wind power is more realistically simulated, and the simulated wind droughts are concentrated within the late summer, as observed, in the WNA region. Similar results are obtained for the Texas region (not shown), where correcting for model bias significantly improves the simulation of wind and solar power variability as well as their associated droughts, while the impact of model resolution is found to be minor.

4. Future Projections of Power Demand and Occurrence of Wind and Solar Power Droughts

Wind and solar resources are climate dependent. As the climate changes, there could be associated changes in cloudiness or windiness. Understanding the changes in wind and solar power and their associated droughts under global warming can inform the transition to net-zero carbon emissions. In this study, we first compare the CESM1.3 transient simulations between historical and future periods to assess the changes in energy demand as well as wind and solar power supply over the WNA and Texas regions. While CESM1.3 LR and HR simulations do not exhibit significant differences in simulating wind and solar droughts in present-day climate, other studies have revealed that the projections of future mean climate change and weather extremes in LR and HR are remarkably different (e.g., Chang et al., 2020; Salathé et al., 2008). Therefore, projections from CESM 1.3 LR and HR simulations are both analyzed here.

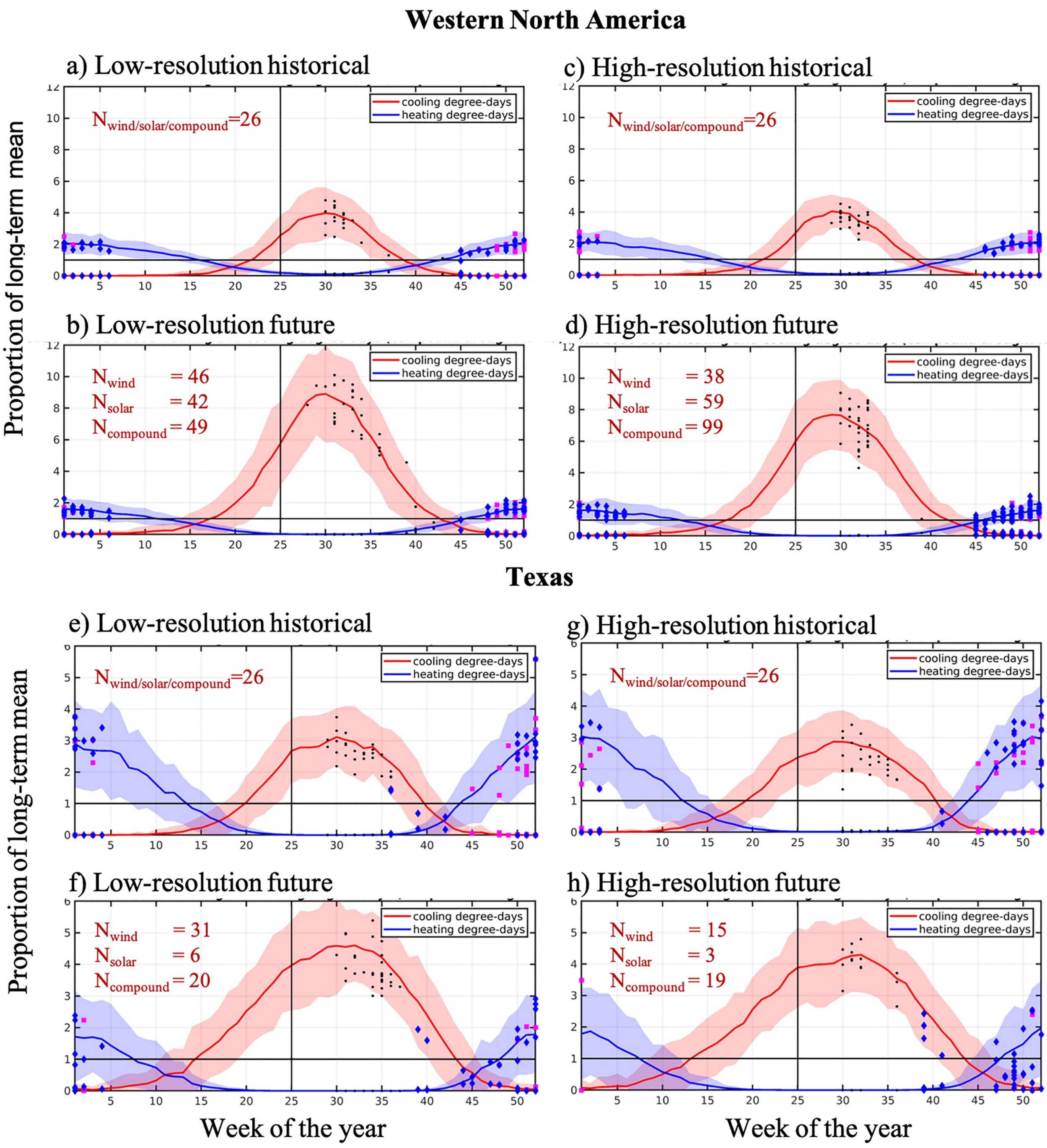

Figure 4. Simulated cooling and heating degree days from CESM1.3 (a, b, e, f) LR and (c, d, g, h) HR over Western North America (WNA) (up panels) and Texas (low panels) regions during (a, c, e, g) historical period of 1951–2000 and (b, d, f, h) future period of 2051–2100. Others are same as Figure 1 bottom panel. Drought numbers are displayed at the left corner. Droughts for both historical and future periods are identified based on the 1st percentile of all weeks across the entire historical periods. All three droughts number are 26 for the historical period.

We first analyze projected changes in the WNA region by comparing the historical period 1951–2000 to the future period 2051–2100. Biases are computed by subtracting the modeled wind/solar power values over the historical period from the observed values during that same historical period. We assumed that the biases are stationary and applied the identical bias correction approach for both the historical and future analyses, given the lack of the future observations. Our analyses suggest that there is no apparent shift in the variability of wind and solar power resources toward the future when compared to historical curves (Figure 4). And the dominant weather patterns associated with the drought events during the future period do not show significant changes compared to the historical period (Figures S5 and S6 in Supporting Information S1). However, droughts numbers change. Note that both historical and future droughts are defined using consistent thresholds derived from the first percentile of historical weeks. So historical droughts number are the same. In the future, the numbers of wind and solar droughts increase significantly in both CESM1.3 HR and LR (Figure 4 top panels). HR simulations predict the compound drought numbers increase by ~3.8 times, while wind droughts are expected to increase by about 1.46 times and solar droughts by 2.3 times (Figure 4). Meanwhile, LR simulations predict the power drought numbers increasing to 1.88, 1.76 and 1.61 times the historical values respectively. In addition, both LR and HR indicate that the demand-side stress on the energy system during summer (cooling degree days) will become much higher in the future compared to the present-day climate, while the demand changes only modestly during winter (warming degree days). LR predicts slightly higher increase in power demand during summer than HR. Generally, LR and HR project consistently that, in the future, energy demand will largely increase during summer, as the numbers of wind and solar power droughts also increase, which will pose a significant challenge for transitioning to wind and solar power in WNA region.

Next, we consider projections of wind and solar power over the Texas region (Figure 4 bottom panels). The demand stress over Texas is projected to increase during the summer and decrease during the winter. The projected increase during cooling degree days in summer is not as large as it is over the WNA region. CESM1.3 simulations also project that wind and solar droughts will generally occur less frequently in the future over Texas, in contrast with the WNA region. The number of compound solar and wind droughts is projected to decrease by ~27% in LR, and solar droughts decreasing by 77% but wind droughts increasing by ~20%. HR projects that compound, wind and solar droughts will decrease by 23%, 42% and 88% respectively. Despite a slight increase in wind droughts in the LR projection, the overall CESM1.3 projection is that power drought events will predominantly decrease over Texas in the future. The different projections of LR and HR could be attributed to the different climate response to anthropogenic forcing in LR and HR simulations, as highlighted in Chang et al. (2020). A more thorough exploration to understand the various projected future changes in the LR and HR climate simulations is desired and planned in a future study.

5. Conclusion and Discussion

This study explores the variability and droughts of wind and solar power over the WNA and Texas regions. Analysis of observations demonstrates that the variability of solar power resource is primarily driven by a strong seasonal cycle, peaking in the summer and dipping in the winter, while the variability of wind power being more affected by the synoptic weather conditions in addition to the seasonal cycle. Consequently, solar droughts are more likely during winter due to the dominant seasonal variability, while wind droughts exhibit strong sensitivity to synoptic weather patterns and are most likely to occur in late summer when the seasonal average wind is at its lowest amplitude.

Our analysis also reveals connections between wind and solar power droughts and synoptic weather patterns. Solar droughts in both regions are associated with a low-pressure system to the west and a high-pressure system to the east, causing strong winds and increased cloudiness. Wind droughts are characterized by a high-pressure system to the north and calm weather with small wind anomalies in the south. One difference between WNA and Texas regions is that the high-pressure system with calm weather in the center is located within the northern part of WNA region but is displaced further away for Texas.

We evaluate the fidelity of climate models in simulating wind and solar power resource variability and their associated droughts at both low and high model resolution. While both model resolutions are capable of accurately simulating solar power variability and its corresponding droughts, they fail to faithfully reproduce the seasonal cycle of the wind power resource. Merely switching to higher resolution does not improve the simulation of wind and solar power variabilities and their associated droughts, but correcting for the bias in the simulated mean climate results in improved fidelity.

Another focus of this paper is to examine the effects of climate on solar and wind power droughts, as well as on the power demand. We find that the projected future changes in power demand and wind and solar power resource availability due to climate change are region-dependent. In the WNA region, there appears to be a robust projected increase in the wind and solar drought occurrence, along with higher power demand, which would pose significant challenges for net-zero energy transition. In the Texas region, on the other hand, there is significant uncertainty in the projected future changes in wind and solar droughts, with the projections being sensitive to the model resolution and/or emission scenarios. Nevertheless, the indications are that Texas projected changes in wind and solar droughts will be smaller in Texas as compared to the WNA region, and there likely to be less of a challenge for the energy transition. These results underscore the need to use multiple models and large ensembles of future projections to assess future power resource availability on the path to net-zero emissions. The responses of these power droughts to future warming exhibit significant variability across different locations, which have profound implications for optimizing renewable energy generation and adapting power system planning and operations to ensure sustainability amidst climate change, and provide valuable insights into a future increasingly reliant on more sustainable energy sources.

We also find that while the horizontal resolution of the climate model has a negligible impact on simulating historical power droughts, it does influence their projected changes. The power droughts, dominated by large-scale pressure systems, can be adequately resolved in coarse resolution. However, finer resolution simulations are essential for capturing small-scale processes, leading to different climate responses to anthropogenic forcing in LR and HR simulations (Chang et al., 2020). This highlights the importance of employing appropriate resolution in energy system modeling. While coarse resolution is sufficient for historical analyses, caution is necessary for future projections to ensuring reliability in energy system assessment and resilience planning. Further investigation is desired and planned to comprehensively understand the projected changes in LR and HR climate simulations in future studies.

In addition, we only adopted a weekly timescale drought definition following Brown et al. (2021). This weekly timescale is anticipated to become relevant in the future as energy storage capacity increases (Albertus et al., 2020), and aligns with societal cycles in electricity demand associated with the calendar week. Alternative drought definitions that consider cumulative impacts may yield different results, underscoring the need for further investigation and validation in future research.

Data Availability Statement

Observations are derived from the latest European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA5) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). Please refer to Hersbach et al. (2020) for detailed information. The Community Earth System Model (CESM) (Meehl et al., 2019) developed by the National Center for Atmospheric Research (NCAR) can be downloaded online (https://escomp.github.io/CESM/versions/cesm2.1/html/downloading_cesm.html). The climate simulations used in this work are available from the following data portal (https://ihesp.github.io/archive/products/ds_archive/CESM-HRMIP.html). Detailed data descriptions are in Chang et al. (2020).

Acknowledgments

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