The Relationship of Smoke and Solar Radiation

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Introduction

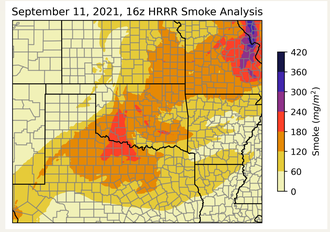
- Wildfire smoke and other particulate matter can block a substantial amount of light (Yu et al. 2016) thus severely inhibiting photovoltaic energy production (Donaldson et al. 2021). However, this research has mostly been performed **near the source** of the smoke.
- Large wildfires can inject smoke as high as the stratosphere (Yu et al. 2019), which can transport aerosols across vast distances, including much of the United States.
- Therefore, there is an importance in diagnosing the spatial and temporal correlations between local to high-altitude smoke and direct-normal solar radiation **in the Midwest** specifically.

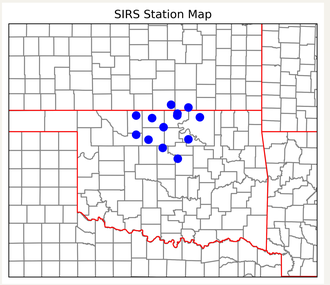
Research Questions

1. What is the relationship between wildfire smoke and surface short-wave radiation?
2. What are the challenges of accurately forecasting surface short-wave radiation due to wildfire smoke?

Methods

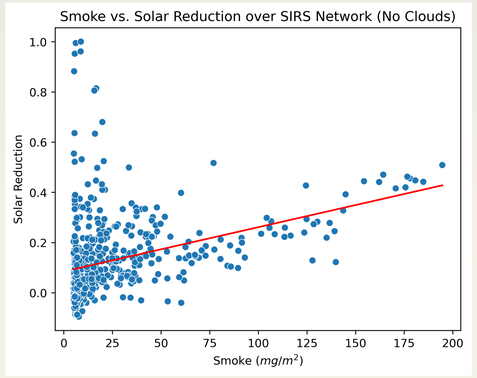
- Used the High-Resolution Rapid Refresh (HRRR) model's Vertically Integrated Smoke (VIS) data and compared it to direct-normal solar measurements from the Atmospheric Radiation Measurement user facility's Southern Great Plains Solar and Infrared Radiation Station (SIRS) network.
- 13 SIRS devices across Kansas and Oklahoma.
- Using data from January 1, 2021, to July 31, 2023, the HRRR-VIS initialization was analyzed to identify when smoke was over each station at 16z.
- An average of the SIRS measurements was calculated from 12-1 pm local time.
- The Python module Pysolar calculated the maximum expected direct-beam short-wave radiation value for each date/location.
- A difference was taken between the expected and observed values to determine reduction.
- September 2021 data was then isolated for further exploration.
- Later in my research, I also included the HRRR model's cloud coverage output over each location in my statistical analysis.



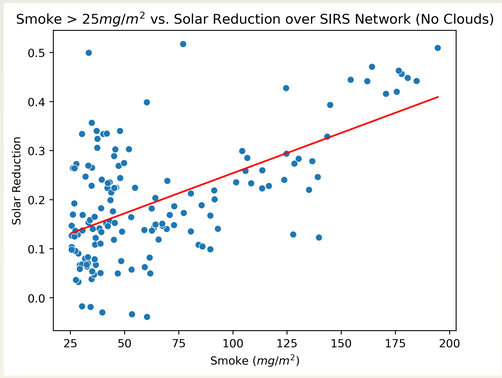


Data

Clouds Filtered Out: Requires 0% cloud cover and at least 5 $\frac{mg}{m^2}$ of smoke.



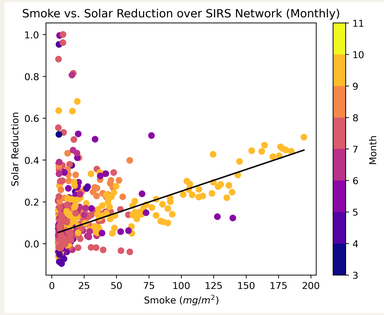
- **N = 577**
- High error with the trendline with small amounts of smoke
- R-score: 0.136



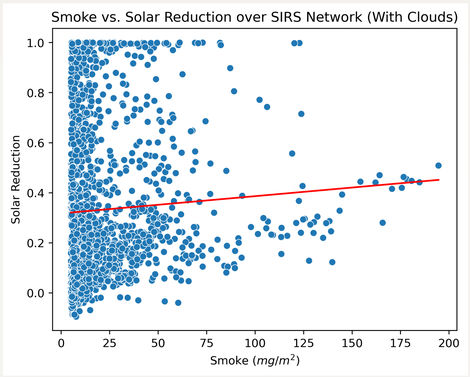
- **N = 149**
- Adding a filter to only include data points where the smoke was above 25 $\frac{mg}{m^2}$ reduces the noise
- R-score: 0.334

Monthly Dependency

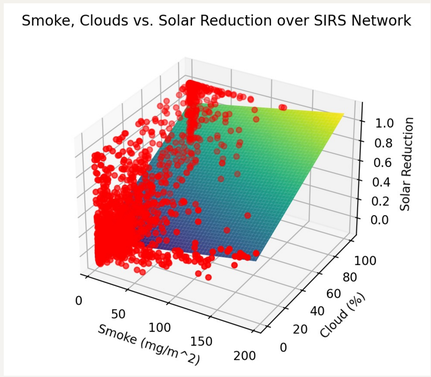
- **N = 577**
- Each color represents one month.
- Many of the orange dots that extend to 200 $\frac{mg}{m^2}$ of smoke are from September 2021. During this time, a series of wildfires burned in California.
- Smoke was not found before March and after October.
- Black line indicates the regression for September data points.
- Regression of September 2021 data: $y = 0.002077x + 0.04348$
- R-score of September 2021 data: 0.737



Including Clouds: Requires at least 5 $\frac{mg}{m^2}$ of smoke, regardless of cloud cover.



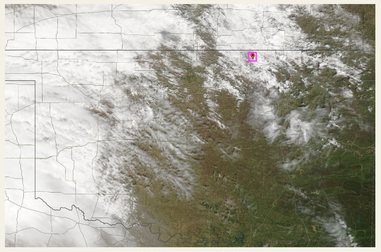
- **N = 1840**
- Significant error across all values
- R-score: 0.002



- **N = 1840**
- Multi-variate regression which includes smoke and cloud data
- R-score: 0.589

Results

- **There is a positive qualitative relationship between wildfire smoke and surface short-wave radiation.**
- Values of smoke above 150 $\frac{mg}{m^2}$ significantly **decreased short-wave radiation by 40-50%**, including fires from US West Coast.
- The best results were from September 2021, which indicate a strong positive relationship with an R-score of 0.74.
- However, inaccuracies with how the HRRR model resolves cloud cover made it difficult to eliminate highly anomalous data.
- For example, this point registered 5 $\frac{mg}{m^2}$ of smoke and no cloud cover according to the HRRR model. Yet, the reduction in short-wave radiation was 95%.

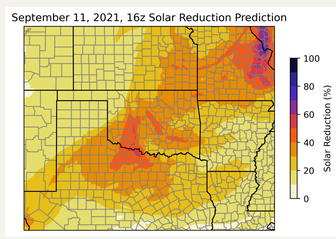


Source: worldview.earthdata.nasa.gov

- Incorporating smoke and cloud data together is potentially part of the solution to this problem, as represented by the multi-linear regression.
- Even with the anomalous data, there was a cluster of data points less than 25 $\frac{mg}{m^2}$ of smoke that obscured up to **30-40% of short-wave radiation**. Therefore, even trace smoke amounts should be considered in solar plant operations.

Future Research

- Create a tool for operational use in solar power production forecasting.
- Extend the length of time to encompass a full day.
- Apply artificial intelligence and machine learning in investigating other meteorological variables such as temperature, wind, moisture, and season.
- Expand short-wave radiation data by exploring other networks.



References

Donaldson, D. L., D. M. Piper, and D. Jayaweera, 2021: Temporal Solar Photovoltaic Generation Capacity Reduction From Wildfire Smoke. *IEEE Access*, **9**, 79841–79852, https://doi.org/10.1109/ACCESS.2021.3084528.

Yu, P., and Coauthors, 2016: Surface dimming by the 2013 Rim Fire simulated by a sectional aerosol model. *J. Geophys. Res. Atmospheres*, **121**, 7079–7087, https://doi.org/10.1002/2015JD024702.

Yu, P., and Coauthors, 2019: Black carbon lofts wildfire smoke high into the stratosphere to form a persistent plume. *Science*, **365**, 587–590, https://doi.org/10.1126/science.aax1748.

Acknowledgments: ARM - Ken Kehoe, Alyssa Sockol, Mia Li, Corey Godine, Dr. Randy Peppler; SCIPP - Rachel Riley, Caylah Cruickshank, Dr. Mark Shafer, Darian Bertrand; OU - Dr. Aaron Hill, Dr. Marcela Loria-Salazar