Exploring Renewable Energy Drought Potential over CONUS

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What are renewable energy (RE) droughts?

- A shortfall of wind or solar energy generation over some time period ***due to weather variability*** compared to normally expected generation for that time of year
- Short-duration (a few hours) events can often be mitigated with battery storage, dispatchable generation, or transmission from other regions
- Longer-duration (1 day +) events are more difficult to cover, especially events with coincident wind & solar droughts
- Most RE drought events are less than 1 week, but some can last months
  - Summer 2021 over Europe
    - Lowest wind summer in the previous 60 years
    - A UK energy company reported that renewable assets generated only 68% of the normally expected power for that time of year

Shagaya Renewable Energy Park, Kuwait. Photo by Jared Lee.

How do we define an RE drought?

Shagaya Renewable Energy Park, Kuwait. Photo by Jared Lee.

- There are many different definitions used in the literature and in the industry
- Duration Given Intensity (DGI)
  - Determines the worst droughts above some fixed intensity threshold
  - Most of the RE drought literature uses DGI methods
    - Capacity factor (CF) value
    - % of long-term mean generation
    - % of long-term day of year generation
    - Wind speed value
- Intensity Given Duration (IGD)
  - Determines the worst droughts for a given duration (commonly used in hydrology)
    - E.g., 1 day, 3 days, 1 week, etc., often paired with a fixed CF or % power threshold
    - Alternatively, fit generalized extreme value (GEV) curves to determine return periods

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

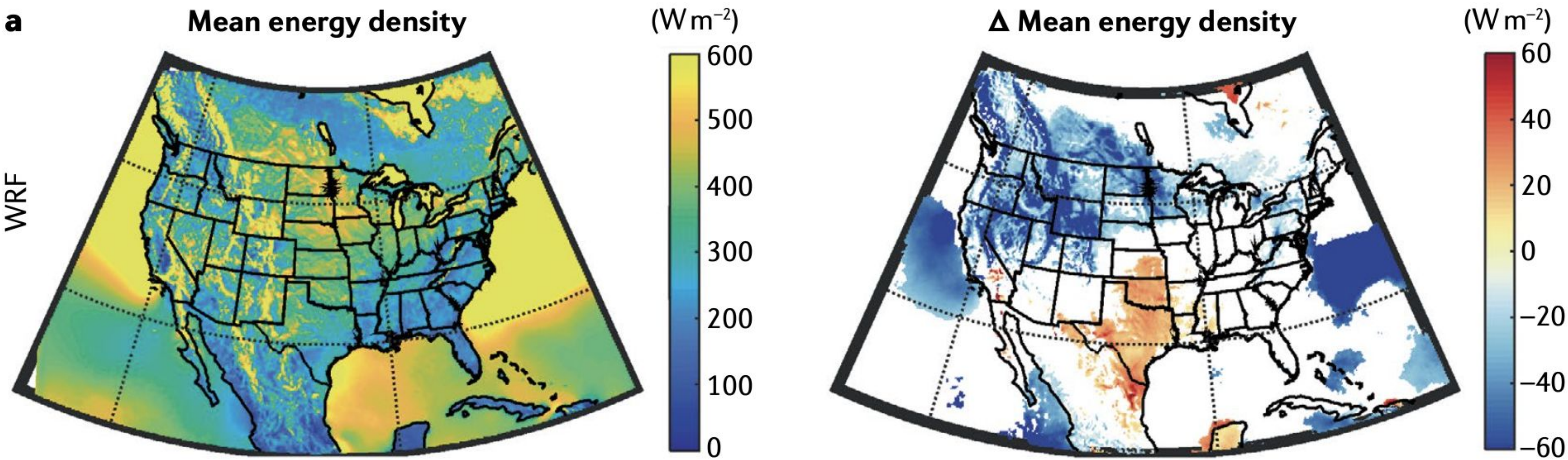


Fig. 3 | **Contemporary and projected mean annual energy density. a** | Mean annual energy density at ~100 m above ground level for 1980–2005 (left panel) and the difference between 2075–2099 and 1980–2005 (right panel). Results are derived using Weather Research and Forecasting (WRF) simulations at 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.

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

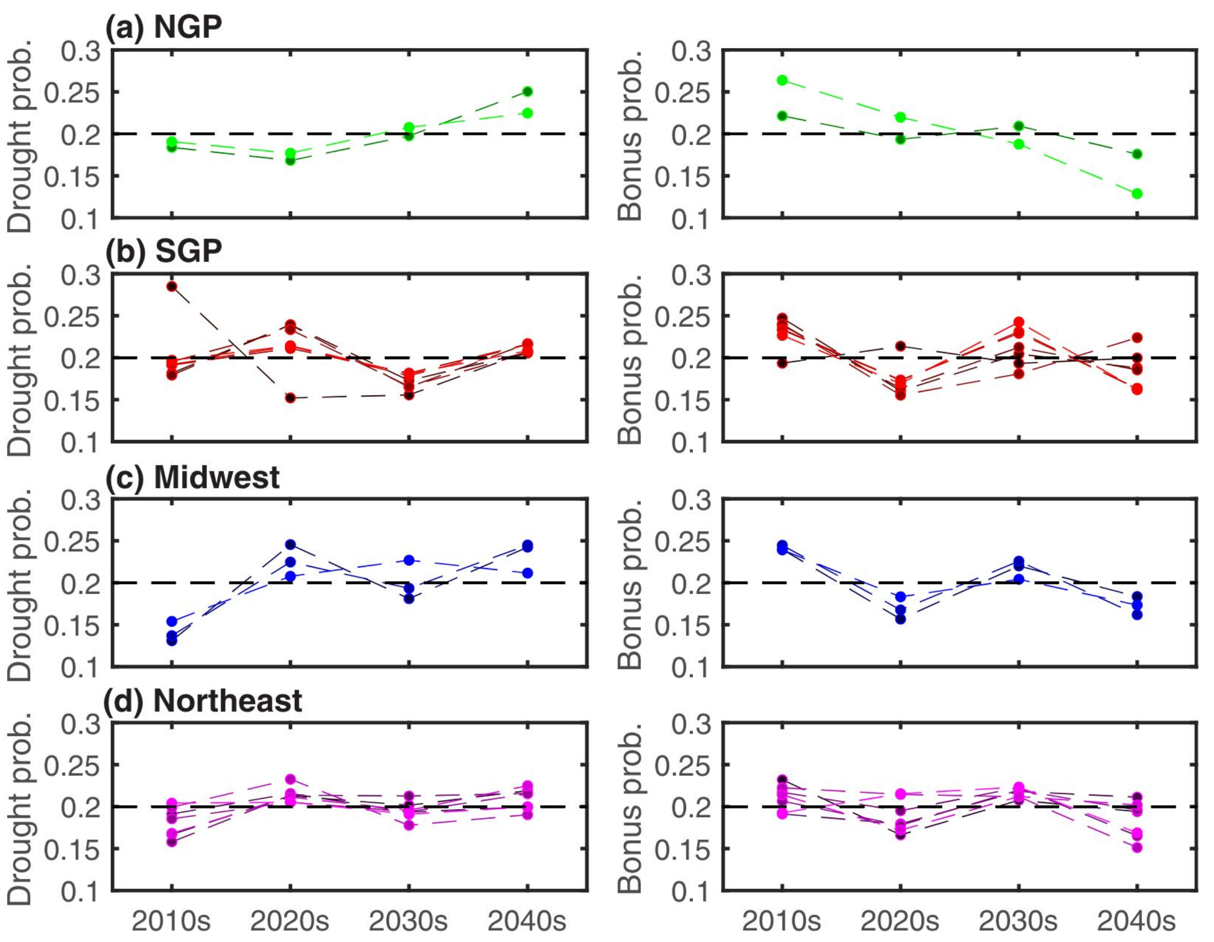
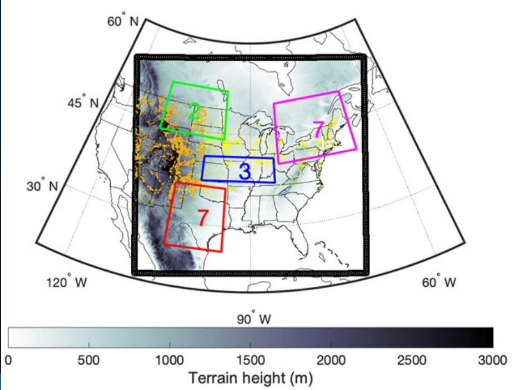


FIG. 9. Time series of the probability that any 30-day period in the given decade (left) will be a wind drought (i.e., will fall below the 20th-percentile 30-day running-mean CF for that period of the year ability or (right) will be a wind bonus period (i.e., exhibit anomalous high CF that fall above 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.

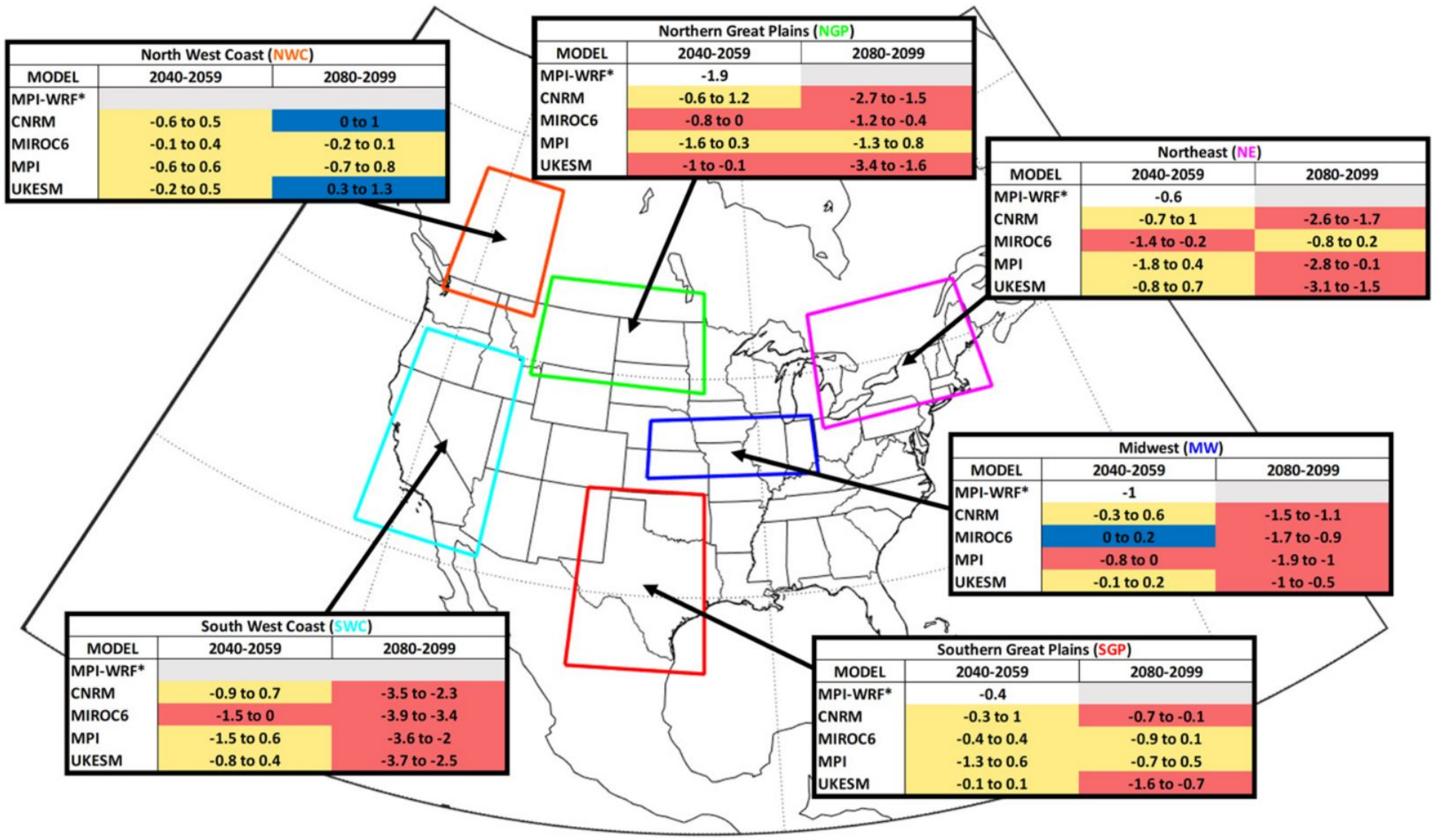
- Slight increase in wind drought probability in Midwest, but otherwise no clear trends in the regions studied through 2040s



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 SSP5-85 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.

Prior work evaluating ERA5 for RE droughts

- In addition, three papers from Wilczak et al. in 2024 and 2025 form a solid foundation for our work in this study
- The ERA5 reanalysis dataset (~31-km grid) is commonly used as the best representation of past atmospheric states for energy system modeling… but ERA5 has non-negligible biases and errors, too
- ERA5 needs to be bias-corrected to reduce errors in assessing wind & solar energy production over time
  - Bias-corrected solar irradiance against SURFRAD, SOLRAD, & DOE ARM stations in U.S. from 1998–2020
  - Bias-corrected 100-m wind speed from a collection of lidars, buoys, tall towers that each had 1–5-year periods of operation
- Droughts of 1–90 days in length studied

energies MDPI

Article

Evaluation and Bias Correction of the ERA5 Reanalysis over the United States for Wind and Solar Energy Applications

James M. Wilczak [1,*], Elena Akish [1,2], Antonietta Capotondi [1,2] and Gilbert P. Compo [1,2]

Journal of Renewable and Sustainable Energy ARTICLE pubs.aip.org/aip/rse

A multi-decadal analysis of U.S. and Canadian wind and solar energy droughts EP

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Journal of Renewable and Sustainable Energy PERSPECTIVE pubs.aip.org/aip/rse

Wind and solar energy droughts: Potential impacts on energy system dynamics and research needs F

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James M. Wilczak,[1,a)] Daniel B. Kirk-Davidoff,[2] Hannah Bloomfield,[3,4] Cameron Bracken,[5] and Justin Sharp[2]

Wilczak et al. (2024a): Prior work evaluating ERA5 for RE droughts

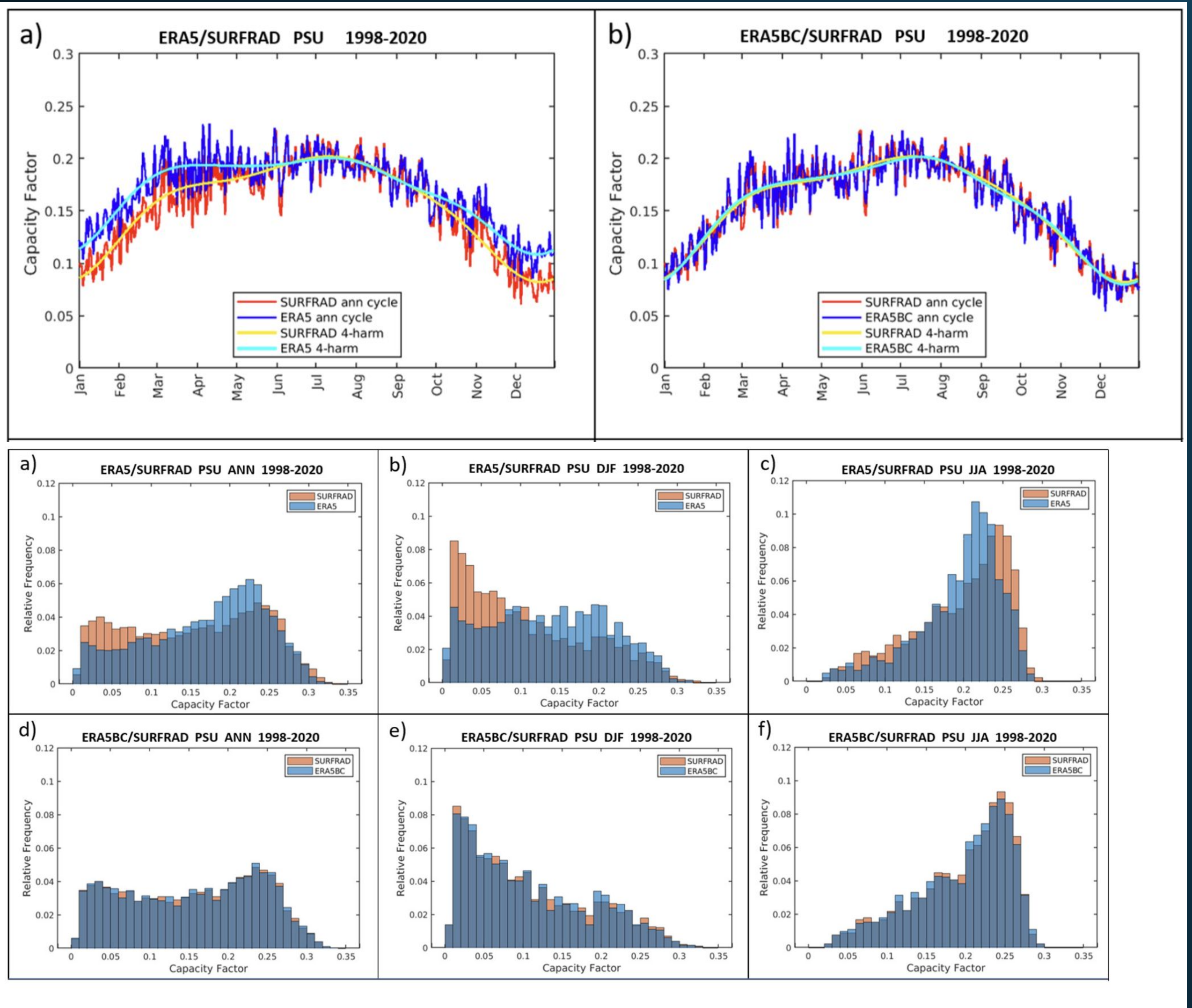
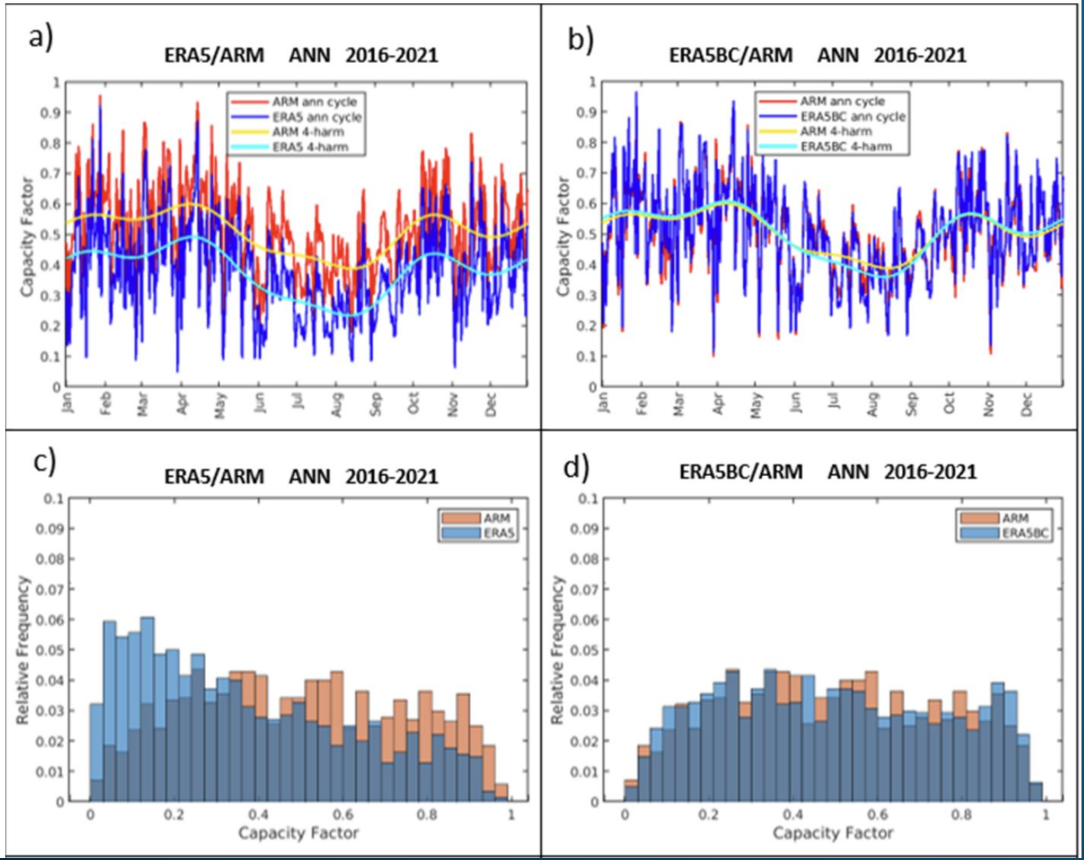


Figure 4. Solar CF histograms for the SURFRAD PSU site (orange) and ERA5 (blue), for annual (**a**), DJF (**b**), and JJA (**c**) periods, for the original ERA5 derived values (**a**–**c**), and for ERA5BC (**d**–**f**).

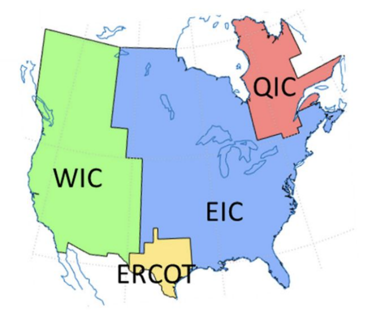
- Bias-corrected ERA5 (ERA5BC) brought solar CF and wind CF much closer to observations than raw ERA5



Wilczak, J. M., E. Akish, A. Capotondi, and G. P. Compo, 2024: Evaluation and bias correction of the ERA5 reanalysis over the United States for wind and solar energy applications. *Energies*, **17**, 1667, https://doi.org/10.3390/en17071667.

Wilczak et al. (2024b): Prior work evaluating ERA5 for RE droughts

- Using ERA5BC over 1959–2022, there are overall slight declines in both wind CF (−2.3%) & solar CF (−1.7%) over the 4-interconnect domain, but significant regional variability for wind in particular
- Wind & solar power are anti-correlated over most of U.S./Canada, except for U.S. Southwest
  - Correlation magnitudes grow with running mean length



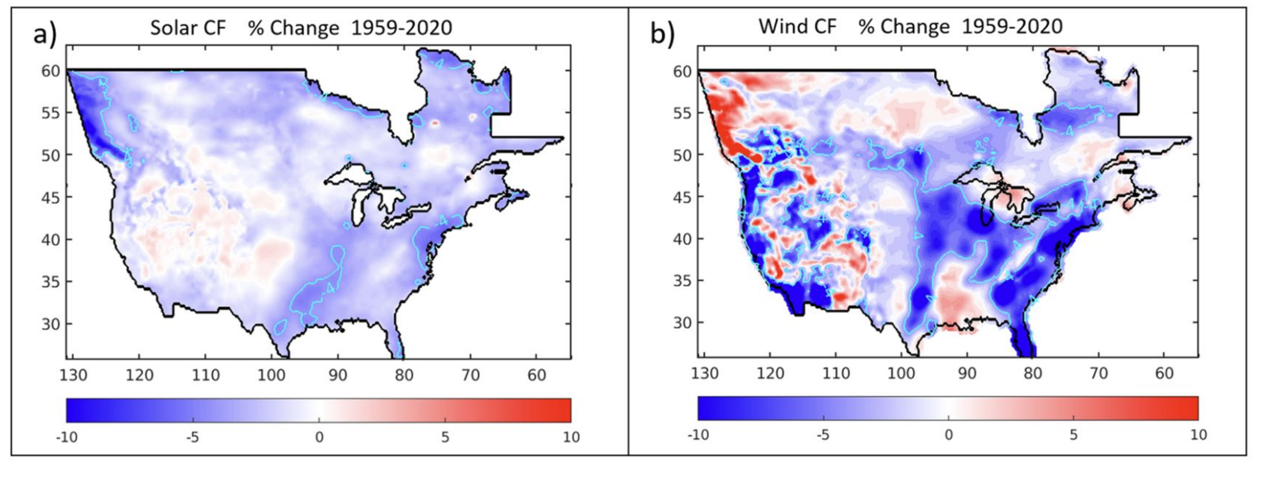


FIG. 4. Maps of (a) percent wind CF change and (b) percent solar CF change over the 1959–2022 period. Cyan contours denote a change of −4%.

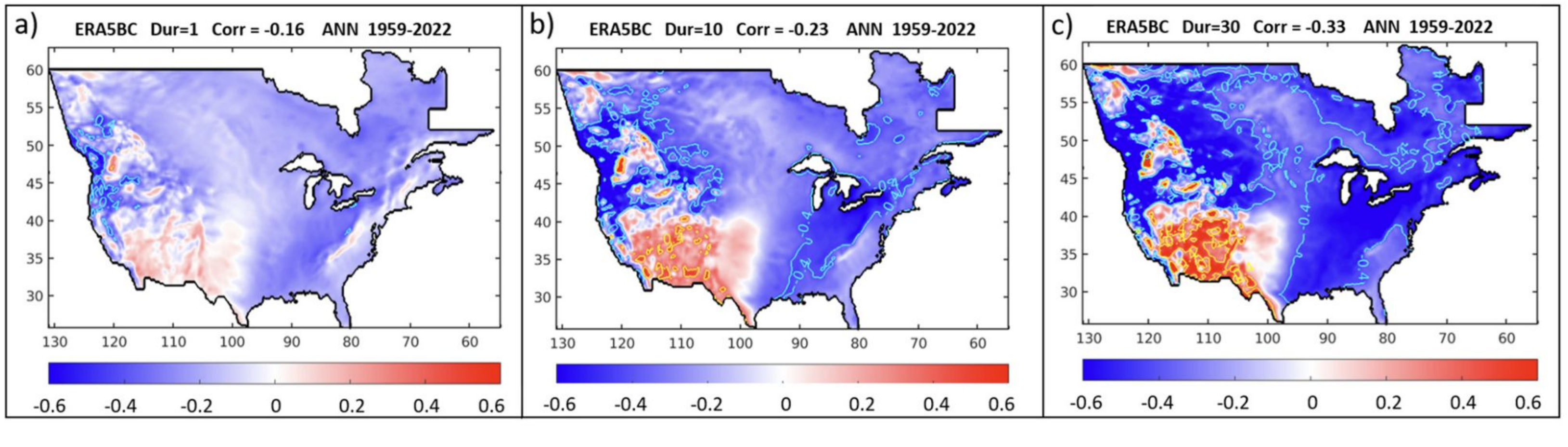


FIG. 6. Correlation coefficients of wind and solar power, for running mean durations of (a) 1, (b) 10, and (c) 30 days. Correlation coefficient values of ±0.4 are contoured.

Wilczak, J. M., E. Akish, A. Capotondi, G. P. Compo, and A. Hoell, 2024: A multi-decadal analysis of U.S. and Canadian wind and solar energy droughts. *J. Renew. Sustain. Energy*, **16**, 056502, https://doi.org/10.1063/5.0219648.

Wilczak et al. (2024b): Prior work evaluating ERA5 for RE droughts

- RE drought (& flood) intensities become stronger when looking at smaller areas like individual interconnects or even sub-regions or individual states
- Large seasonal variability in drought intensities & durations
- Relying on only wind or only solar in a small region with no multi-day storage or strong interregional transmission would require significant overbuilding

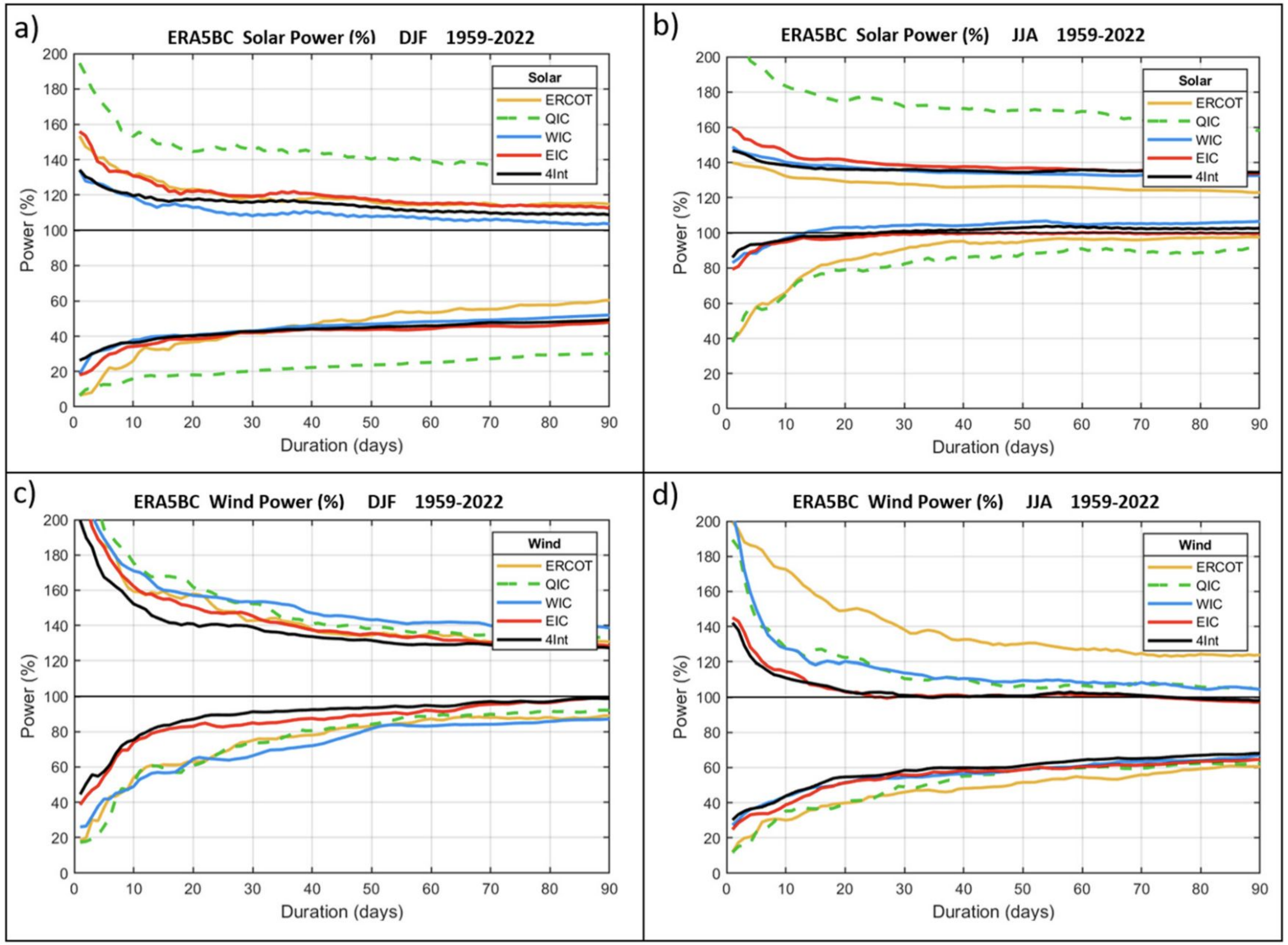


FIG. 16. Intensity–duration diagrams of the largest and smallest normalized power values in the 64-year analysis period, for (a) solar in winter (DJF), (b) solar in summer (JJA), (c) wind in DJF, and (d) wind in JJA. Color-coded lines are for the four interconnect regions (ERCOT, QIC, WIC, EIC, and for the 4Int combination of all four interconnects).

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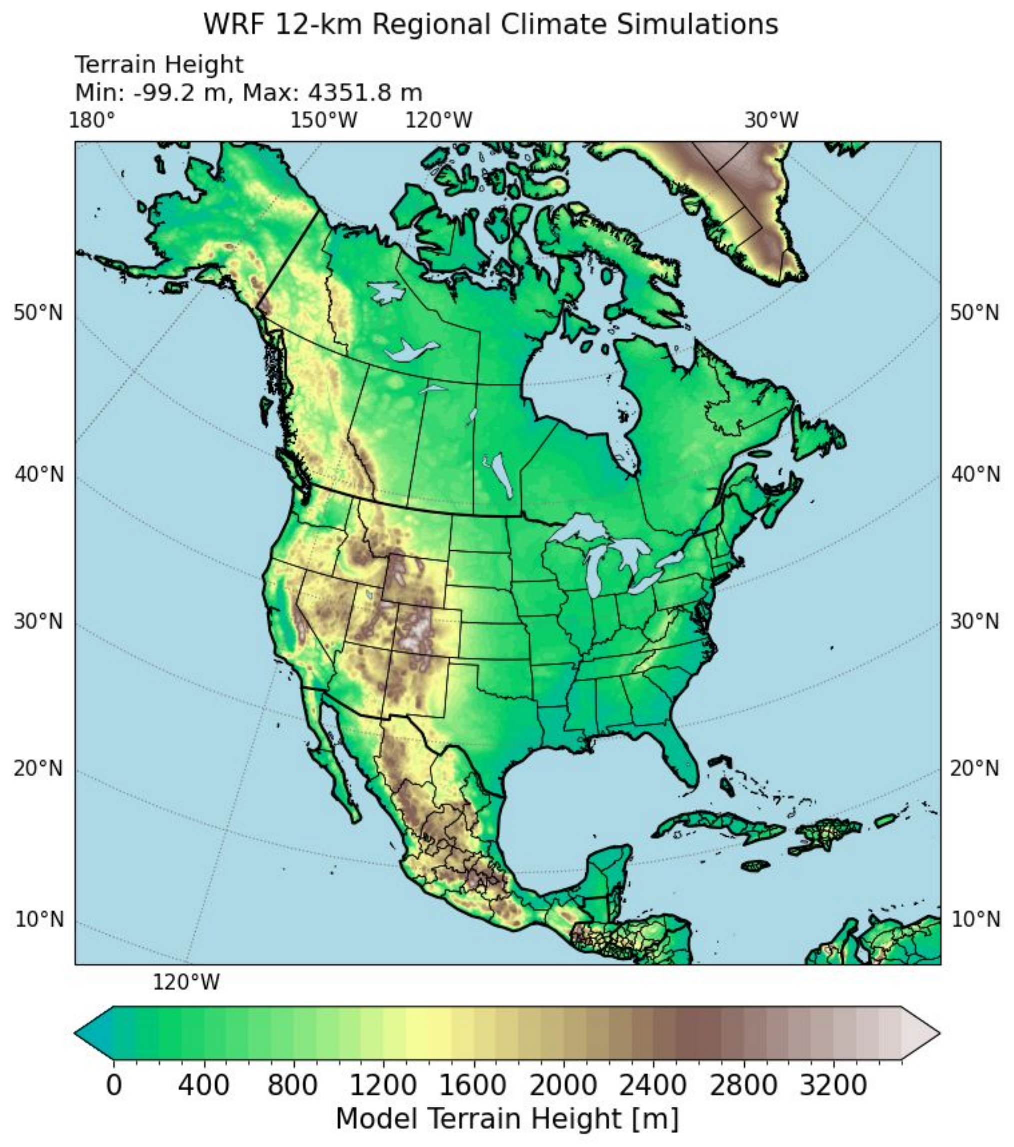
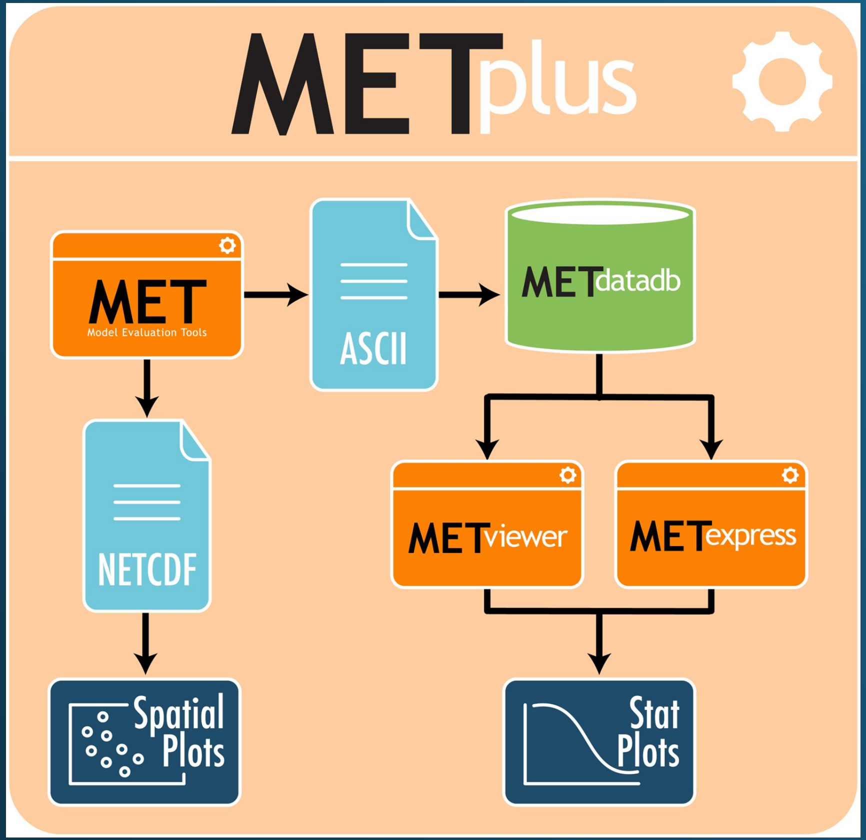
WRF Regional Climate Simulations



- WRF regional climate simulations
  - Historical climate: 1960–1999
    - Simulations done through 1968 so far
  - Future climate: 2040–2079
  - 12-km grid covering North America
  - Forced by a CMIP6 climate model
    - MPI-ESM-LR (1° grid spacing) model
    - GHG concentrations follow SSP5-85
    - Grid nudging at low wavenumbers
  - Output following NA-CORDEX conventions, and will be contributed to NA-CORDEX
    - Daily variables
    - 6-hourly variables
    - 1-hourly variables (including RE vars)
  - Output will be made available publicly with a DOI through NSF NCAR RDA
    - DOI to come soon with periodic updates of data

MODE – Method for Object-based Diagnostic Evaluation

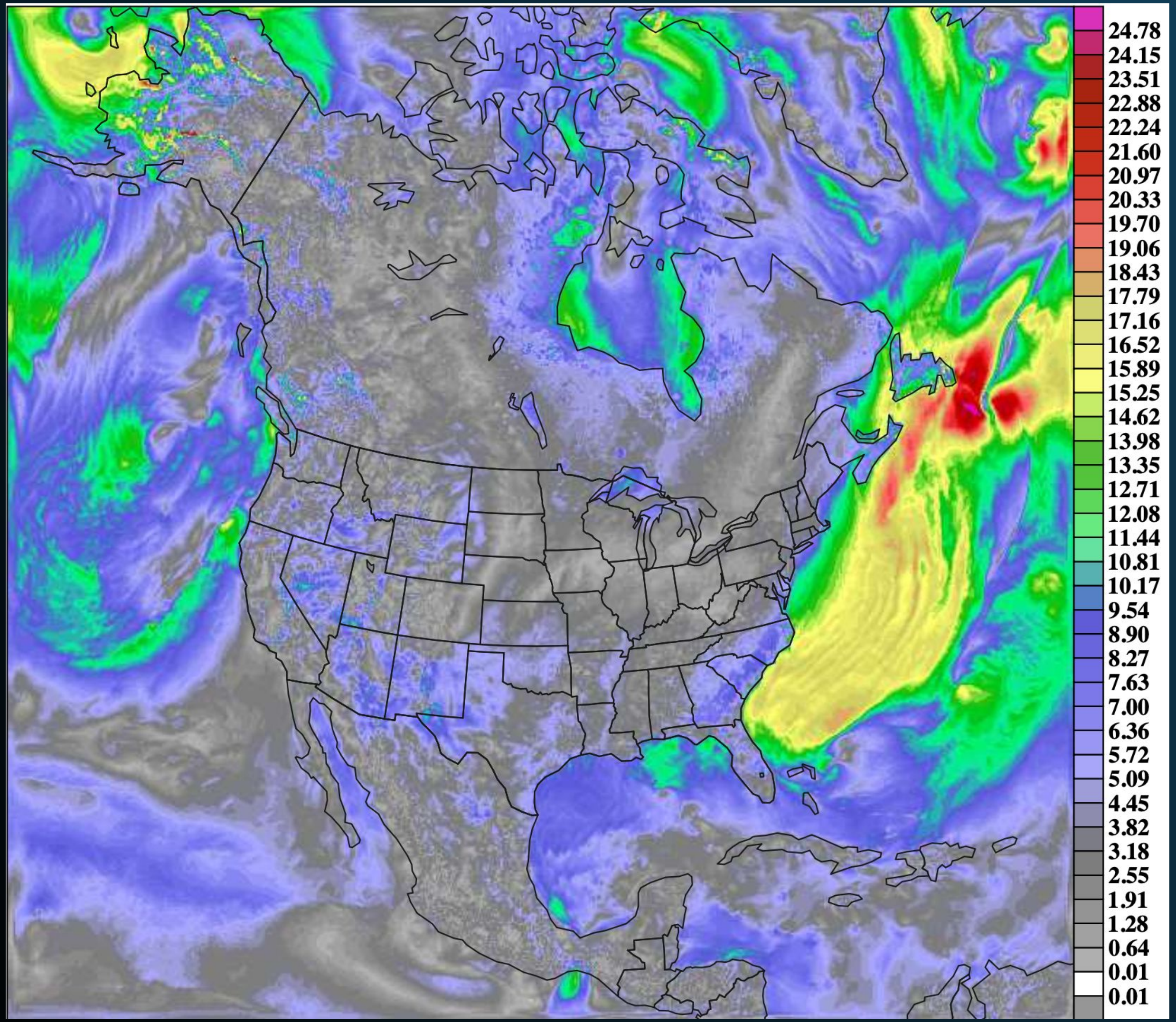
- Model Evaluation Tools (MET) is a community NWP model verification toolkit
  - Development was sponsored by NSF NCAR, NOAA, and U.S. Air Force
  - Used operationally at several national centers
- MODE (Method for Object-based Diagnostic Evaluation) was developed as one of the tools in MET to enable assessment and verification of objects beyond just POD/FAR
  - Primary use case is for comparing model precipitation fields against either observations or another model, but can be applied to other fields as well
  - Defines "objects" and characteristics of them
    - Centroid, axis angle, object area, intensity, location, etc.
  - Can be used to compare climatological distributions of selected object attributes



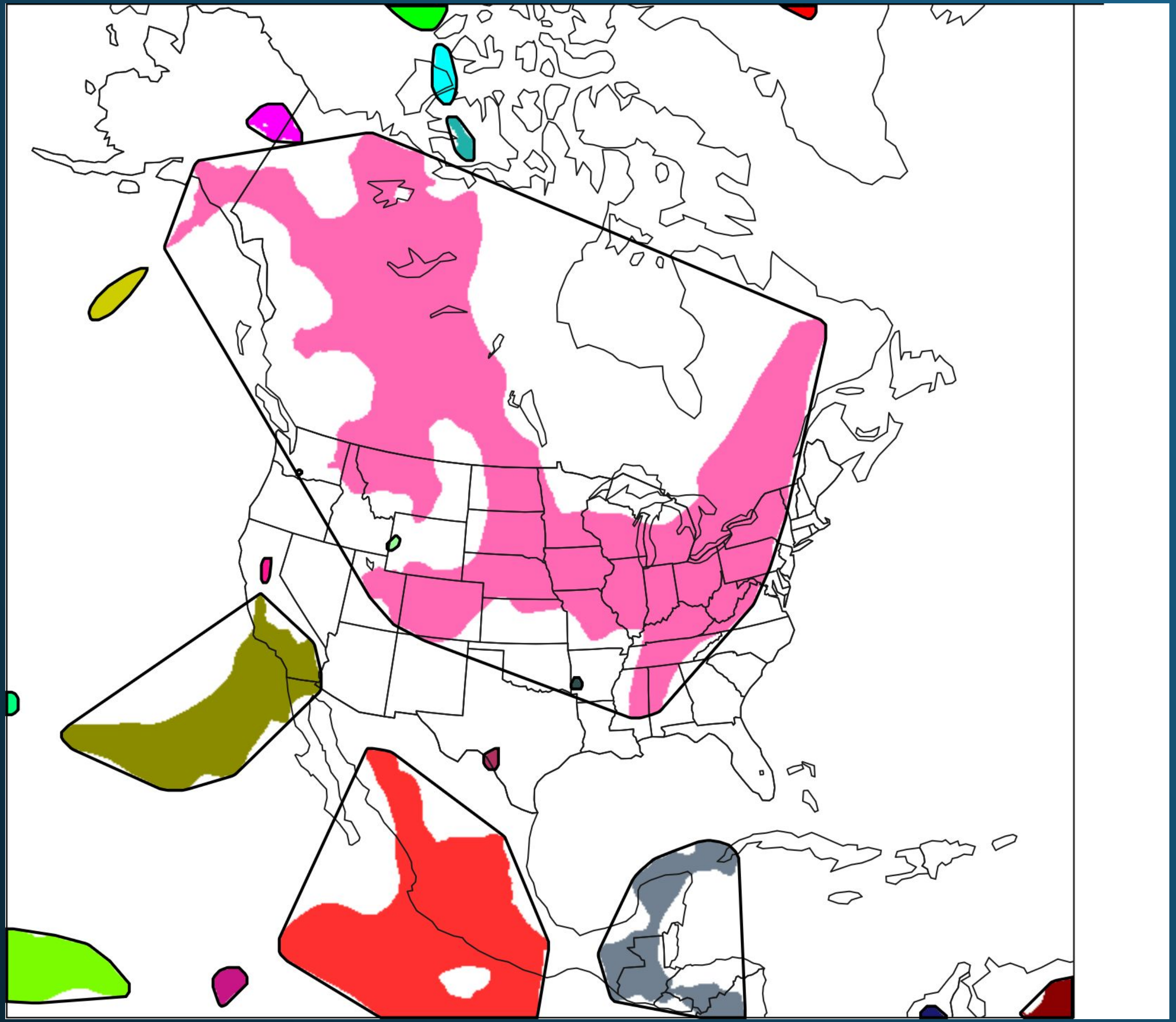
https://dtcenter.org/community-code/metplus

Example MODE analysis

WRF 24-h average 10-m wind speed, valid 1962-10-30_1800



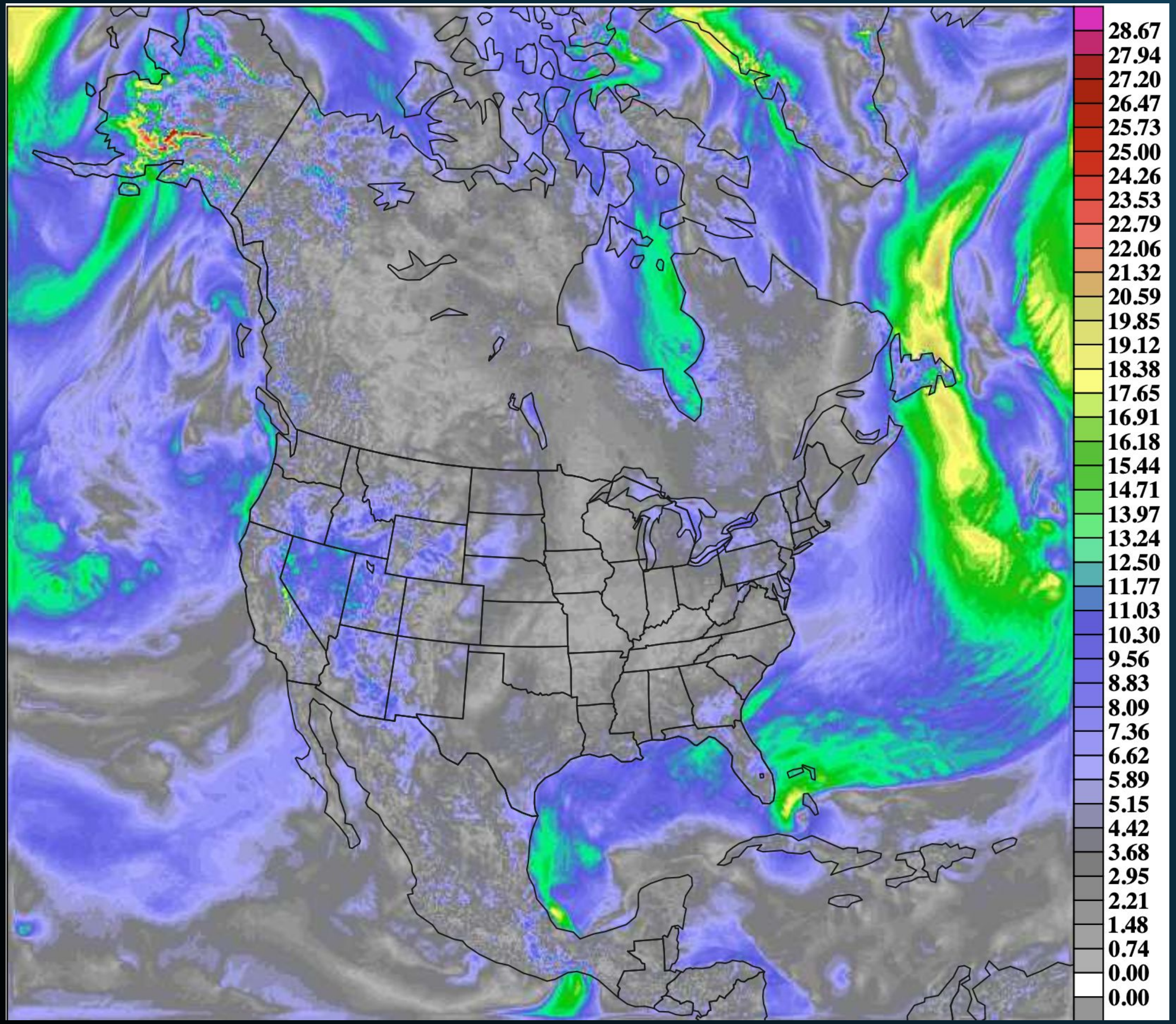
MODE objects for WS_{10} < 3.0 m/s



Cumulative area: 71,977 grid squares (10,364,688 km^2)

Example MODE analysis

WRF 24-h average 10-m wind speed, valid 1962-10-31_1800



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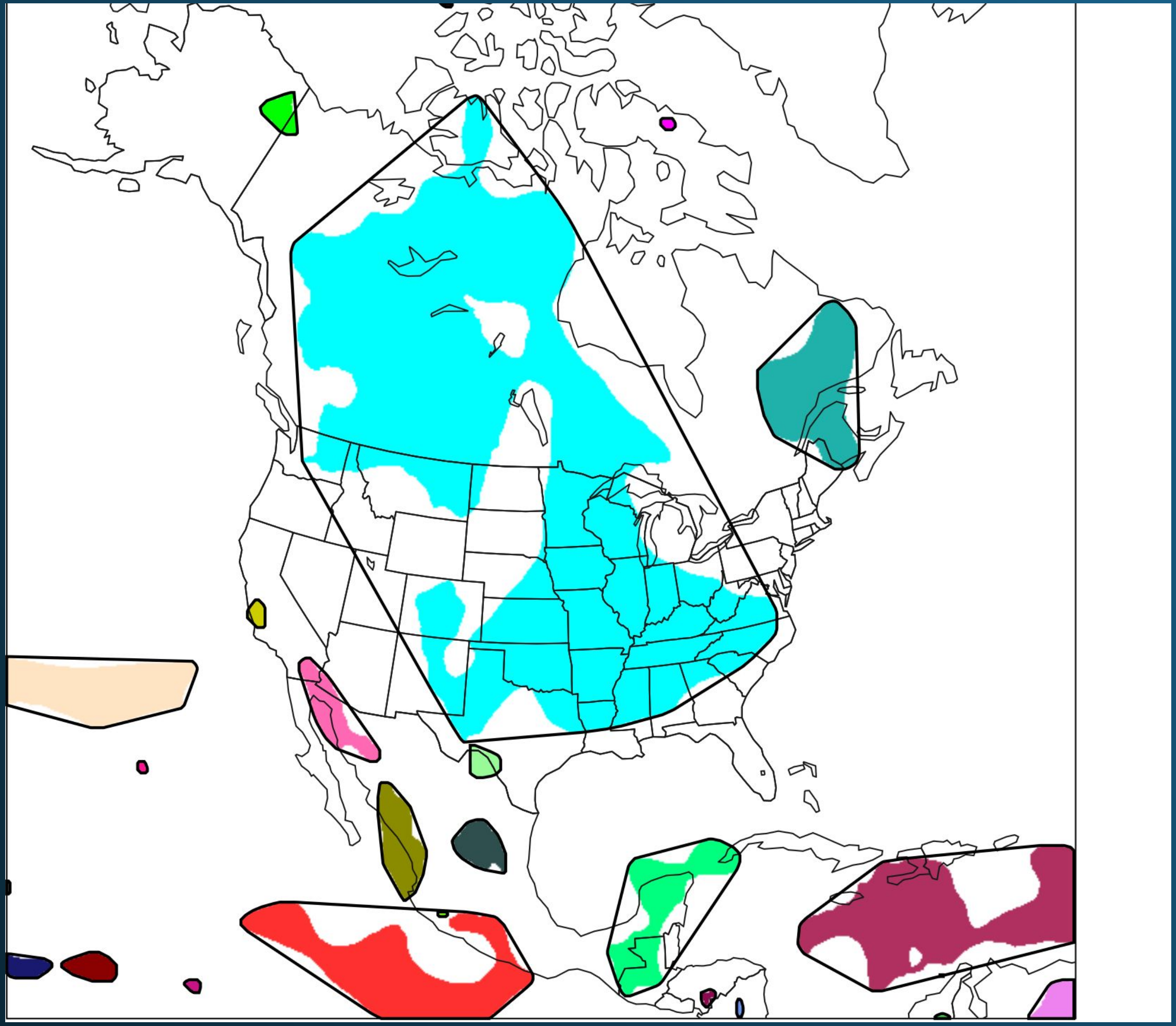
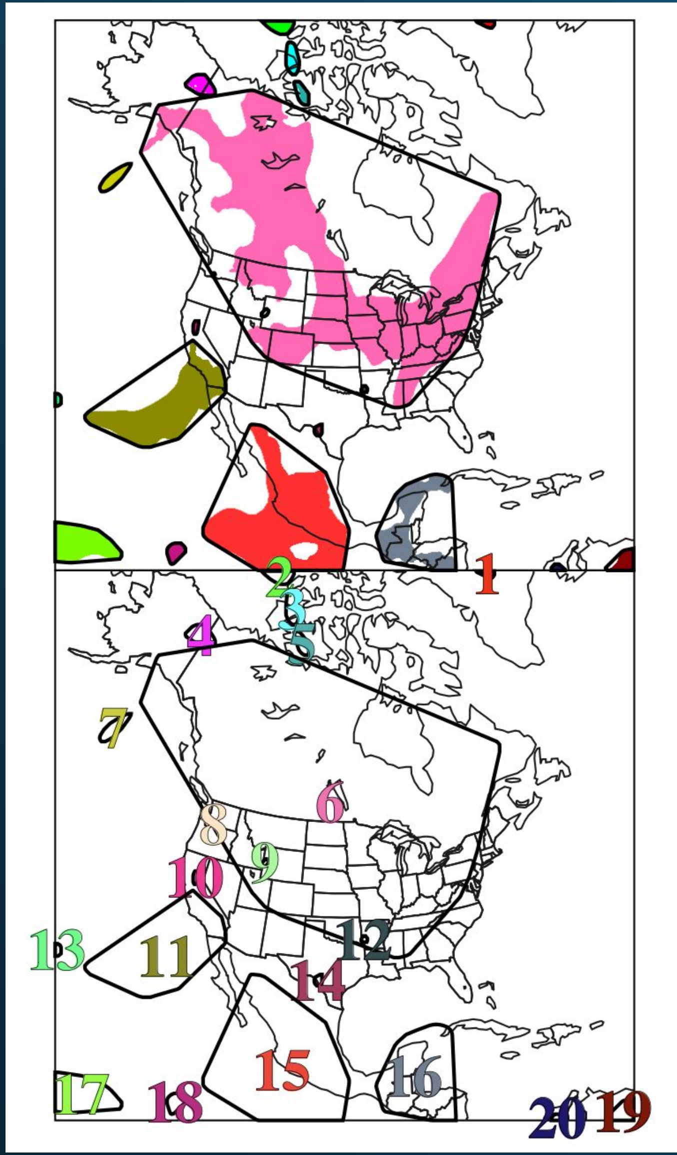
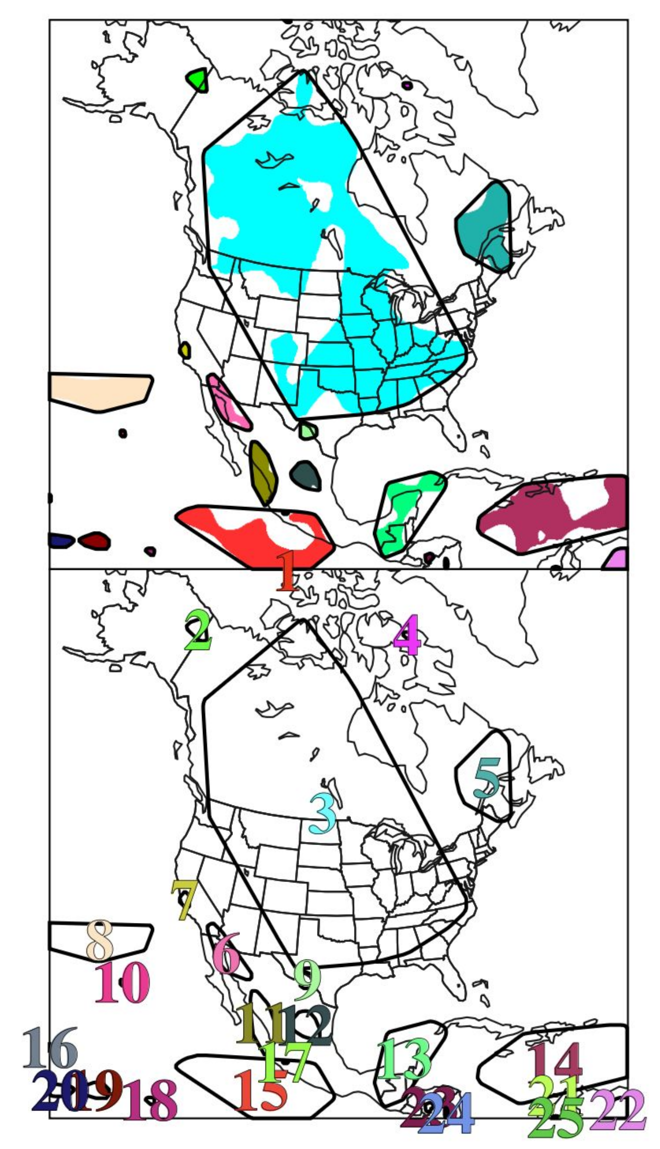


Cumulative area: 75,562 grid squares (10,880,928 km^2)

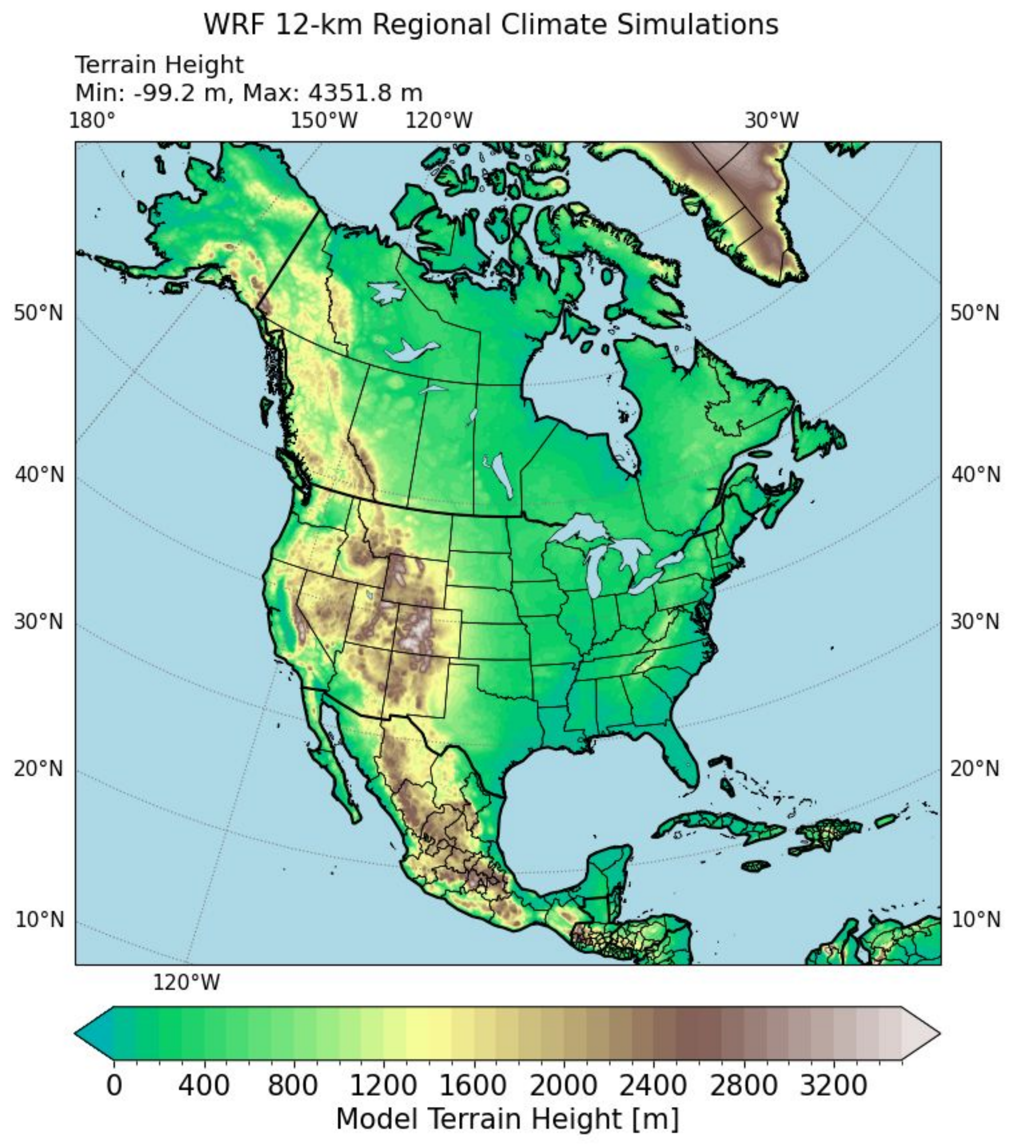
Research plan

- Convert 12-km WRF hourly output into both 100-m wind & solar irradiance CFs
- Calculate rolling averages of these wind & solar CFs for various temporal durations (e.g., 1, 3, 5, 7 days)
- Over the main interconnects (WIC, EIC, QIC, ERCOT), build climatologies of object attributes
  - Individual object area
  - Individual object 50th & 90th percentile intensities
  - Total object area
- Compare stats from historical climate WRF to both ERA5, ERA5BC, and future climate WRF





Summary



- Building off of previous work by Wilczak et al., which bias-corrected ERA5 for wind & solar capacity factors over North America and analysis of RE droughts using ERA5BC
- Currently producing 12-km WRF regional climate simulations (30+ years historical climate, 30+ years future climate)
  - Driven by SSP5-85 for upper-bound estimate of potential changes
- Using MODE to define drought objects for wind, solar, and combined wind+solar droughts, generating climatologies
  - Compare statistics of climatologies of WRF historical with ERA5 and with WRF future

Questions? Suggestions? Contact me:
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