Status of Climate Change Projections on Wind & Solar Resources

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Haupt et al. (2016): Using patterns to assess variability & change

- Analyzed 50-km regional climate model (RCM) simulations around mid-century for the entire U.S., comparing them to a 35-km climate reanalysis dataset (CFDDA) in the current climate
- Patterns in future climate runs are comparable to patterns in current climate, but occur at different frequencies
- Changes in both wind & solar resource by mid-century have regional, seasonal, and diurnal variability, but also generally stay within ±10% of current resource
  - For instance, in summer, solar resource is projected to increase marginally most places in CONUS, while wind is projected to increase in the southern U.S. but decrease in the northern U.S.
  - Wind speed projected to decrease more often than it increases across U.S.
  - Some pattern change frequency can exceed ±20%

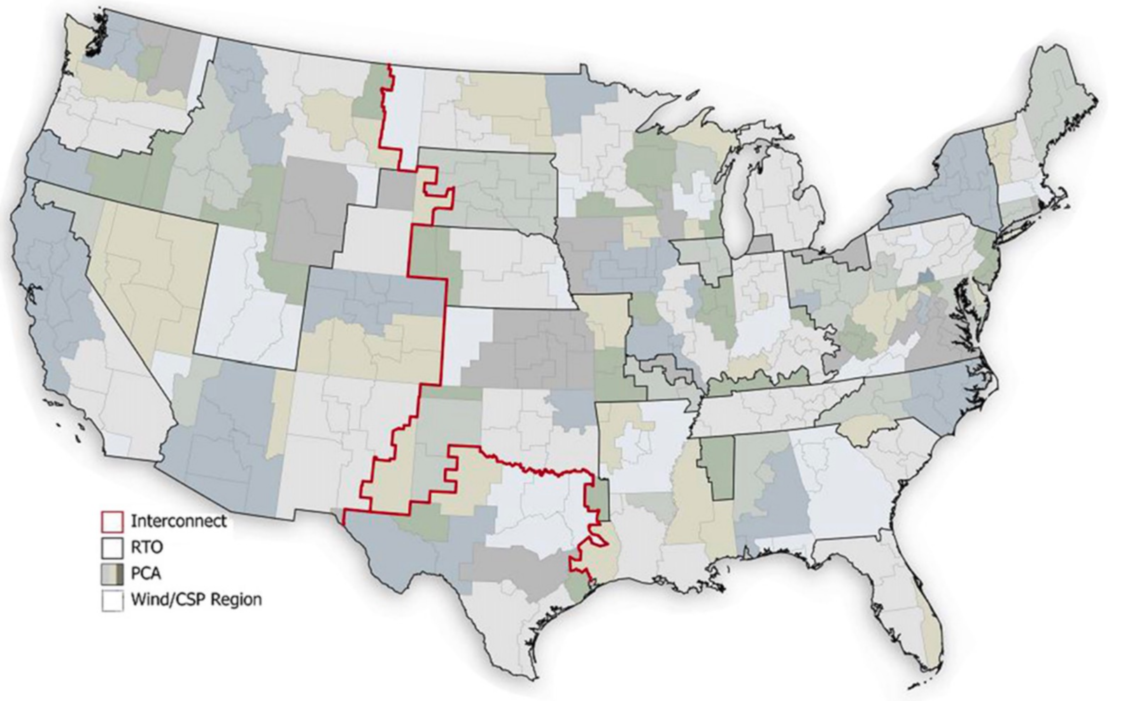

FIG. 2. NREL's ReEDS subregions over CONUS (courtesy of NREL).

Haupt, S. E., J. Copeland, W. Y. Y. Cheng, Y. Zhang, C. Ammann, and P. Sullivan, 2016: A method to assess the wind and solar resource and to quantify interannual variability over the United States under current and projected future climate. *J. Appl. Meteor. Climatol.*, **55**, 345–363, https://doi.org/10.1175/JAMC-D-15-0011.1.

Haupt et al. (2016): Using patterns to assess variability & change

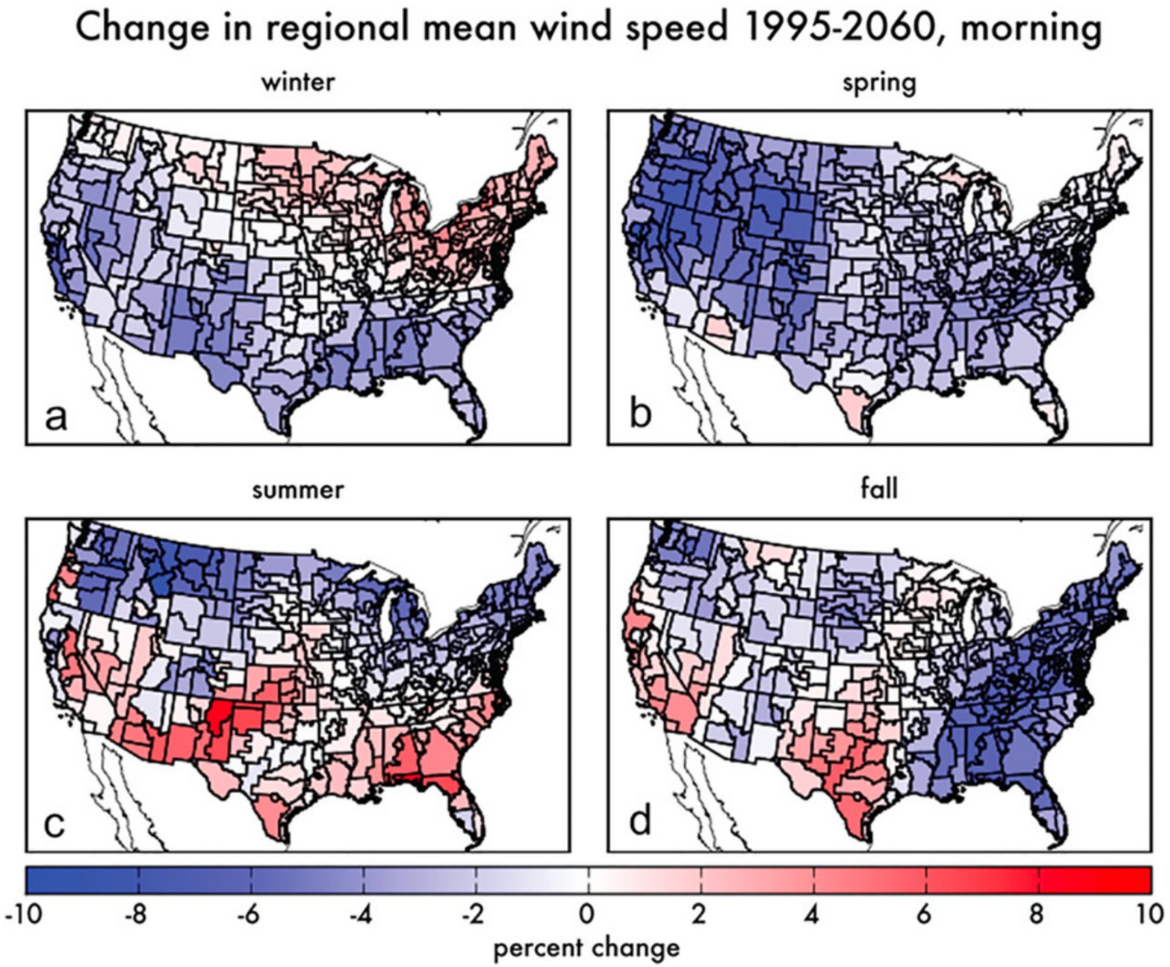

FIG. 10. Projected future changes in hub-height wind speed from current morning (0600–1300 CST) hours for each season: (a) winter, (b) spring, (c) summer, and (d) fall.

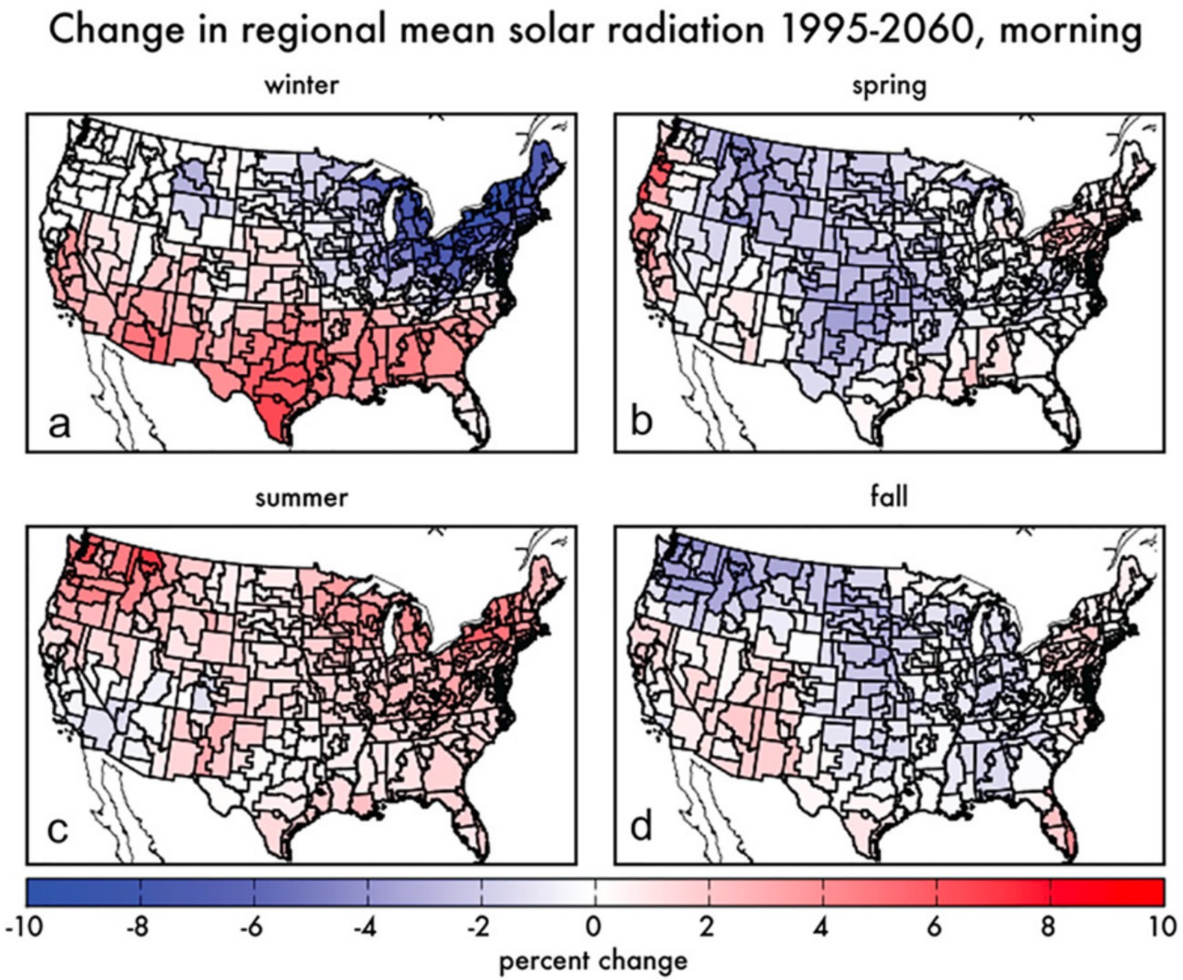

FIG. 12. Projected future changes in solar irradiance from current morning for each of the four seasons: (a) winter, (b) spring, (c) summer, and (d) fall.

Haupt, S. E., J. Copeland, W. Y. Y. Cheng, Y. Zhang, C. Ammann, and P. Sullivan, 2016: A method to assess the wind and solar resource and to quantify interannual variability over the United States under current and projected future climate. *J. Appl. Meteor. Climatol.*, **55**, 345–363, https://doi.org/10.1175/JAMC-D-15-0011.1.

Craig et al. (2018): Climate change implications on energy sector

Power System Component	Component-Level Impacts (Agreement among Studies, Quality of Evidence, and Confidence in our Evaluation)	Potential Power System Planning and Operations Implications
Electricity Demand	- Increased annual total and, to a greater extent, peak electricity demand (high, robust, high)	- Increased total generation - Increased investment requirement in generation or demand response and more peaked electricity prices
Thermal Generators	- Increased summertime curtailments largely contingent on enforcement of thermal discharge regulations (high, robust, high)	- Reduced capacity value of thermal units, requiring additional capacity investments - If curtailments correlated, increased operational reserve requirements
Transmission	- Reduced transmission capacity during peak demand periods (medium, low, medium)	- Increased transmission investment - Exacerbated congestion and contingencies

Craig, M. T., S. Cohen, J. Macknick, C. Draxl, O. J. Guerra, M. Sengupta, S. E. Haupt, B.-M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renew. Sustain. Energy Rev.*, **98**, 255–267, https://doi.org/10.1016/j.rser.2018.09.022.

Craig et al. (2018): Climate change implications on energy sector

Hydropower	- Reduced summertime hydropower resource in California and the Pacific Northwest (medium, medium, medium) - Reduced annual hydropower resource across South (medium, medium, medium)	- Reduced capacity value, depending on release schedule and head height, requiring additional capacity investments - Increased dispatching of other units
Wind	- Decreased wind resources on average across US (low, medium, low) - Large regional and temporal (seasonal and time of day) heterogeneity in wind resource changes (medium, medium, medium)	- Increased wind investment or reliance on other zero-carbon technologies to meet decarbonization targets - Regional changes in capacity values, requiring increased capacity investments
Solar	- Decreased solar PV resource in California (medium, low, low) - Increased solar PV and CSP resource in the Southeast (high, medium, medium) - Greater average increases in CSP than solar PV resource across US (high, medium, high) - Large regional and temporal (seasonal and time of day) heterogeneity in solar resource changes (medium, medium, medium)	- Increased solar investment or reliance on other zero-carbon technologies to meet decarbonization targets - Regional changes in capacity values, requiring increased capacity investments - Increased investment in CSP relative to PV plants

Craig, M. T., S. Cohen, J. Macknick, C. Draxl, O. J. Guerra, M. Sengupta, S. E. Haupt, B.-M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renew. Sustain. Energy Rev.*, **98**, 255–267, https://doi.org/10.1016/j.rser.2018.09.022.

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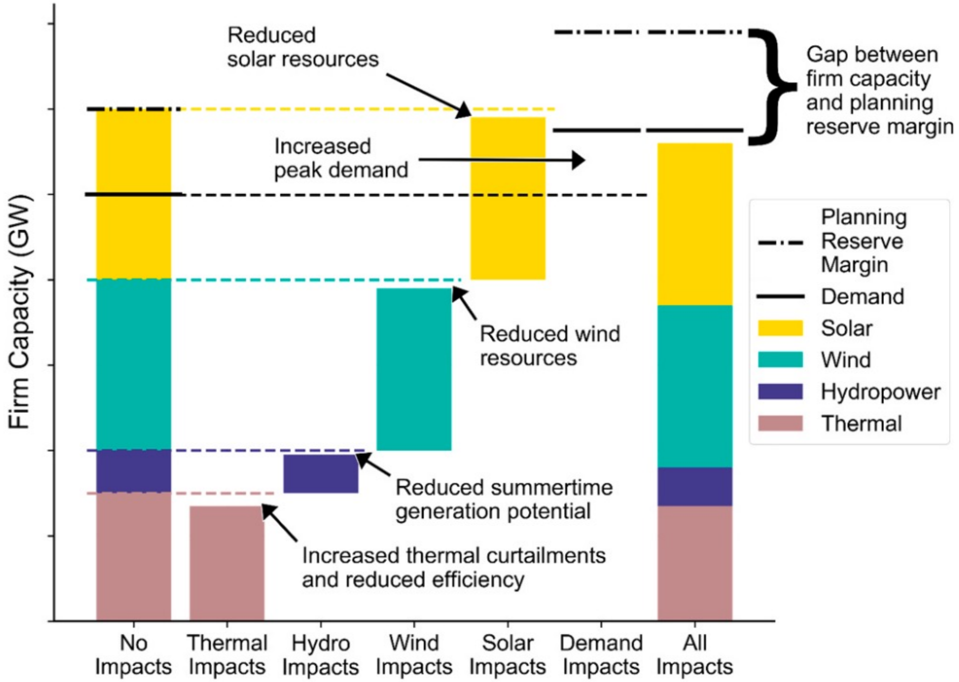


Fig. 1. Potential component-level and system-level impacts of climate change on demand (black line), the planning reserve margin (black dashed line), and firm capacity by generation type (bars). Absolute and relative magnitude of component-level impacts are based on literature surveyed in Section 4. System-level impacts result in firm capacity falling significantly short of the planning reserve margin absent additional investment.

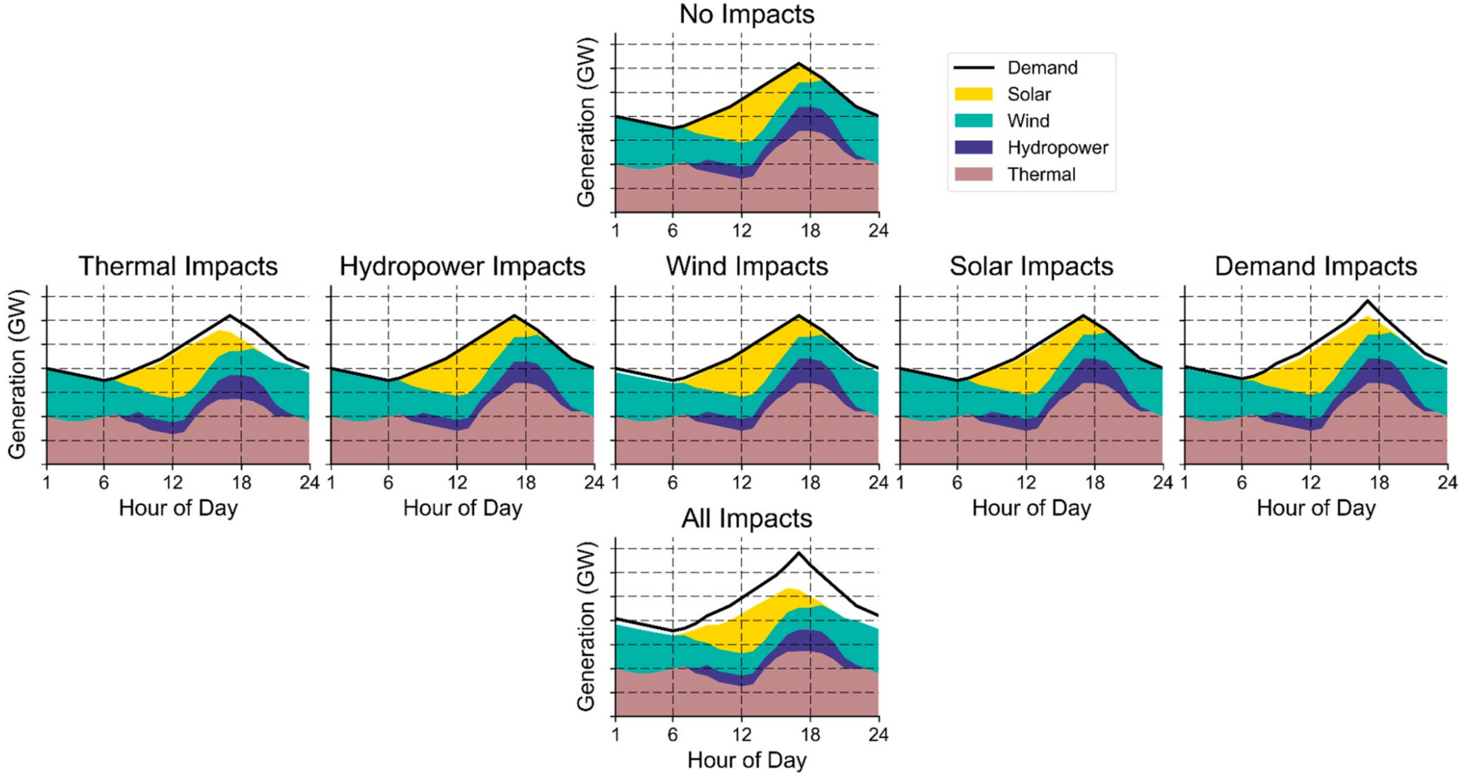


Fig. 2. Illustrative generation profile for a day without climate change impacts (top row) and with potential component-level (middle row) and system-level (bottom row) climate change impacts. Component-level impacts approximate average potential impacts, so impact magnitudes differ among components. The gap between demand and the generation profile indicates a generation shortfall that must be made up via redispatching.

Pryor et al. (2020): Mean annual wind energy density changes

- Very helpful review of dozens of studies conducted to that point examining wind energy resource changes in future climate
- With 12-km WRF driven by MPI LBCs, found that mean energy density likely to increase in Southern Plains, but decrease in much of northern/western U.S. by late-century

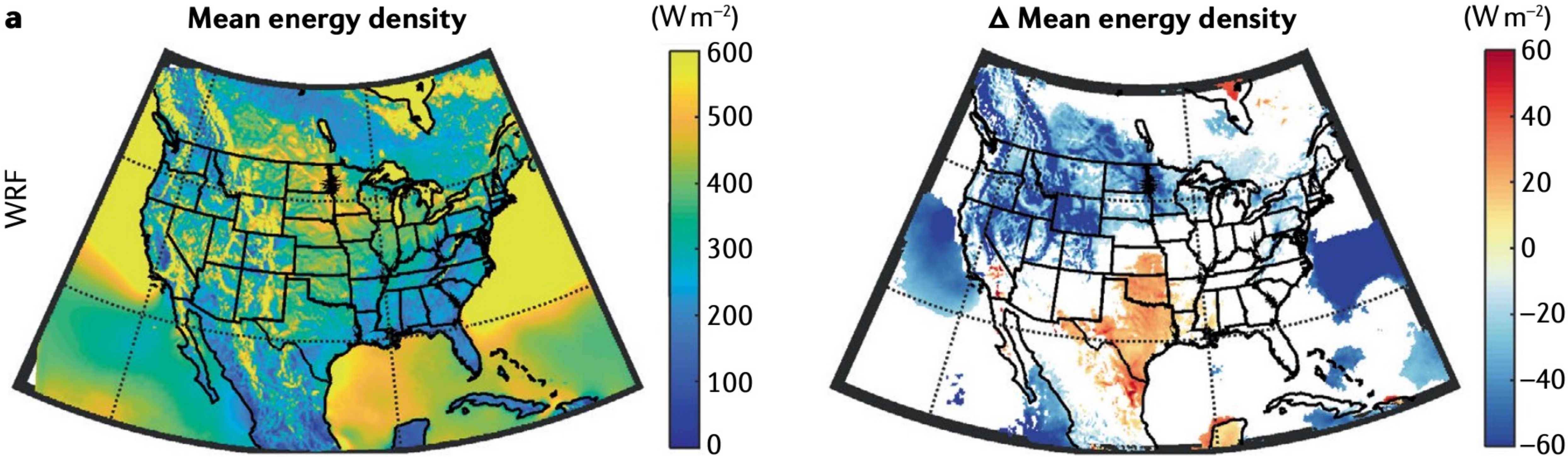


Fig. 3 | **Contemporary and projected mean annual energy density. a** | Mean annual energy density at ~100 m above ground level for 1980–2005 (left panel) and the difference between 2075–2099 and 1980–2005 (right panel). Results are derived using Weather Research and Forecasting (WRF) simulations at 12-km resolution within lateral boundary conditions from the Max Planck Institute Earth System Model at Low Resolution[94]. **b** | As in panel **a**, but mean annual energy density at

Pryor, S. C., R. J. Barthelmie, M. S. Bukovsky, L. R. Leung, and K. Sakaguchi, 2020: Climate change impacts on wind power generation. *Nat. Rev. Earth Environ.*, **1**, 627–643, https://doi.org/10.1038/s43017-020-0101-7.

Pryor et al. (2020): Mean annual wind energy density changes

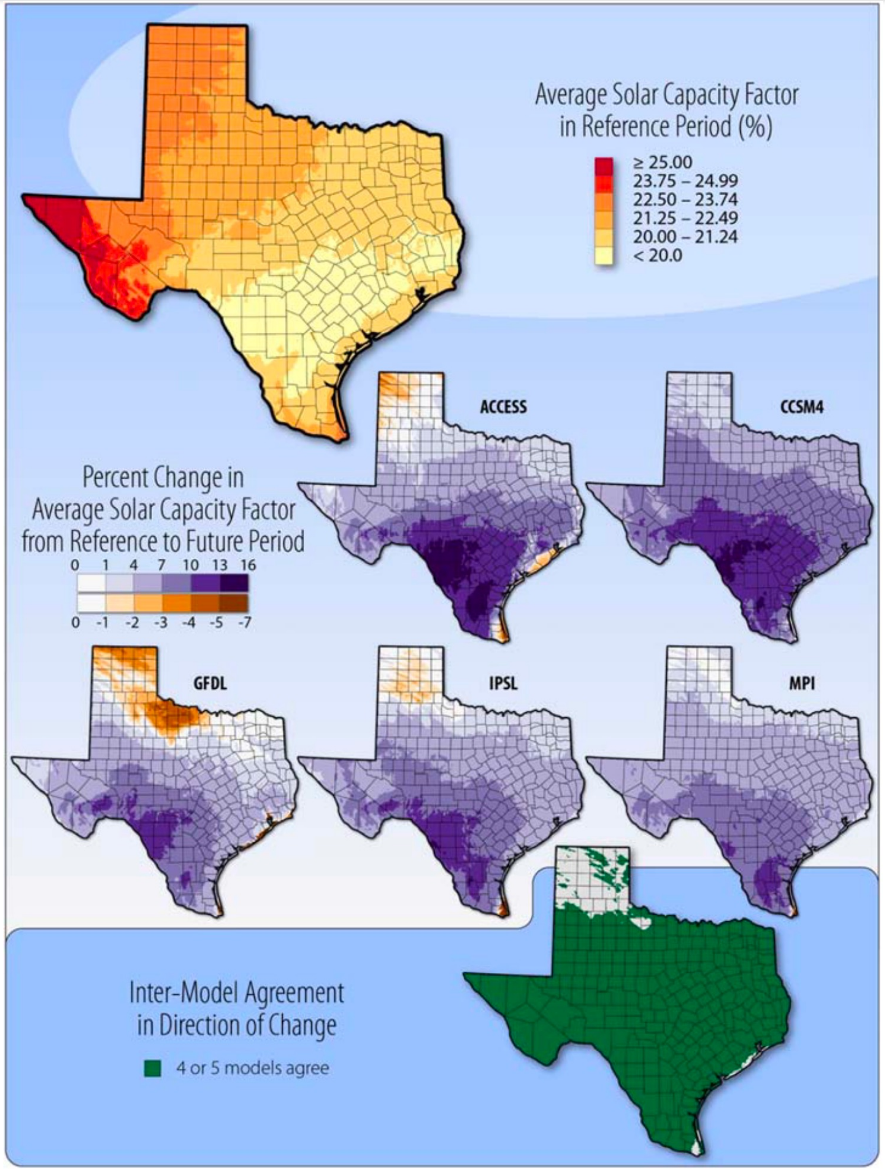
Table 3 | **Précis of research projecting wind resources for the coming decades**

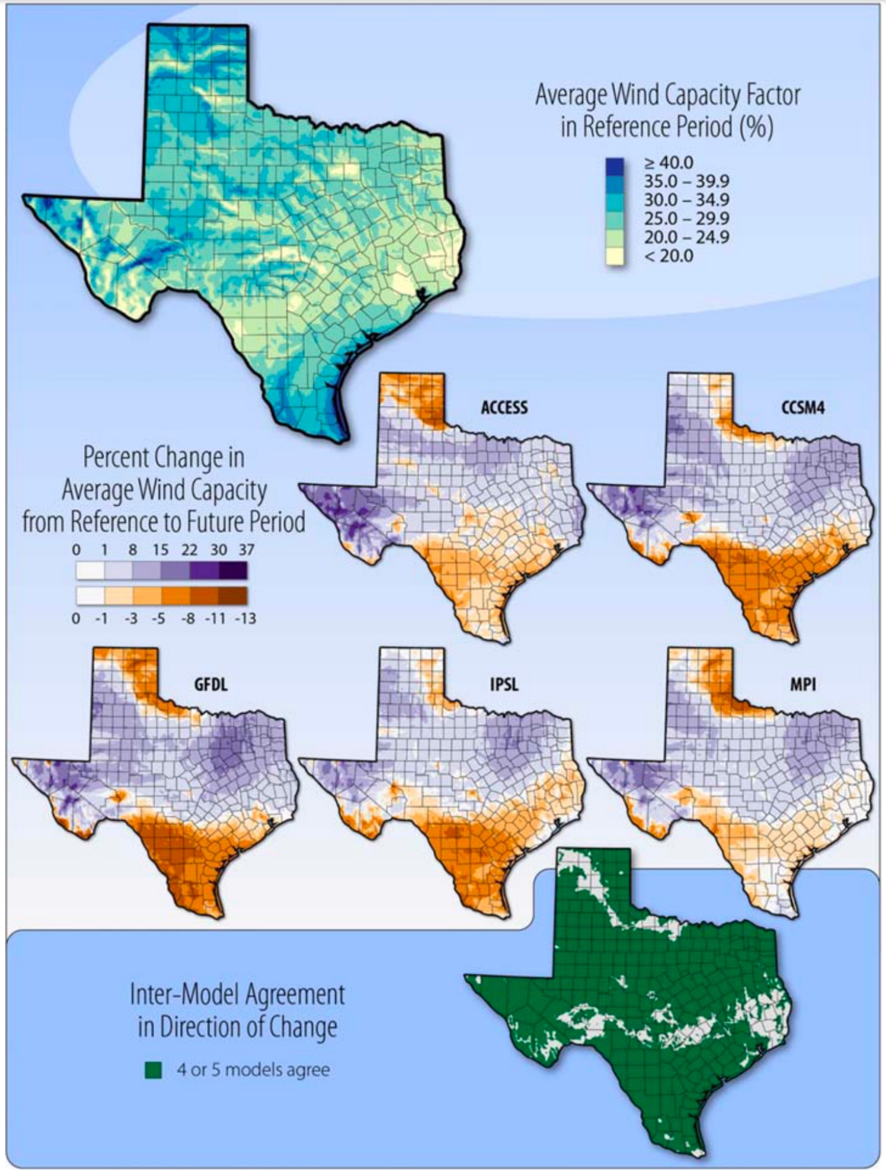
Region	Variable	Models/method (and resolution)	Projected change	Time period	Ref.
North America					
CONUS	*E*	1GCM, 1RCM (50 km)	<2% lower in south-west; 3% higher in Central Plains	(2041–2062) – (1979–2000)	18
CONUS	*E*	2GCM, 3RCM (50 km)	No emergence from natural variability	(2041–2062) – (1979–2000	80
CONUS	WS (90th percentile)	4GCM, 5RCM (50 km)	No change in Central Plains. Lower over western USA	(2041–2062) – (1979–2000	82
CONUS	WS	5GCM (1–3°)	Up to 5–10% increase in winter; declines in summer	(2079–2099) – (1979–1999)	98
CONUS	Seasonal mean WS at hub height	1GCM, 1RCM (50 km)	Remains within ±10% of contemporary climate	(2040–2069) – (1985–2005)	175
Eastern USA	WS (90th percentile)	3GCM, 3RCM (50 km) plus statistical downscaling	Up to −5%	(2041–2060) – (1981–1998)	100
Eastern USA	AEP	1GCM, 1RCM (12 km)	Up to +8% in Southern Plains; up to −5% in Northern Plains	(2075–2099) – (1980–2005)	94
S. California	Annual mean WS	12 RCM–GCM combinations (50 km)	Within ±2%	(2051–2071) – (1980–2000)	176
High Plains of central USA	*E* (80 m)	1GCM, 1RCM (50 km)	2–3% increase in Kansas; 1–2% decrease in central Colorado	(2040–2070) – (1970–2000)	95
N. America	AEP	10GCM (1–2°)	Increased AEP over Mexico. Declines over western USA. Large model-to-model divergence	(2020–2040) – (1980–2005) and (2020–2040) – (1980–2005)	177
Western Canada	*E*, WS	1GCM, 1RCM (45 km)	Change < σ (ensemble model mean)	(2031–2060) – (1971–2000)	178
Offshore areas around Mexico	*E* (50 m)	1GCM (25 km)	Declines exceed IAV in current climate	(25 years end of the 21st century) – (1985–2011)	179

Pryor, S. C., R. J. Barthelmie, M. S. Bukovsky, L. R. Leung, and K. Sakaguchi, 2020: Climate change impacts on wind power generation. *Nat. Rev. Earth Environ.*, **1**, 627–643, https://doi.org/10.1038/s43017-020-0101-7.

Losada Carreño et al. (2020): Wind/solar in Texas

- Reference period:
  - 1995–2005
- Future period:
  - 2040–2050
- Changes in wind CF agree well across models
  - Changes from +1.3–3.5% annual avg
  - Increases in W & E TX
  - Decreases in Panhandle & S TX
  - Seasonal changes rather small
  - Increased CF over most of day
- Changes in solar CF agree well across models, too
  - Increase in most areas except Panhandle

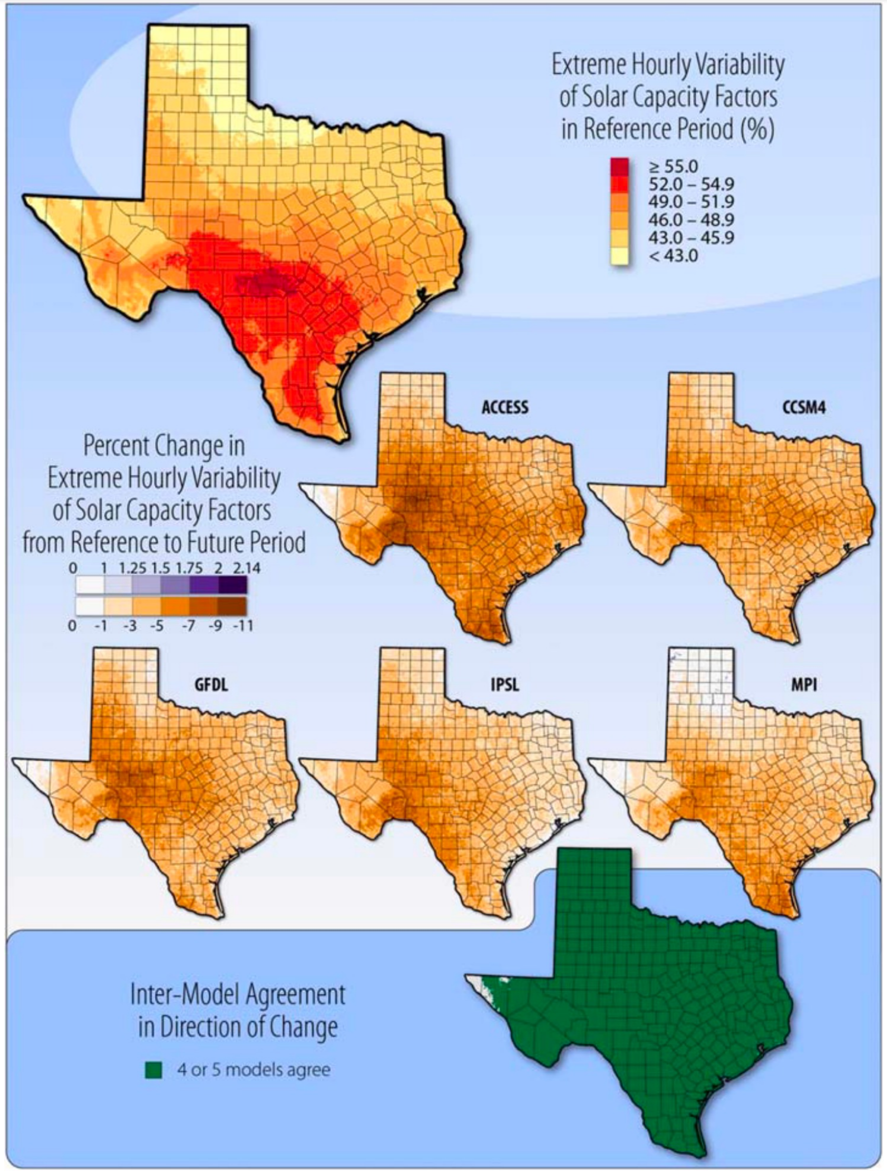


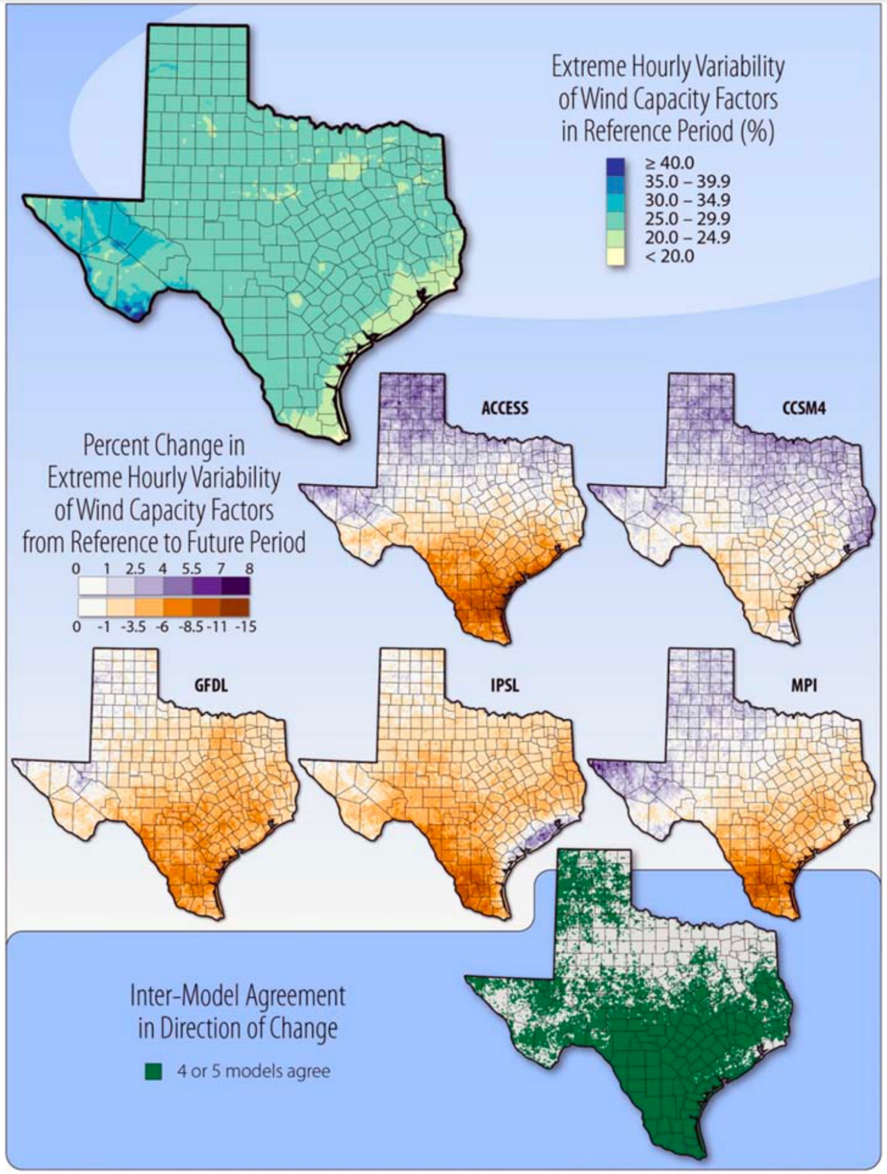


Losada Carreño, I., M. T. Craig, M. Rossol, M. Ashfaq, F. Batibeniz, S. E. Haupt, C. Draxl, B.-M. Hodge, and C. Brancucci, 2020: Potential impacts of climate change on wind and solar electricity generation in Texas. *Clim. Change*, **163**, 745–766, https://doi.org/10.1007/s10584-020-02891-3.

Losada Carreño et al. (2020): Wind/solar in Texas

- Reference period:
  - 1995–2005
- Future period:
  - 2040–2050
- Changes in 95th percentile hourly variability solar CF agrees well across models
  - Roughly 3–10% less extreme hourly CF variability almost statewide
- More disagreement in 95th percentile hourly variability wind CF, though
  - Extreme hourly variability mostly decreases in S TX
  - Increases in Panhandle
  - Mixed signal in between





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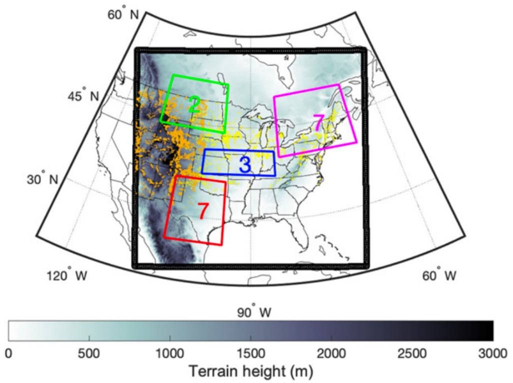
Pryor et al. (2023): Probability of wind drought/bonus

- WRF at 12-km grid spacing, dynamically downscaling MPI-ESM-LR under RCP8.5 forcing from 2010–2049
- 14 of 19 wind farms examined retain capacity factor variability in the 2040s consistent with that from the 2010s, but the remaining 5 farms all saw decreases in 50th percentile annual capacity factor
- Wind drought probability trending upward and wind bonus probability trending downward for Northern Great Plains
  - But even these small trends are within the envelope of current interannual variability
- Slight increase in wind drought probability in Midwest, but otherwise no clear trends in the regions studied through 2040s



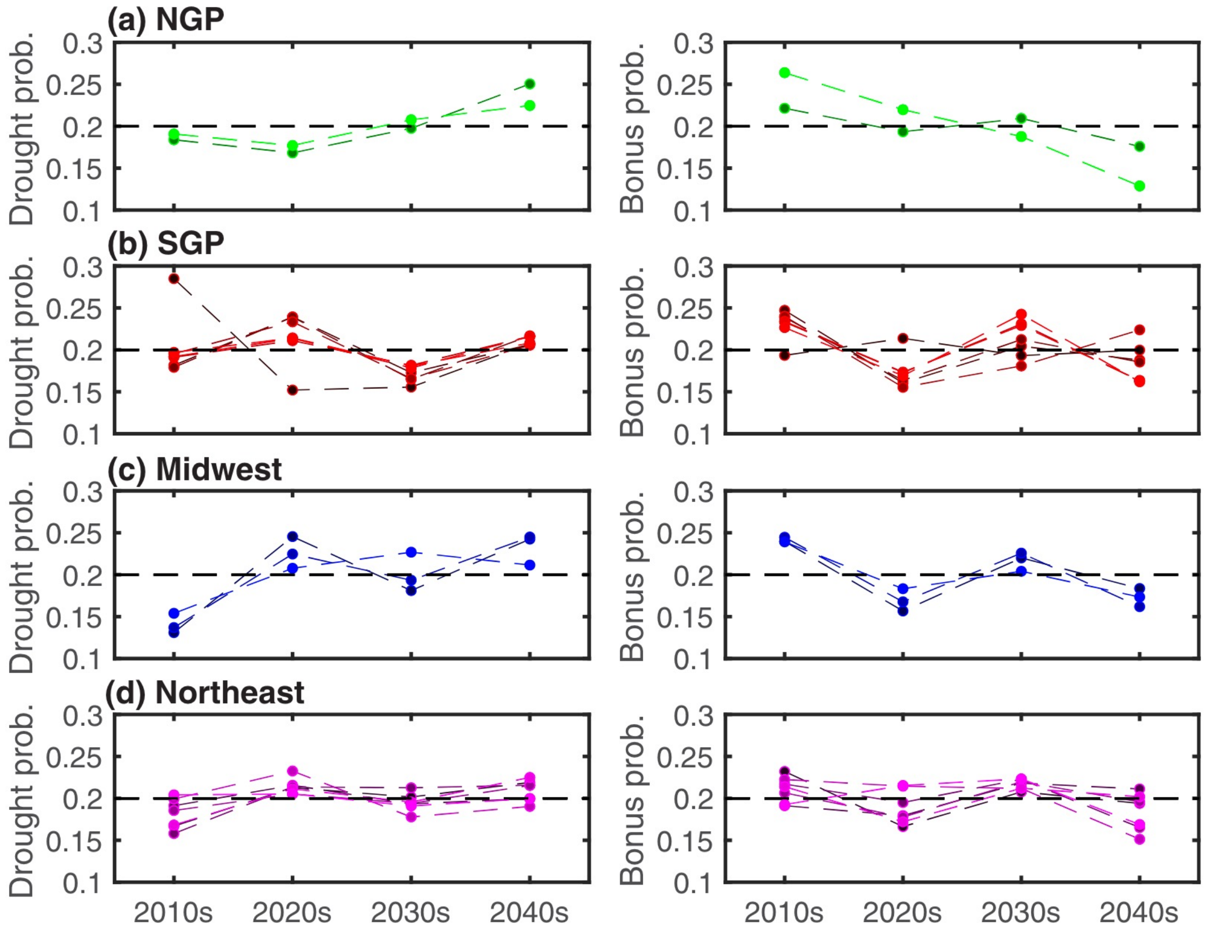
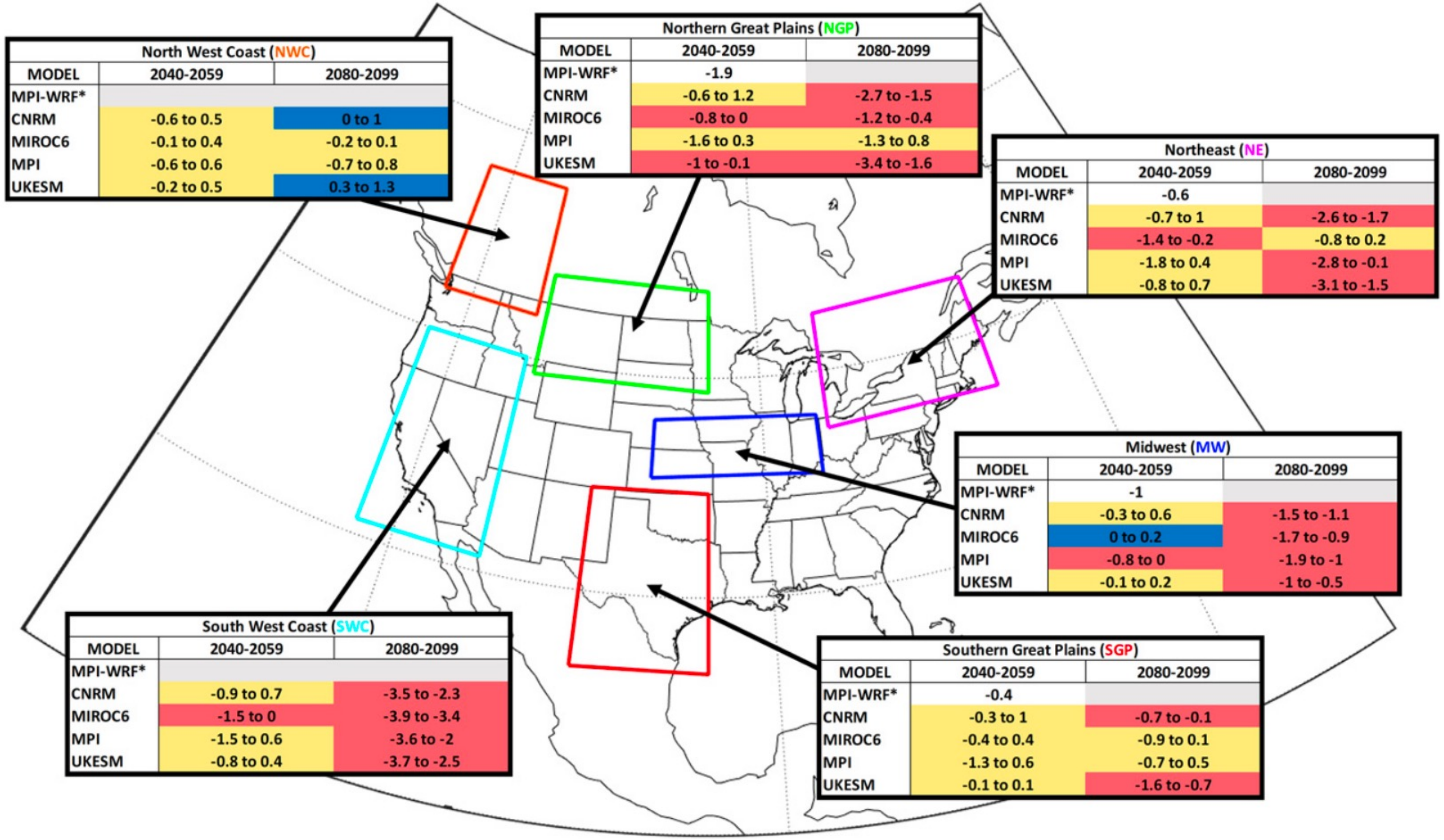


FIG. 9. Time series of the probability that any 30-day period in the given decade (left) will be a wind drought (i.e., will fall below the 20th-percentile 30-day running-mean CF for that period of the year ability or (right) will be a wind bonus period (i.e., exhibit anomalous high CF that fall above the 80th-percentile 30-day running-mean CF for that period of the year. The regions are listed in west–east order: (a) northern Great Plains, (b) southern Great Plains, (c) Midwest, and (e) Northeast. Wind farm locations are color coded by the regions shown in Fig. 3, with different locations in a given region denoted by the varying hues (as in Fig. 4). The horizontal dashed black line in each panel shows a probability of 0.2.

Pryor, S. C., J. J. Coburn, R. J. Barthelmie, and T. J. Shepherd, 2023: Projecting future energy production from operating wind farms in North America. Part I: Dynamical downscaling. *J. Appl. Meteor. Climatol.*, **62**, 63–80, https://doi.org/10.1175/JAMC-D-22-0044.1.

Coburn and Pryor (2023): Probability of wind drought/bonus

- Part II to Pryor et al. (2023)
- Statistical downscaling of four climate models using the SSP585 scenario for both mid- and late-century
- Current climate is 2000–2019
- For mid-century, generally small changes of inconsistent sign in median annual CF across the models, though a majority have a slight decrease
- For late-century, more consistently negative trends in median annual CF, except in NWC (but only 1 farm analyzed there)



North West Coast (NWC)

MODEL	2040-2059	2080-2099
MPI-WRF*		
CNRM	-0.6 to 0.5	0 to 1
MIROC6	-0.1 to 0.4	-0.2 to 0.1
MPI	-0.6 to 0.6	-0.7 to 0.8
UKESM	-0.2 to 0.5	0.3 to 1.3

Northern Great Plains (NGP)

MODEL	2040-2059	2080-2099
MPI-WRF*	-1.9	
CNRM	-0.6 to 1.2	-2.7 to -1.5
MIROC6	-0.8 to 0	-1.2 to -0.4
MPI	-1.6 to 0.3	-1.3 to 0.8
UKESM	-1 to -0.1	-3.4 to -1.6

Northeast (NE)

MODEL	2040-2059	2080-2099
MPI-WRF*	-0.6	
CNRM	-0.7 to 1	-2.6 to -1.7
MIROC6	-1.4 to -0.2	-0.8 to 0.2
MPI	-1.8 to 0.4	-2.8 to -0.1
UKESM	-0.8 to 0.7	-3.1 to -1.5

Midwest (MW)

MODEL	2040-2059	2080-2099
MPI-WRF*	-1	
CNRM	-0.3 to 0.6	-1.5 to -1.1
MIROC6	0 to 0.2	-1.7 to -0.9
MPI	-0.8 to 0	-1.9 to -1
UKESM	-0.1 to 0.2	-1 to -0.5

South West Coast (SWC)

MODEL	2040-2059	2080-2099
MPI-WRF*		
CNRM	-0.9 to 0.7	-3.5 to -2.3
MIROC6	-1.5 to 0	-3.9 to -3.4
MPI	-1.5 to 0.6	-3.6 to -2
UKESM	-0.8 to 0.4	-3.7 to -2.5

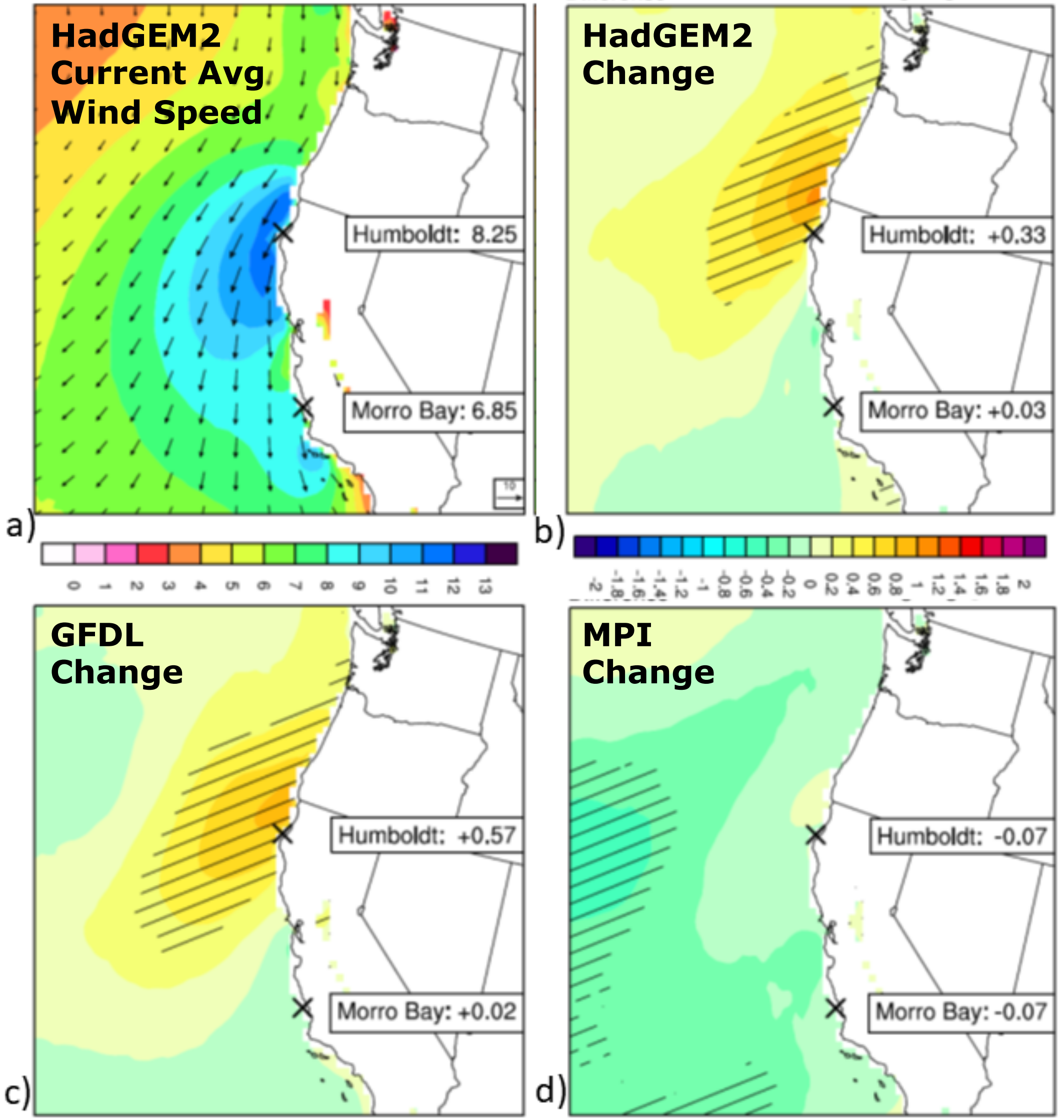
Southern Great Plains (SGP)

MODEL	2040-2059	2080-2099
MPI-WRF*	-0.4	
CNRM	-0.3 to 1	-0.7 to -0.1
MIROC6	-0.4 to 0.4	-0.9 to 0.1
MPI	-1.3 to 0.6	-0.7 to 0.5
UKESM	-0.1 to 0.1	-1.6 to -0.7

FIG. 15. Synthetic precis of projected differences in the median annual CF [P50(CF)] for the midcentury and end of the century for the pairs from Part I and this paper. Results are for the SSP585 and are summarized across wind farms in a given region (see Fig. 1). Results for MPI-WRF dynamical downscaling are the differences of 2040–49 vs 2010–19. Results for the statistical downscaling are shown for 2040–59 and 2080–99 vs 2000–19, and the range denotes the variations across the downscaled ESMs. The shading denotes the direction of change: red indicates that all projections from the five ESMs are lower in the future, blue indicates that all projections are higher, and yellow indicates that the projected changes span 0.

Coburn, J., and S. C. Pryor, 2023: Projecting future energy production from operating wind farms in North America. Part II: Statistical downscaling. *J. Appl. Meteor. Climatol.*, **62**, 81–101, https://doi.org/10.1175/JAMC-D-22-0047.1.

Bukovsky et al. (2024): West Coast marine clouds & offshore wind



- Complex cloud processes can impact stability & turbulence characteristics, and thus offshore wind
- 100-m wind speed in MJJA in future climate (2025–2055) compared to current climate (1975–2005), with WRF forced by three climate models
- Low-level jet strengthens over northern California
- HadGEM2 and GFDL show increase in wind speed (statistically significant)
- MPI shows weak decrease in wind speed (not sig.)
- All three models show negligible change in wind speed near Morro Bay (not significant)
- Small increase in low-level cloud fraction, LLJ strength


Photos by Sue Ellen Haupt

Bukovsky, M., S. E. Haupt, S. McGinnis, T. Juliano, A. Mitra, R. Krishnamurthy, and V. Ghate, 2024: Assessing the impact of clouds on offshore wind off the US West Coast in a changing climate. *Environ. Res. Energy*, submitted.

Upcoming Research: Closer look at RE droughts in U.S.

- NSF-funded project, Cornell/NSF NCAR collaboration
- Integrated WRF (I-WRF) framework to enable end-to-end, containerized, multi-node simulation, validation, and visualization
  - I-WRF's ultimate goal is to lower the bar for multi-disciplinary researchers & students who wish to use WRF in parallel on multiple platforms, ranging from desktops to clouds to supercomputers
- Science Use Case 2: Climate Change Impacts on Wind & Solar Resources
  - Quantify variability & change in the frequency of occurrence and/or intensity of extended (30–90-day) regional wind & solar production droughts & bonus periods
  - Use WRF-Solar-Wind at 4-km grid spacing over CONUS to downscale MPI climate simulation
  - Targeting 2015–2054, validating the first 9–10 years with METplus

I-WRF

Project website: https://i-wrf.org

About Project Summary Science Teams Using I-WRF

Use Case

Climate Change Impacts on Wind and Solar Resources

Science Leads: Sara C. Pryor (Cornell), Sue Ellen Haupt and Jared Lee (NSF NCAR)

COMING SOON

Summary

- Studies show up to ±10% changes in wind & solar resource generally in the U.S., but changes are regionally & seasonally dependent (same with changes in wind/solar variability)
- Still substantial uncertainty in the details among models
- Best estimates of changes in wind drought/bonus frequency are still within range of current interannual variability
- To be most useful, climate projections should include information on variability on multiple temporal & spatial scales
- Directly using coarse-resolution climate model output is insufficient for these scientific questions — for instance, in 100-km climate models, the Rockies become a modest ridge, which has big consequences for synoptic patterns
- Farm-scale estimates require high-resolution model simulations (cloud-resolving scales)
- **Ideally, one needs to have a *physically consistent, high-resolution database* of irradiance, temperature, humidity, precipitation, etc., both in current and future climate, for whole energy system modeling and coordinated planning!**

Photos by Jared Lee at Shagaya Renewable Energy Park, Kuwait