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Research Applications Laboratory

ESIG ENERGY SYSTEMS INTEGRATION GROUP

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Dunkelflaute and Solar Drought Potential in North America

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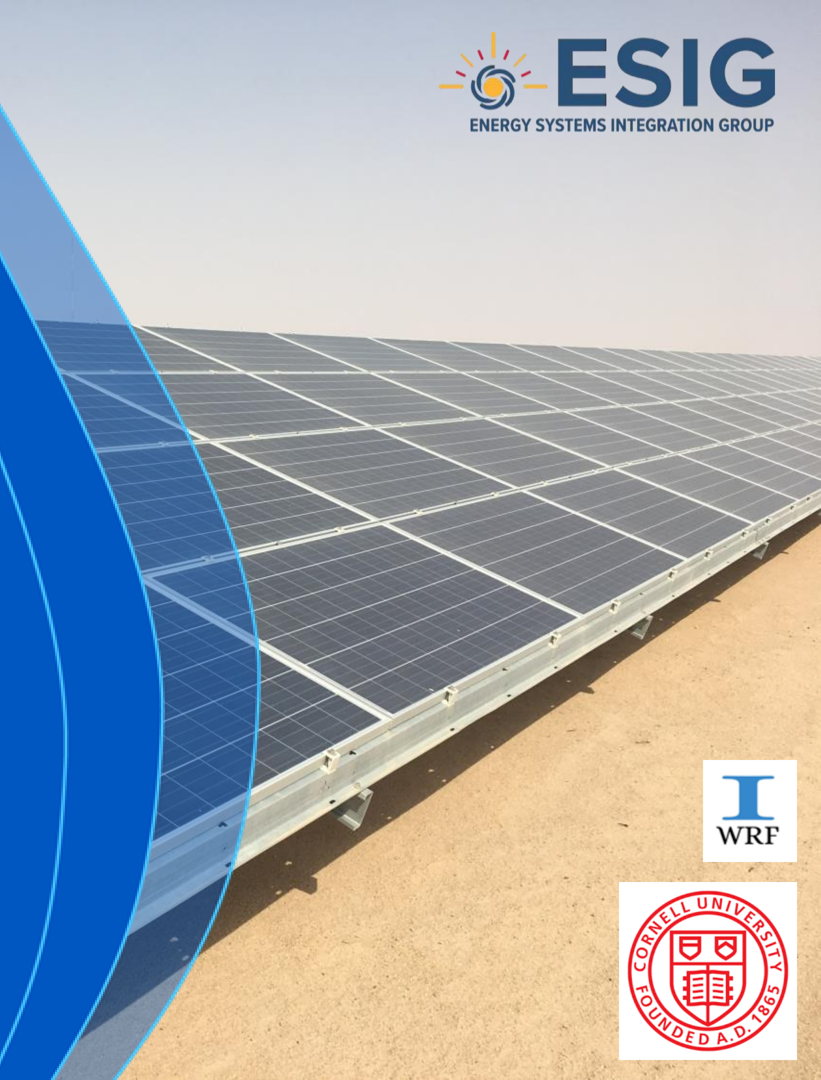

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What are renewable energy (RE) droughts?

- 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.

What are renewable energy (RE) droughts?

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

- There are many different definitions used in the scientific literature and in 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

Prior work evaluating ERA5 for RE droughts

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- Three papers from Wilczak et al. in 2024–2025 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
- ***Bias-corrected ERA5 (ERA5BC) brought solar CF and wind CF much closer to observations than raw ERA5***

energies

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

Cite as: J. Renewable Sustainable Energy **16**, 056502 (2024); doi: 10.1063/5.0219648
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James M. Wilczak,[1,a)] Elena Akish,[1,2,b)] Antonietta Capotondi,[1,2,c)] Gilbert P. Compo,[1,2,d)] and Andrew Hoell[1,e)]

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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Published Online: 28 April 2025

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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. (2024b): RE droughts in ERA5

- 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

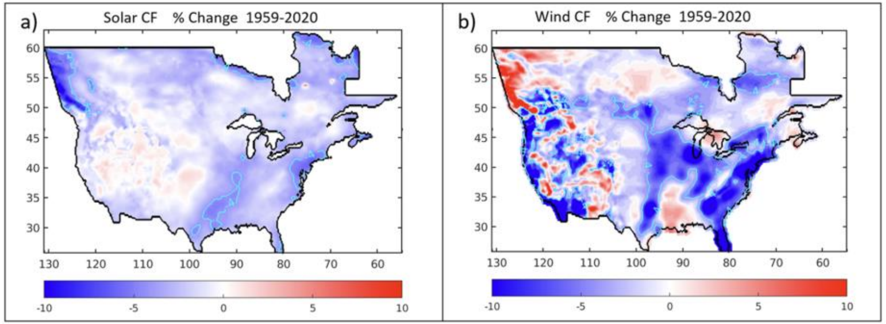


FIG. 4. Maps of (a) percent wind CF change and (b) percent solar CF change over the 1959–2022 period. Cyan contours denote a change of −4%.

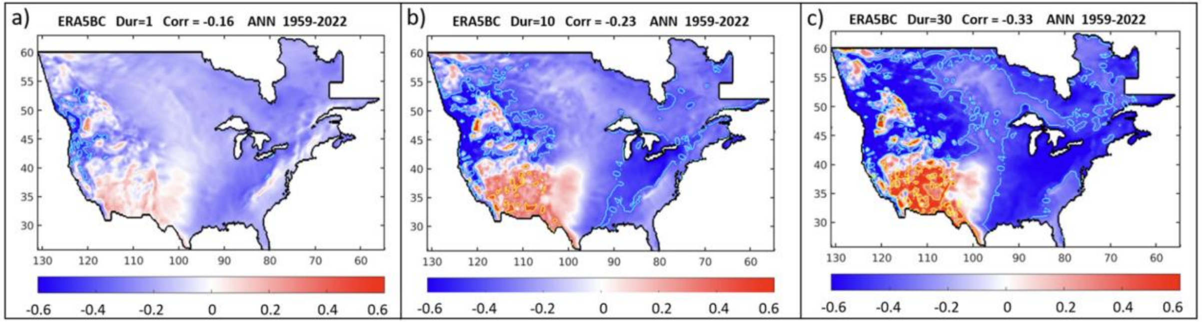


FIG. 6. Correlation coefficients of wind and solar power, for running mean durations of (a) 1, (b) 10, and (c) 30 days. Correlation coefficient values of ±0.4 are contoured.

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): RE droughts in ERA5

- 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 solar in a small region with no multi-day storage or strong interregional transmission would require significant overbuilding

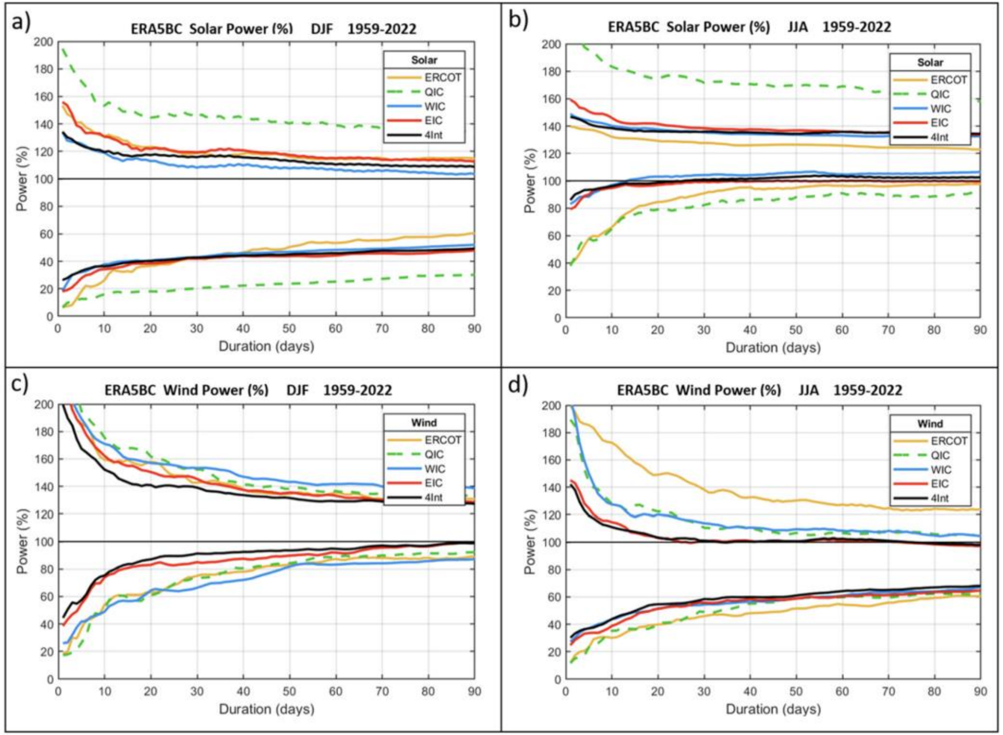
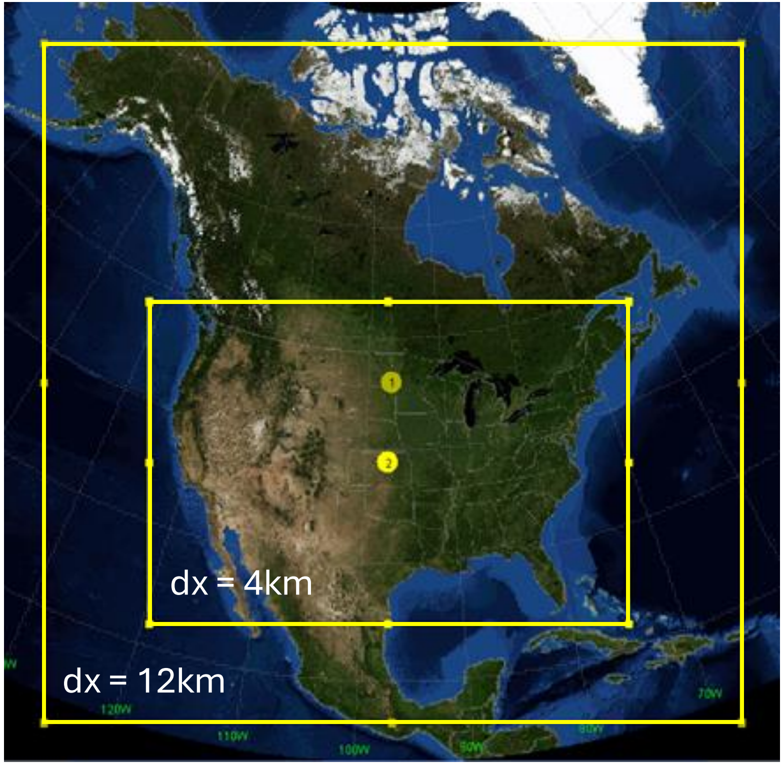


FIG. 16. Intensity–duration diagrams of the largest and smallest normalized power values in the 64-year analysis period, for (a) solar in winter (DJF), (b) solar in summer (JJA), (c) wind in DJF, and (d) wind in JJA. Color-coded lines are for the four interconnect regions (ERCOT, QIC, WIC, EIC, and for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

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.

WRF NA-CORDEX simulations

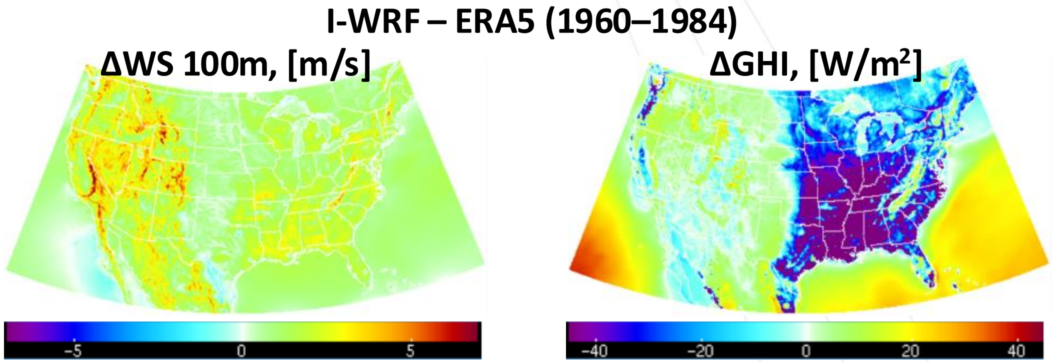


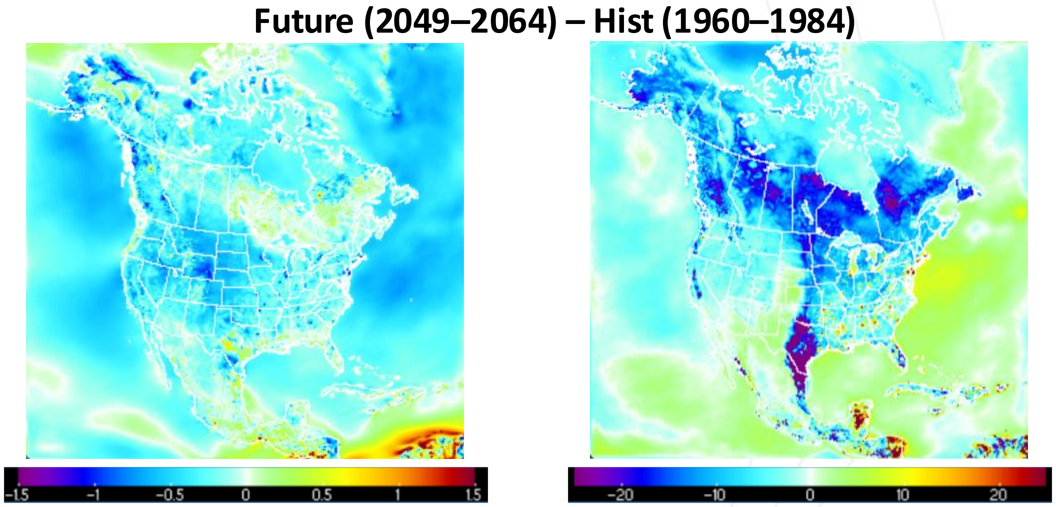
WRF v4.6.1 regional climate simulations

- Historical climate: 1960–1999 (all 40 years complete)
- Future climate: 2040–2069 (will extend to 2079) following SSP5-8.5 GHG concentrations
- 12-km grid covering North America, 4-km nest for select years (configuration details: https://github.com/levinzx/NA-CORDEX-CMIP6-CORNELL)
- Forced by a CMIP6 climate model
  - MPI-ESM1-2-LR (1° grid spacing) model
  - Spectral nudging at low wavenumbers above PBL
  - Land use/land cover and aerosol changes
- Output following NA-CORDEX conventions
  - Daily, 6-hourly, and 1-hourly variables (incl. RE vars)
- Output will be made available publicly with a DOI through NSF NCAR GDEX repository (https://gdex.ucar.edu)

Initial comparisons of WRF NA-CORDEX to ERA5

- **Contemporary climate comparable to reference reanalysis (ERA5)**
- **Differences found in regions with known ERA5 bias**
  - Negative bias in near-surface wind speeds over western U.S. (Pryor et al. 2020 *JAMC*, Pryor and Barthelmie 2021 *Nat. Energy*)
  - +21.2% bias in GHI over temperature humid sites (eastern U.S.) (https://solcast.com/validation-and-accuracy)
- **Resource projections**
  - Generally decreased wind resource BUT increases in Texas & Canada (consistent with Pryor et al. 2020 *Nat. Reviews*, Coburn and Pryor 2023 *JAMC*)
  - Decreased GHI, especially over areas with increased wind energy, increases in temperate semi-arid areas





Estimating capacity factors from WRF outputs

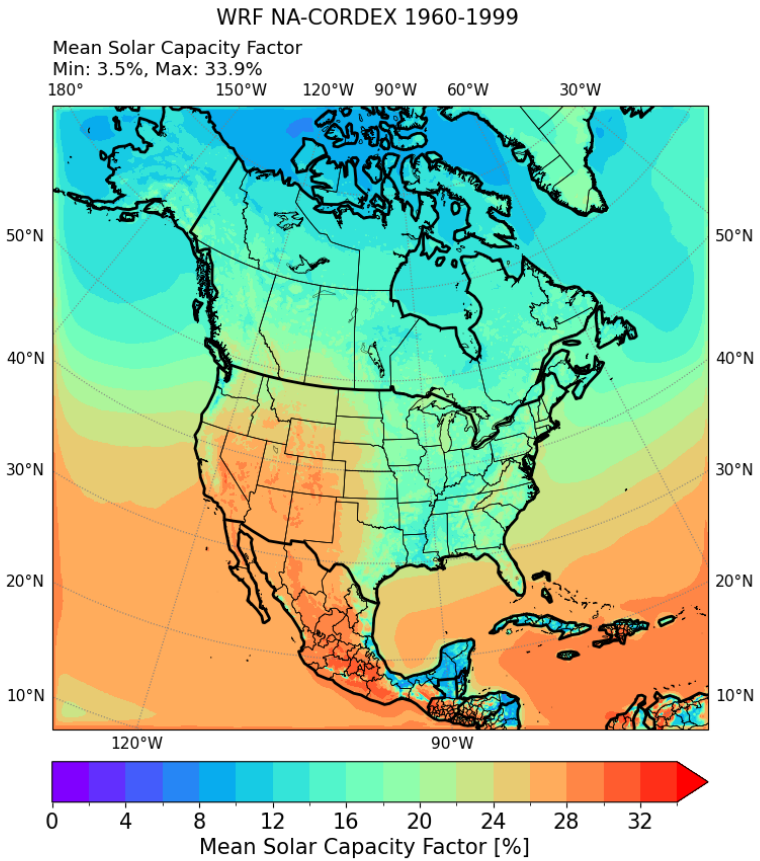
Solar CF:

- At every grid point and every hour, use the *pvlib* Python library to estimate the power output from a 5-MW fixed-tilt PV array
  - Fixed tilt angle is equal to the latitude

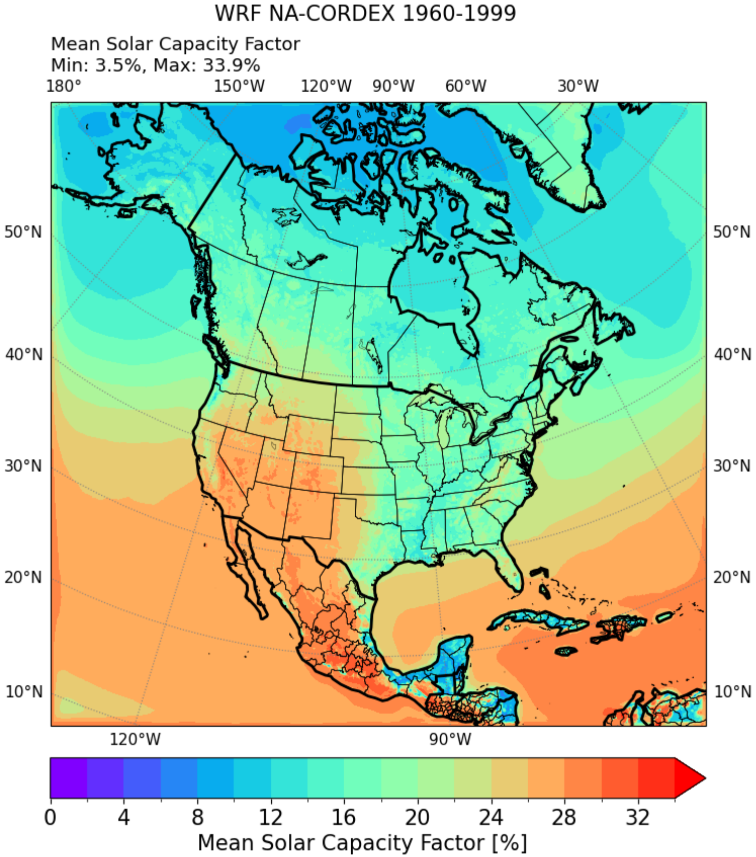
Wind CF:

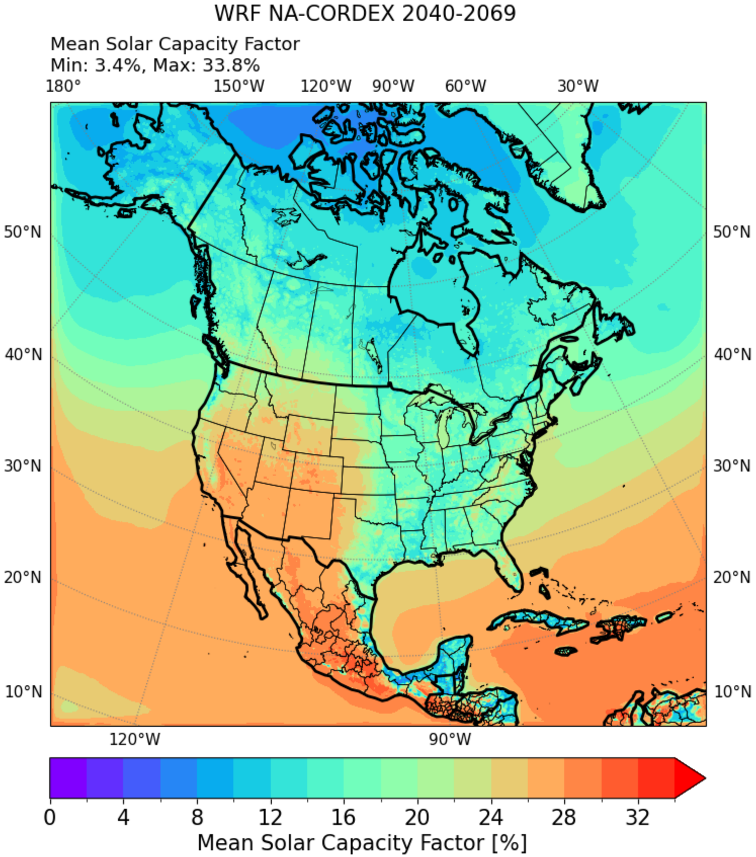
- At every grid point and every hour, use the *windpowerlib* Python library to estimate the power output from a single turbine
  - Land points: One of three turbines selected based on IEC class, determined by 30-year mean 100-m wind speed at that grid point
  - Water points: A single offshore-class turbine

Hourly NetCDF files of both solar CF and wind CF generated, and will be shared publicly alongside the WRF NA-CORDEX output



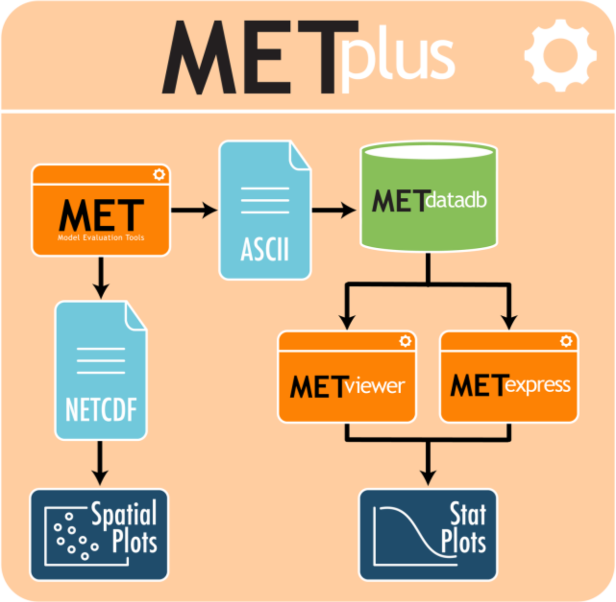
Estimated mean solar CF, historical & future





MODE:
Method for Object-based Diagnostic Evaluation

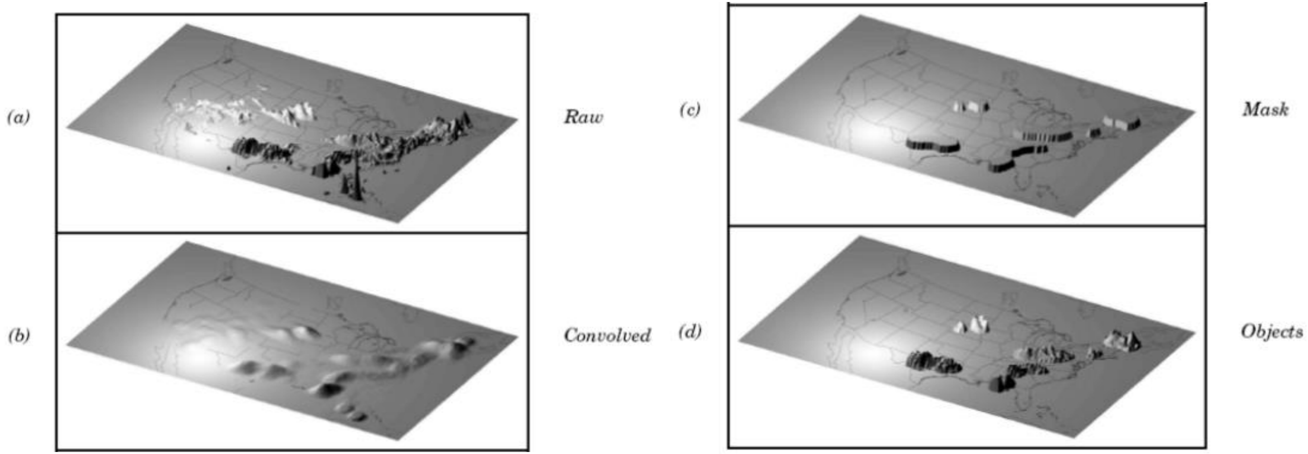
- Model Evaluation Tools (MET) is a community NWP model verification toolkit with 3500+ users worldwide
  - Development was sponsored by NSF NCAR, NOAA, USAF
  - Used operationally at several national centers
  - Over 150 traditional statistics & diagnostic methods for both point and gridded datasets, with online documentation for each component
  - Developed to allow for reproducible results by sharing config files
- MODE 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 — such as capacity factor
  - 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

Identifying an object with MODE

- Two criteria (both are configurable by the user):
  - Convolution radius governs size of objects of interest
  - Threshold (“mask”) governs outer edge of objects
- Once identified, objects retain spatially distributed data within them

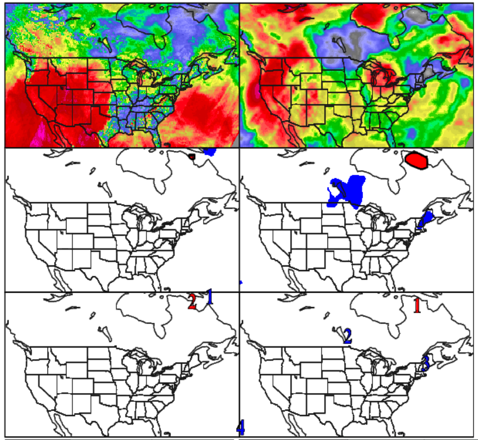


Initial MODE configuration

- MET v13.0.0 beta 2
  - Includes bug fixes to read in CORDEX grid metadata
- METplus v6.2.0
- Solar CF from WRF CORDEX simulations & ERA5BC
- Convolution radius 4 grid points (~100 km)
- Solar CF object threshold: 50% below national average of CF 25%, meaning objects are thresholded at < 12.5% CF
- Regridded to ERA5 grid
- Mean solar CF calculated over consecutive 7-day periods

MODE: capacity_factor_solar at Surface vs Pmp_dly at Surface

WRF CORDEX ERA5BC



Fcst	Obs	Interest
2	1	0.7732
1	1	NA
1	2	NA
2	2	NA
1	3	NA
2	3	NA
1	4	NA
2	4	NA

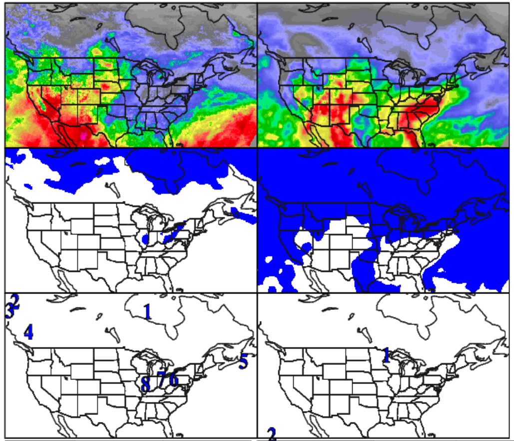
	Forecast	Observation
Model	IWRF	
Field	capacity_factor_solar	Pmp_dly
Level	Surface	Surface
Units	None	None
Initial	1985 06 23 00:00:00	1985 06 23 00:00:00
Valid	1985 06 23 00:00:00	1985 06 23 00:00:00
Accum	168:00:00	168:00:00

Centroid/Boundary	2.00	4.00
Convex Hull/Angle	0.00	1.00
Aspect/Area	0.00	1.00
Int Area/Curvature	2.00	0.00
Complexity/Intensity	0.00	0.00
Total Interest Thresh	0.70	

	Forecast	Observation
Mask M/G/P	on/off/off	on/off/off
Conv Radius	4	4
Conv Thresh	<=0.125	<=0.125
Obj Filters	0	0
Inten Perc	p50	
Merge Thresh	<=0.125	<=0.125
Merging	none	none
Matching	match/merge	
Simple/M/U	2/1/1	4/1/3
Area	149	1669
Area M/U	30/119	333/1336
Cluster	1	1
MMI	0.3866	0.0000
MMI (F+O)	0.0000	

MODE: capacity_factor_solar at Surface vs Pmp_dly at Surfac

WRF CORDEX ERA5BC



Fcst	Obs	Interest
1	1	NA
2	1	NA
3	1	NA
4	1	NA
5	1	NA
6	1	NA
7	1	NA
8	1	NA
1	2	NA
2	2	NA
3	2	NA
4	2	NA
5	2	NA
6	2	NA
7	2	NA
8	2	NA

	Forecast	Observation
Model	IWRF	
Field	capacity_factor_solar	Pmp_dly
Level	Surface	Surface
Units	None	None
Initial	1965 12 26 00:00:00	1965 12 26 00:00:00
Valid	1965 12 26 00:00:00	1965 12 26 00:00:00
Accum	168:00:00	168:00:00

Centroid/Boundary	2.00	4.00
Convex Hull/Angle	0.00	1.00
Aspect/Area	0.00	1.00
Int Area/Curvature	2.00	0.00
Complexity/Intensity	0.00	0.00
Total Interest Thresh	0.70	

	Forecast	Observation
Mask M/G/P	on/off/off	on/off/off
Conv Radius	4	4
Conv Thresh	<=0.125	<=0.125
Obj Filters	0	0
Inten Perc	p50	
Merge Thresh	<=0.125	<=0.125
Merging	none	none
Matching	match/merge	
Simple/M/U	8/0/8	2/0/2
Area	9641	35598
Area M/U	0/9641	0/35598
Cluster	0	0
MMI	0.0000	0.0000
MMI (F+O)	0.0000	

VERY PRELIMINARY initial results

Example outputs for 7-day solar CF drought objects

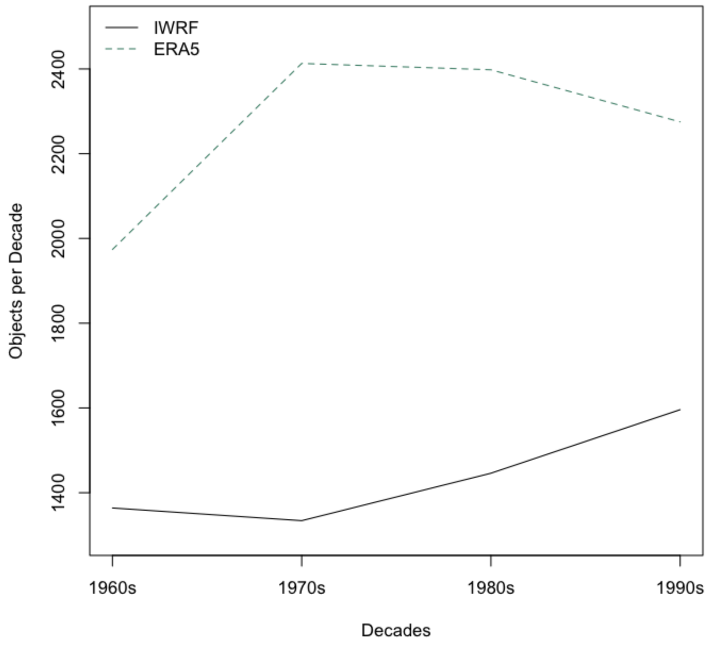
	ERA5BC historical (1960–1999)	WRF historical (1960–1999)	WRF future (2040–2069)
# of Objects	9,060	5,740	6,500
Mean Area	1,743,000 km^2	350,050 km^2	282,000 km^2
Area 50th Percentile	32,500 km^2	73,125 km^2	26,250 km^2
Mean CF 10th Percentile	9.5%	8.0%	8.1%
Mean CF 50th Percentile	11%	9.9%	10%
Mean CF 90th Percentile	12%	12%	13%

NOTE: There are LOTS of caveats to these preliminary results, and they will change as we refine and continue our analysis!

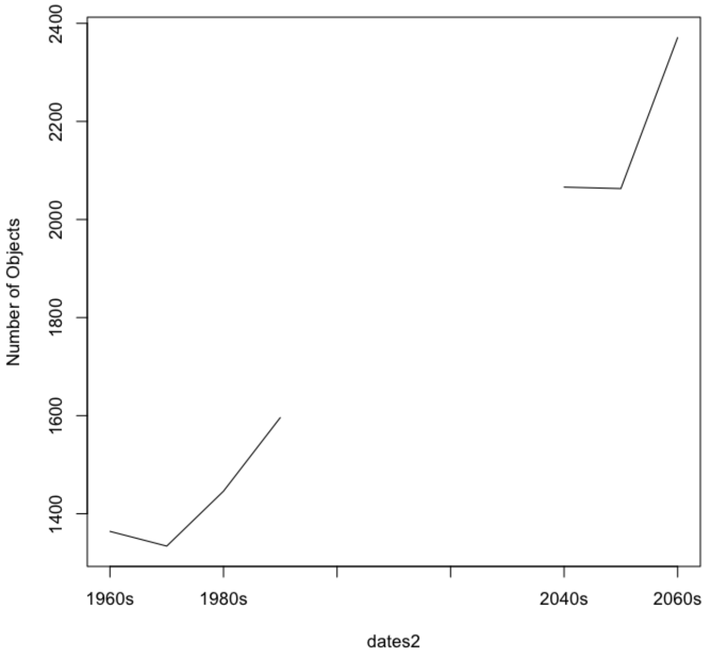
VERY PRELIMINARY initial results

Example 7-day solar CF drought objects per decade

WRF & ERA5BC (historical)

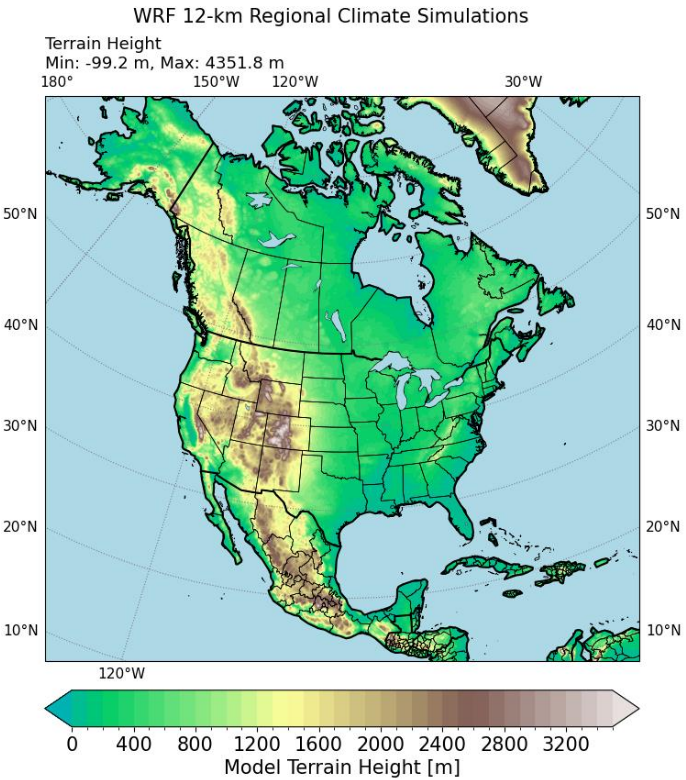


WRF (historical & future)



NOTE: There are LOTS of caveats to these preliminary results, and they will change as we refine and continue our analysis!

Summary and next steps



- Building on previous work in RE droughts by Pryor et al. and Wilczak et al. in particular
- Nearly finished producing downscaled 12-km WRF regional climate simulations (40 years historical, 40 years future using SSP5-8.5)
  - Output will be made publicly available on NSF NCAR GDEX
- Using MODE to define drought objects for wind, solar, and combined wind+solar droughts, generating climatologies to assess any changes from historical to mid-century climate
- **Next steps (solar, wind, joint solar+wind drought objects):**
  - Reference CF at each grid point, rather than domain-wide value
  - Rolling X-day means, rather than consecutive periods
  - Repeat analysis for 1-day, 3-day, 30-day events (more?)
  - Regional analysis constrained to interconnect regions

Questions? Suggestions? Contact me:
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https://i-wrf.org

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Supplemental Slides

Estimated mean wind CF, historical & future