Exploring Renewable Energy Droughts with I-WRF and Modeling Air Quality over the Northeast US

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I-WRF: Science Use Case #2: NCAR's Role – Understanding Renewable Energy Droughts

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?

Maui Wind Farm – Video by S.E. Haupt

- 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

WRF

Mitigating RE Droughts

Open questions regarding Renewable Droughts:

- Need to understand patterns better to alleviate
- Does wind + solar help? Where are gaps?
- What spatial scale averaging is needed to mitigate droughts – do larger balancing authorities help?
- What time frames for storage are needed to mitigate droughts?
- Will over-deploying renewables mitigate droughts?

These issues require **new spatial/temporal approaches**

Haupt, S. E., 2025: Wind droughts threaten energy reliability. *Nat. Clim. Chang.*, **15**, 814–815, https://doi.org/10.1038/s41558-025-02383-1.

News & views

Wind energy

https://doi.org/10.1038/s41558-025-02383-1

Wind droughts threaten energy reliability

Sue Ellen Haupt

Check for updates

Wind energy is helping to mitigate climate change. But now a study shows that climate change may make wind power less reliable.

Wind energy is a zero-carbon source of energy that is crucial for reducing the carbon dioxide (CO_2) emissions that cause global warming while providing inexpensive power to keep electricity grids running. It is, however, highly variable and sometimes not available, which can result in so-called wind droughts. Some studies have analysed the potential for wind droughts on a regional basis and quantified them in terms of intensity, duration and return period[1–4]. Now, in a study in *Nature Climate Change*, Meng Qu et al.[5] discuss the potential for wind droughts and their likely increase in frequency under projected climate change conditions on a global scale. They find that record-breaking, and even record-shattering, wind droughts may become more likely in the future. Their work provides a warning that climate change could threaten the reliability of wind power.

As the global energy markets transition to low-carbon energy, more wind plants are being installed to meet the need for inexpensive clean energy. The International Energy Agency estimates that by 2030, renewable energy will provide 46% of global electricity. In 2023, wind electricity generation increased by 10%[6] and is expected to grow another 300% by 2030 to support net-zero emissions by 2050 (ref. 7). Wind power, however, is highly variable and subject to the whims of passing weather patterns. This means that lulls in wind, or wind droughts, can threaten the energy supply, particularly as we move towards high penetration of wind energy in the future in order to mitigate CO_2 emissions. At the same time, the world is warming due to anthropogenic production of CO_2, also likely to affect the wind resource and its variability, which has been a topic of study in the field for some time[8,9]. Previous studies have focused on the regional impacts of projected climate change on wind droughts.

The study by Qu et al. presents a robust global analysis using hourly data from 21 climate models from the recent Coupled Model Intercomparison Project Phase 6 (CMIP6) set of runs across three separate Shared Socioeconomic Pathway emissions scenarios. Their rigorous analysis projects the potential for more frequent and longer droughts by the end of the twenty-first century, which is likely to make the electricity grid more difficult to manage and degrade reliability. This presents a conundrum – the same renewable energy that has the potential to mitigate global warming is at risk due to that projected warming, as the authors' study projects an increase in wind drought duration across both global and regional scales. They additionally seek to interpret the causes of these increases, tracing them primarily to decreasing frequency of mid-latitude cyclones, those weather-producing storms that progress across the same densely populated regions that host most of the world's wind farms – North America, Europe, western Russia and central China. Finally, Qu et al. assess whether these same regions are likely to experience record-breaking wind droughts. Indeed, for most of those regions, at least some of the CMIP6 models project longer or more intense wind droughts than have ever been experienced in the past. Although this work would ideally be accomplished with higher-resolution simulations that better resolve terrain, land–water boundaries and smaller-scale processes, such datasets are not yet available on the global scale. Some higher-resolution studies[10] show that results are similar to those accomplished with the global models.

Another recent paper suggests that understanding these droughts is the first among a number of possible steps towards alleviating them[11]. First, deploying a mix of wind and solar power is likely to help, as in many locations those resources are negatively correlated. Second, averaging over larger regions lowers the extent of the drought; thus, larger transmission authorities are better able to balance over a larger region. Third, further coupling of storage with renewables will allow excess power to be stored during times of high renewable energy availability. Finally, over-deploying renewable energy resources may be an efficient method of assuring that clean energy is available even when wind is not available.

All of these approaches will require the ability to better forecast the renewable energy droughts. Further research identifying the atmospheric patterns most susceptible to low wind power generation holds the potential for better planning on how to fill in the power supply during those time periods. These issues will continue to provide fodder for studying better ways to leverage renewable energy as a path towards net-zero energy production. The work by Qu et al. is a step in that direction and sets the stage for a better understanding of wind droughts and their causes.

Wind energy provides an increasing amount of clean, renewable energy, such as from this wind farm in Maui, Hawaii, USA.

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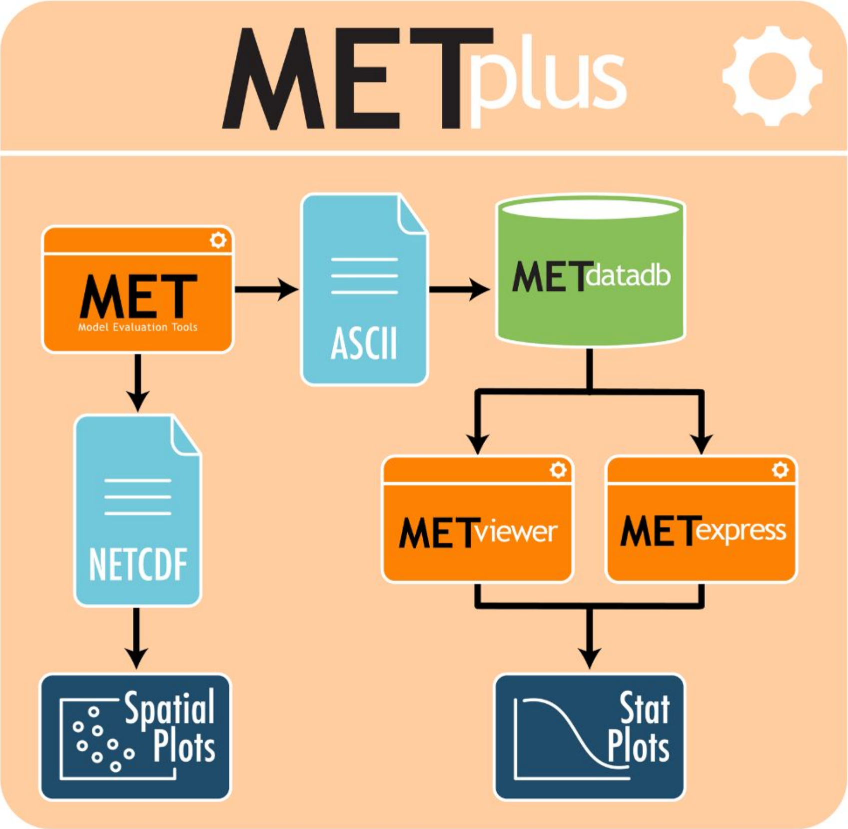
nature climate change

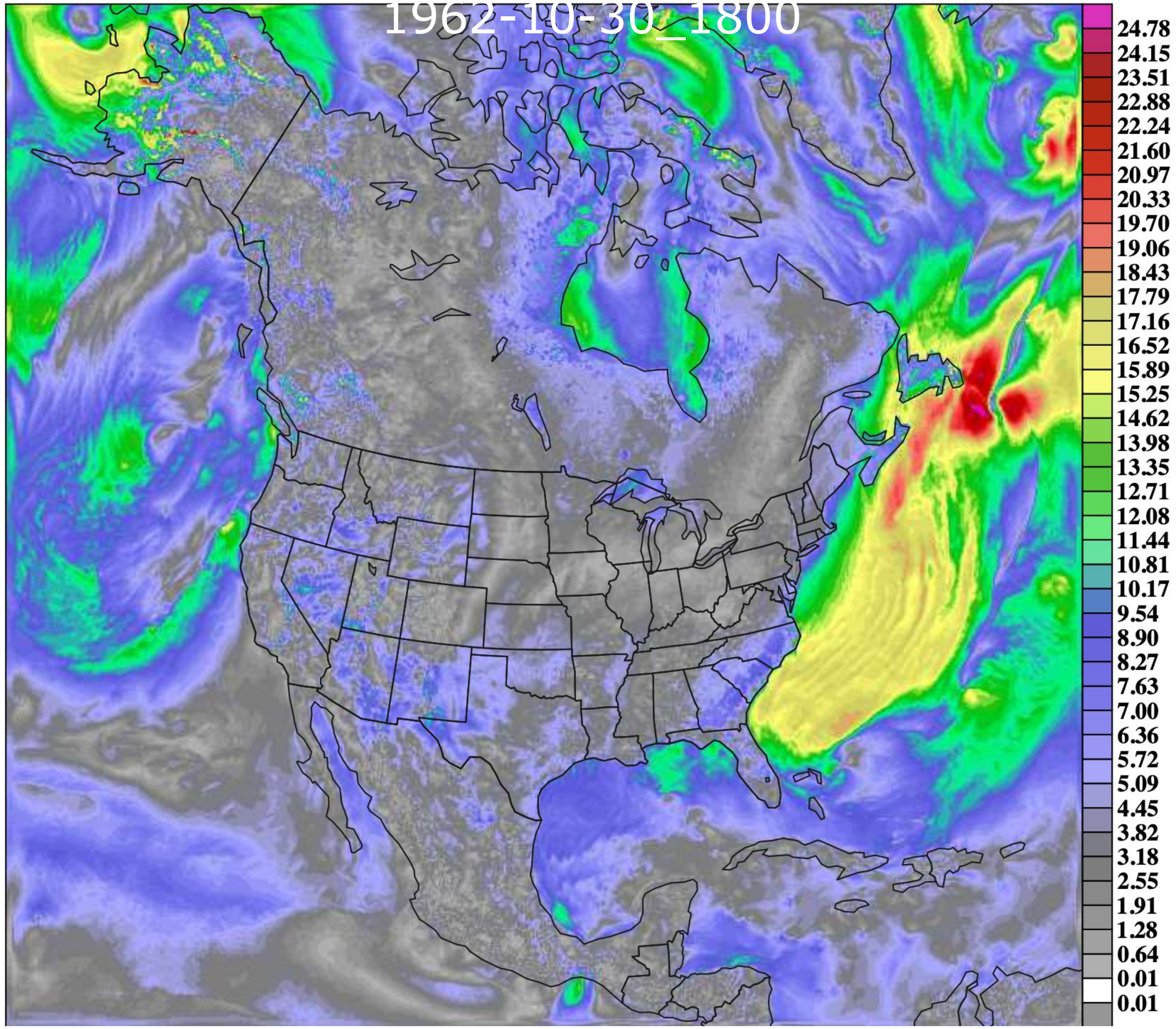
MODE – Method for Object-based Diagnostic Evaluation

- 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

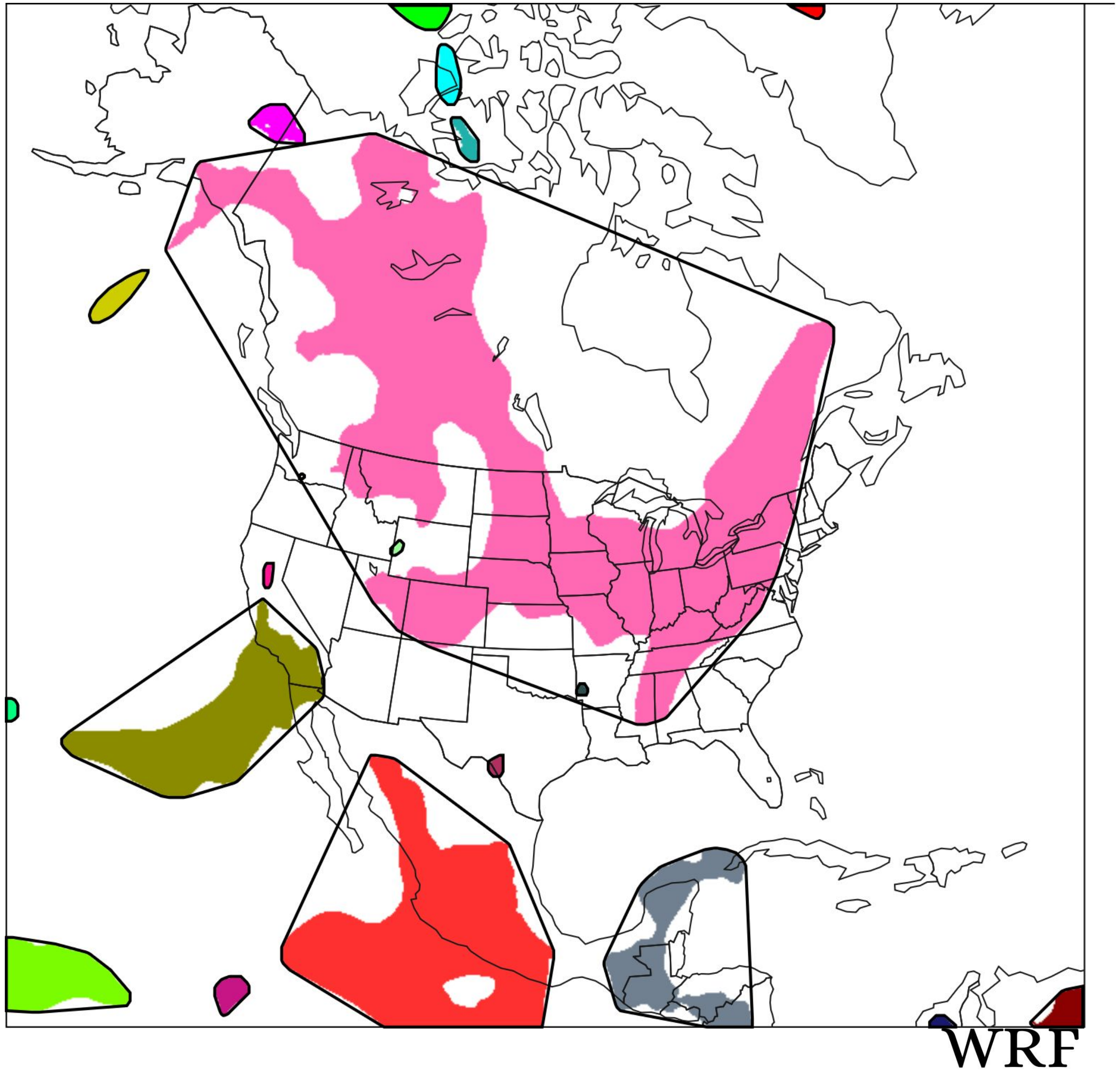


Example MODE analysis

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



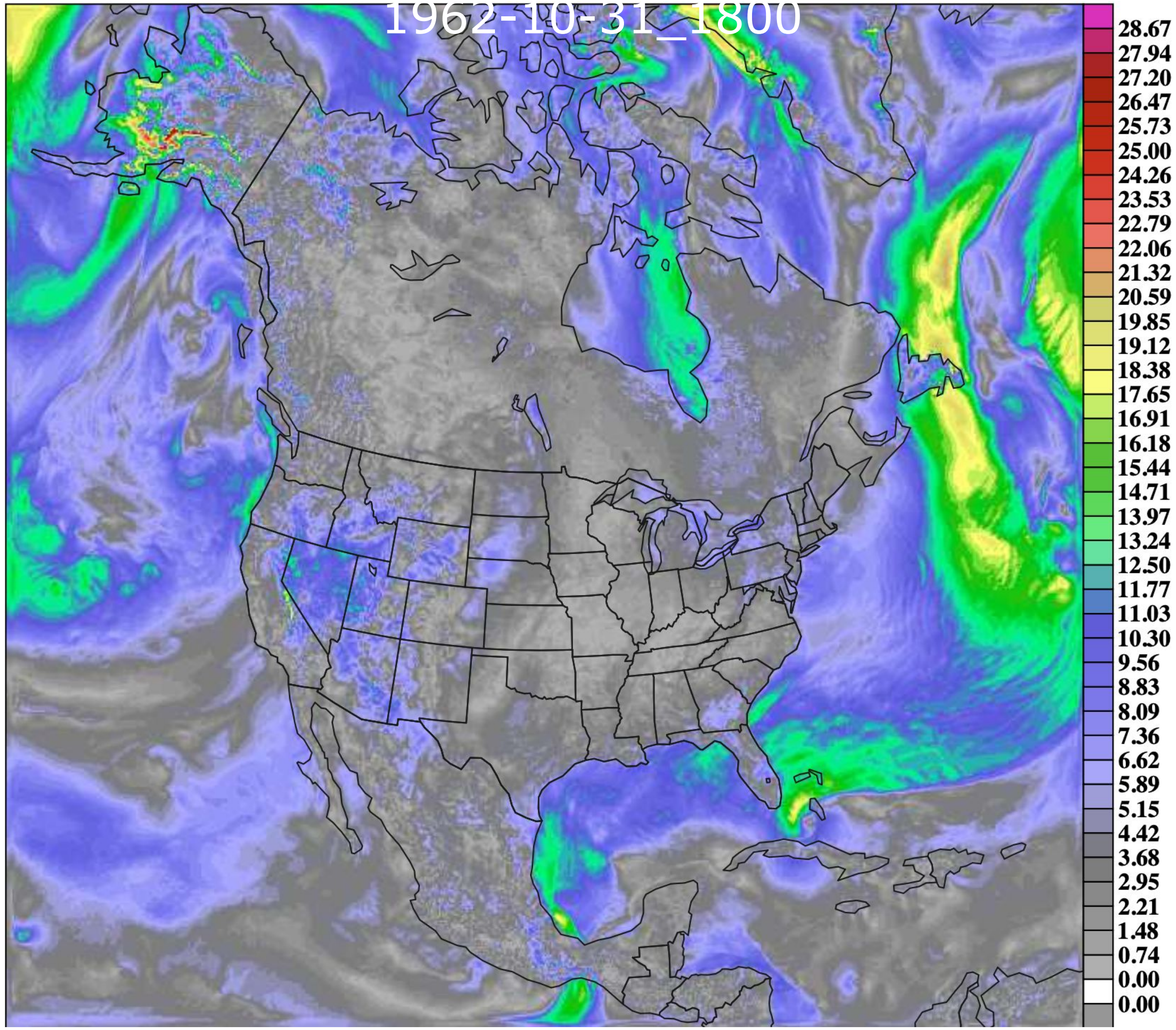
MODE objects for $WS_{10} < 3.0$ m/s



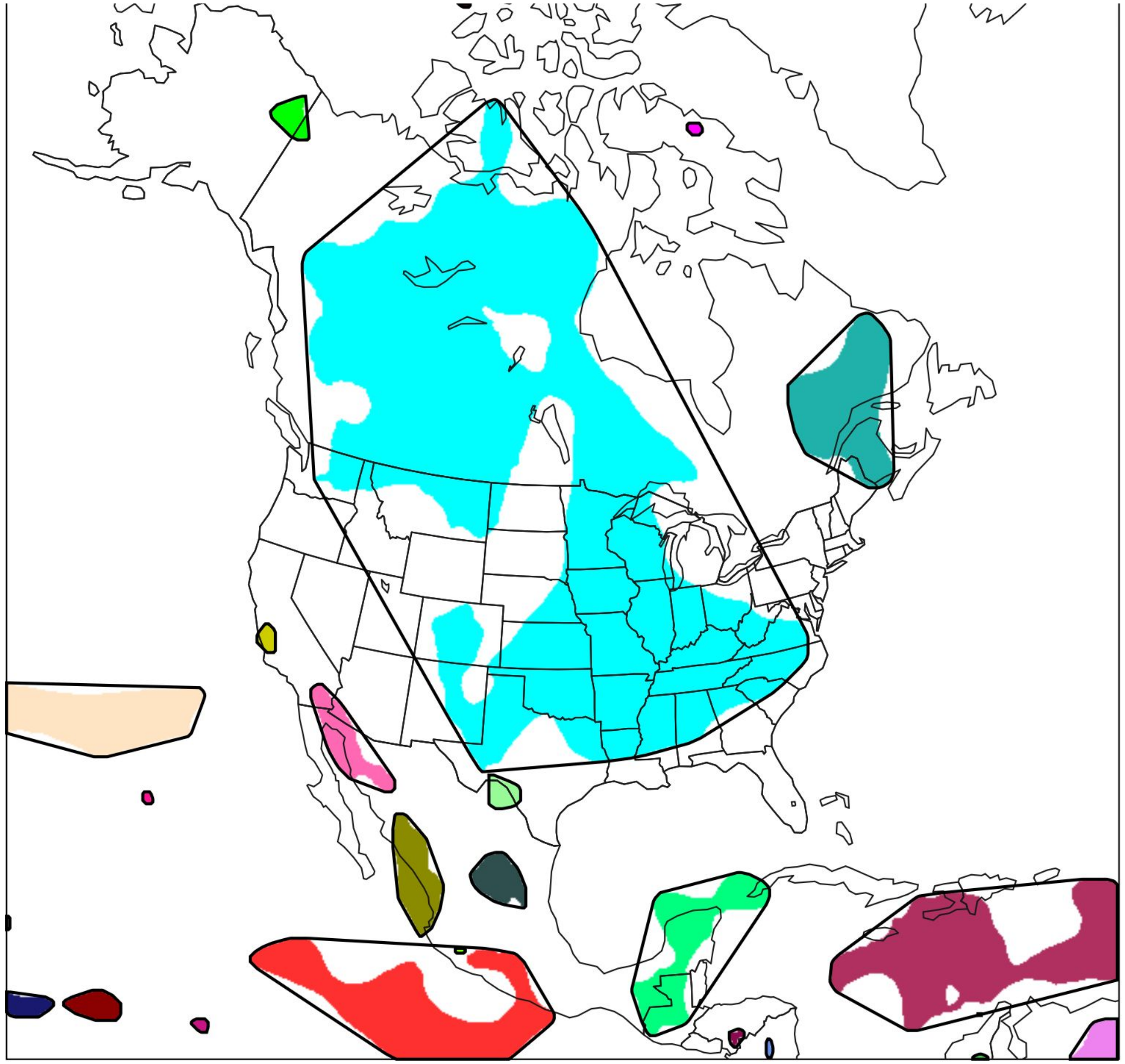
Cumulative area: 71,977 grid squares (10,364,688 km^2)

Example MODE analysis

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



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



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

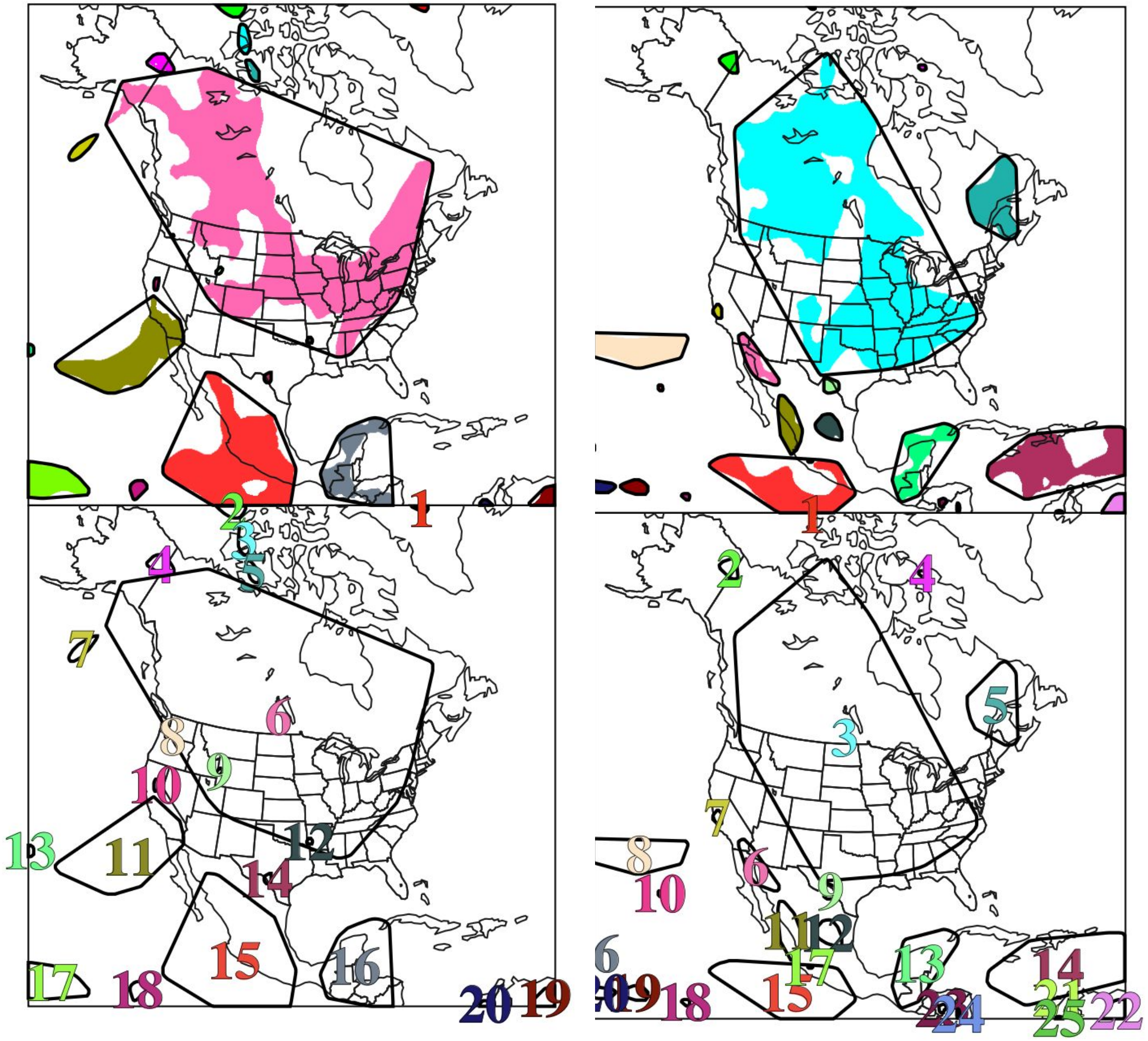
Case #2: NCAR Research Status

Completed / In Progress:

- Wrote Python scripts to generate files of estimated **capacity factor (CF)** for both wind and solar at every grid point and hour in the NA-CORDEX files, using the *windpowerlib* and *pvlib* Python packages.
- Identifying and **correcting metadata and CF-compliance issues** in WRF CORDEX files
- **Updating METplus** code to enable it to correctly ingest and process CORDEX-formatted files

Next Steps:

- Calculate rolling averages of these wind & solar CFs for various temporal durations (e.g., 1, 3, 5, 7 days) – (IGD)
- 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



I-WRF Science Use Case #3

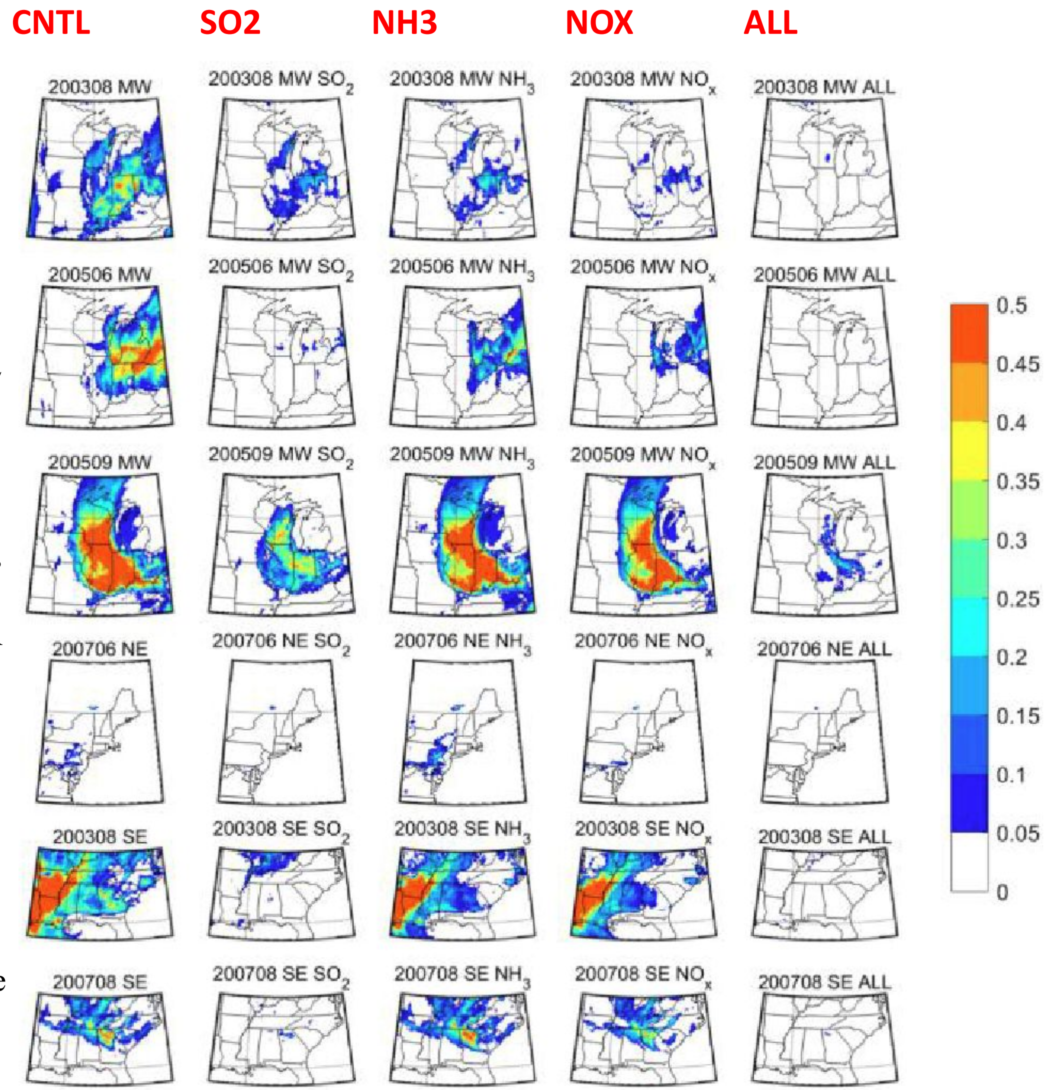
Plans for Air Quality Studies

Urban Air Quality (AQ)

- Containerize WRF-Chem for this science use case, democratizing its use.
- What impacts will interannual variability and trends have on urban AQ in the Northeast U.S.?
- Assess periods of extreme aerosol optical depth and near-surface small particulate matter (PM2.5)

AP Photo/Adam Rountree

Results from previous simulations with WRF-Chem (applied with a grid spacing of 12 km) where scenarios of precursor emission reductions (2005 to 2015) were applied to historical events with extreme near surface particle concentrations. The maps show events that impacted different parts of the eastern USA and show the probability of hourly $PM_{2.5}$ concentration >35 μgm^{-3} over the 3 days of each extreme events for simulations with 2005 (control experiment, left column), 2015 SO_2, 2015 NH_3, 2015 NO_x, and 2015 (ALL, right column) emissions. Areas with probability less than 0.05 are shown in white.



Guo, Y., P. Crippa, A. Thota, and S. C. Pryor, 2021a: Extreme aerosol events over eastern North America: Part 2. Responses to changing emissions. *J. Geophy. Res. Atmos.*, **126**, e2020JD033759, https://doi.org/10.1029/2020JD033759.

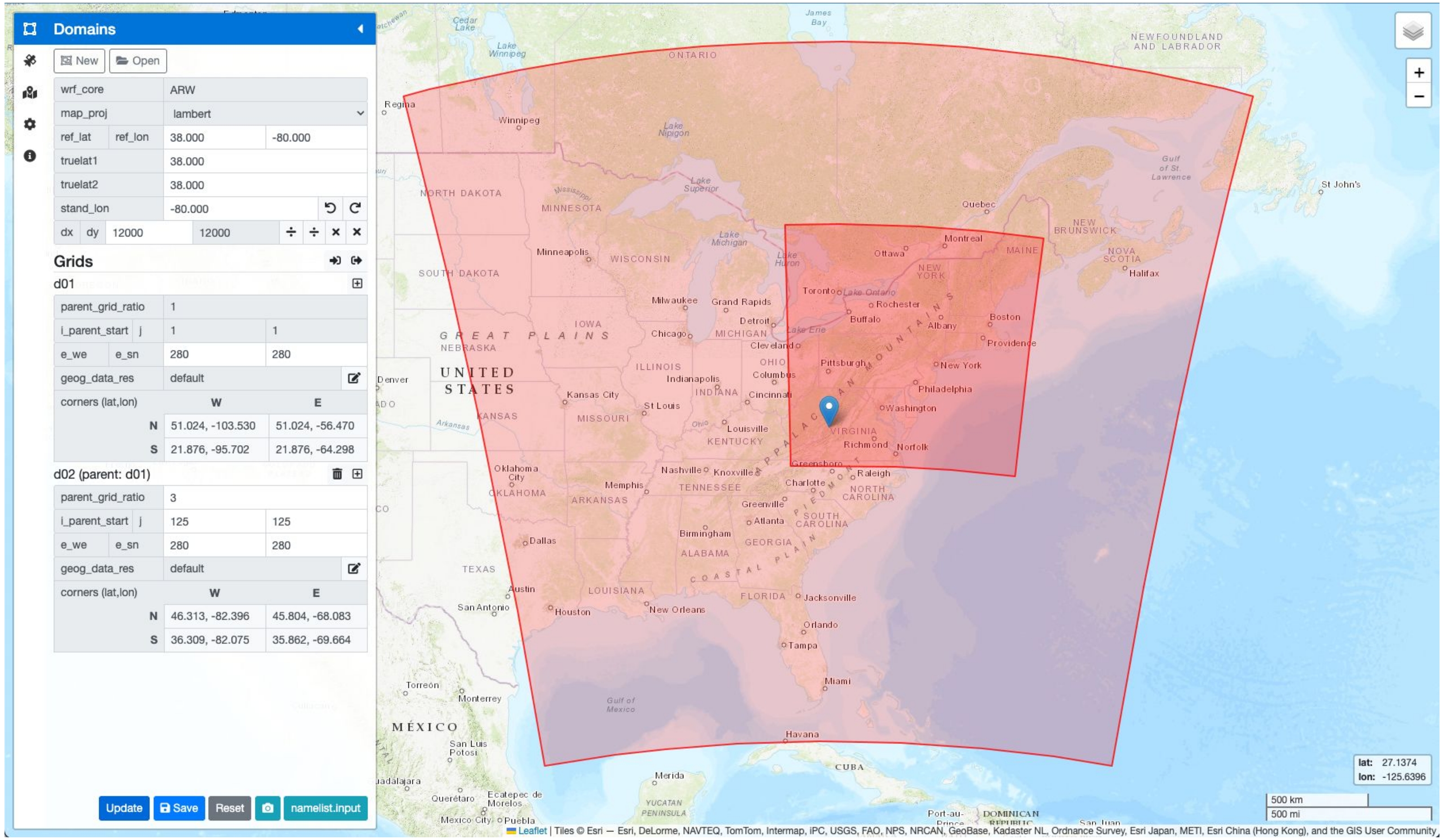
Case #3: Research Status

Completed / In Progress:

- Docker container of WRF-Chem built for Red Cloud
- Apptainer container of WRF-Chem built for Derecho, Jetstream2
- Initial demo of WRF-Chem container being tested on Derecho
- WRF nested domain built

Next Steps:

- Demonstrate use of container for cases of current and projected future AQ
- Analyze results to quantify projected changes in AQ.



wrf_core: ARW
map_proj: lambert
ref_lat, ref_lon: 38.000, -80.000
truelat1: 38.000
truelat2: 38.000
stand_lon: -80.000
dx, dy: 12000, 12000

Grids

d01

parent_grid_ratio	1	
i_parent_start, j	1	1
e_we, e_sn	280	280
geog_data_res	default	
corners (lat,lon)	W	E
N	51.024, -103.530	51.024, -56.470
S	21.876, -95.702	21.876, -64.298

d02 (parent: d01)

parent_grid_ratio	3	
i_parent_start, j	125	125
e_we, e_sn	280	280
geog_data_res	default	
corners (lat,lon)	W	E
N	46.313, -82.396	45.804, -68.083
S	36.309, -82.075	35.862, -69.664

lat: 27.1374
lon: -125.6396

Leaflet | Tiles © Esri — Esri, DeLorme, NAVTEQ, TomTom, Intermap, iPC, USGS, FAO, NPS, NRCAN, GeoBase, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), and the GIS User Community

Publications from the Project

Journal Papers (4)

1. Zhou, X. & Pryor, S.C. (2025). Urban Effects on Precipitation from Deep Convection over the Northeastern United States in Current and Future Climates. *Journal of Geophysical Research*, in review.
2. Zhou, X., Letson, F., Crippa, P. & Pryor, S.C. (2024). Urban Effect on Precipitation and Deep Convective Systems over Dallas-Fort Worth . *Journal of Geophysical Research: Atmospheres.*
3. Knepper, R., Pryor, S.C., Wineholt, B, Bukovsky, M. & Lee, J. (2023). The I-WRF Framework: Containerized Weather Modeling, Validation, and Verification. *Proceedings of the Practice and Experience in Advanced Research Computing (PEARC23).*
4. Haupt, S. E., 2025: Wind droughts threaten energy reliability. *Nat. Clim. Chang.*, **15**, 814–815, https://doi.org/10.1038/s41558-025-02383-1

Conference/Workshop Presentations (17)

1. X. Zhou, S.C. Pryor, J.A. Lee, S.E. Haupt, J. Dudhia & R. Knepper (2026). *I-WRF North American Regional Climate Simulations for Solar and Wind Energy in a Changing Climate and More.* Presentation at the 106th Annual Meeting of the American Meteorological Society, Houston, TX.
2. J.A. Lee, A.R. Siems-Anderson, S.E. Haupt, J.M. Wilczak, S.C. Pryor, X. Zhou & R. J. Barthelmie (2026). *Investigating Renewable Energy Drought Potential over the U.S.* Presentation at the 106th Annual Meeting of the American Meteorological Society, Houston, TX.
3. R. Knepper, J.A. Lee, S.E. Haupt & S.C. Pryor (2025). *Streamlining WRF Deployment with I-WRF: A Portable Framework for Research and Education.* Poster presented at the 2025 NSF CSSI/Cybertraining/SCIPE Meeting, Denver CO.
4. Lee, J. A., Siems-Anderson. A., Haupt, S.E., Wilczak, J.M., Zhou, X., Pryor, S.C. & Barthelmie, R.J. (2025). *Exploring renewable energy drought potential over CONUS. Presentation at the 8th International Conf. on Energy & Meteorology.* Padova, Italy.
5. Lee, J. A. (2024). *Career Conversations Panel: Data-Intensive Climate Science.*. Panelist at the MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support, Alabama A&M University, Huntsville, AL.
6. Lee, J.A. & Trumbore, B. (2024). *I-WRF Interactive Tutorial, MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support*. Alabama A&M University, Huntsville, AL.
7. Zhou X., Letson F., Crippa P., Bukovsky M. & Pryor S.C. (2024). *Influence of urbanization on deep convection in different climates.*. AGU Fall Meeting. Washington D.C.
8. Knepper, R., Pryor, S.C., Lee, J.A. & Haupt, S.E. (2024). *CSSI: Frameworks: Large Scale Atmospheric Research Using an Integrated WRF Modeling, Visualization, and Verification Framework (I-WRF)*. Poster presented at the 2024 NSF CSSI PI Meeting, Charlotte, NC.
9. Knepper, R. (2024). *I-WRF: Containerized Framework for Weather Modeling, Verification, and Visualization*. Presentation at the 2024 International Conference on Digital Government Research.
10. Lee, J.A. (2024). *Status of Climate Change Projections on Wind & Solar Resources*. Presentation at the 2024 Energy Systems Integration Group Forecasting & Markets Workshop.
11. Knepper, R. (2024). *I-WRF: Containerized Framework for Weather Modeling, Verification, and Visualization*. Presentation at the 2024 Minority Serving-Cyberinfrastructure Consortium Annual Meeting.
12. Knepper, R. (2024). *I-WRF Update.*. Presentation at the Spring 2024 Coalition for Academic Scientific Computing Spring Meeting.
13. Knepper, R., Pryor, S.C., Zhou, X., Lee, J.A. & Haupt, S.E. (2024). *I-WRF: Containerized WRF, MET, and MET Plus for Portability, Scaling, and Outreach*. 104th Annual Meeting of the American Meteorological Society.
14. Knepper, R., Pryor, S.C., Haupt, S.E. & Lee, J (2023). *CSSI: Frameworks: Large Scale Atmospheric Research Using an Integrated WRF Modeling, Visualization, and Verification Framework (I-WRF)*. Poster presented at the 2023 NSF CSSI PI Meeting, Houston, TX.
15. Zou, X., Letson, F., Crippa, P. & Pryor, S.C. (2022). *Urban Impacts on Deep Convection in the Southern Great Plains*. Presentation at the American Geophysical Union Fall Meeting 2022.
16. Barthelmie R.J., Zhou X. and Pryor S.C. (2026): Historical and Future Wind Extremes over North America. 11th European Windstorm Workshop. Delft, The Netherlands, 17–19 June 2026.
17. Lee, J. A., A. R. Siems-Anderson, S. E. Haupt, J. M. Wilczak, S. C. Pryor, X. Zhou, and R. J. Barthelmie, 2026: Dunkelflaute and Solar Drought Potential in North America. *ESIG 2026 Forecasting and Meteorology in Power Systems Workshop*, Energy Systems Integration Group, Denver, CO, 15–16 Jun 2026.