Status of Reanalysis Products and Renewable Energy Applications at NOAA's Physical Sciences Laboratory

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NOAA Global Reanalysis Products

- CORe – Conventional Observation Reanalysis for Climate Modeling.
  1950-present, GFS-FV3, 0.7 deg grid, 64 levels, ENKF, 80 ensemble members
  Does not assimilate satellite radiances to avoid spurious jumps due to changing satellite constellations.

- Replay Reanalysis
  1994- 2023, GFS-FV3, 13 km, 127 levels

- 20CR – Twentieth Century Reanalysis
  1836-2015, GFS, 75 km grid, 64 levels, ENKF, 80 ensemble members

Legacy products:

- CFSR - Climate Forecast System Reanalysis; CFSv2
  1979-2011, 2012-present, GFS, ~38km, 64 levels, GSI

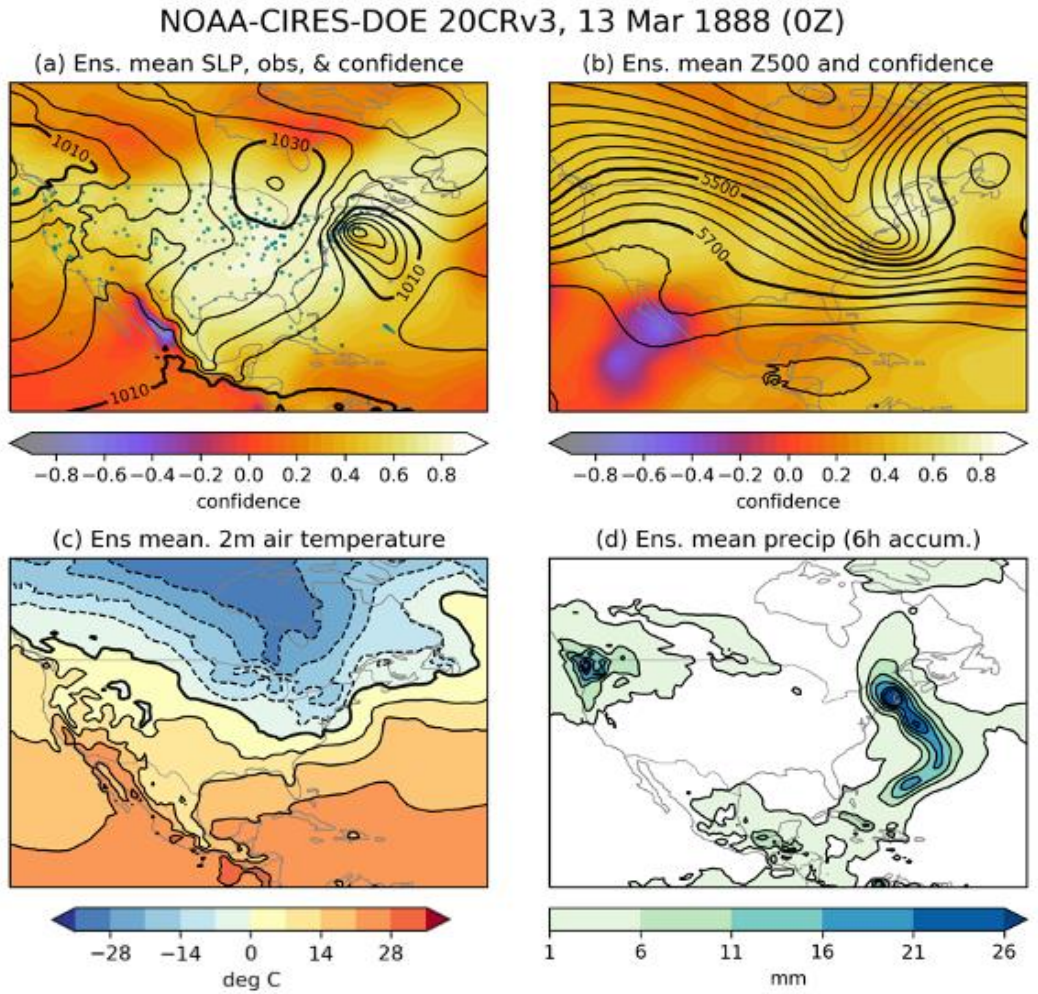
- NCEP/DOE reanalysis 2
  1979-present, GFS, T62, 28 levels, 3D-var, updated parameterizations

- NCEP/NCAR reanalysis
  1948-present, GFS, T62, 28 levels, 3D-var

NOAA's Replay Reanalysis

- 0.25 degree GFS-FV3/MOM6/Cice/WW3 coupled model run in a series of 12-hour forecasts.
- Conceived as a relatively inexpensive way to initialize coupled GFS re-forecasts given that the MOM6 ocean data assimilation and Cice data assimilation components of the forecast system are not yet operational.
- Ocean is constrained by ORAS5's currents, temperature, and salinity, and sea-ice concentration and thickness with adjusted ORAS5 values
- Snow coverage over land is updated through data assimilation of satellite and in-situ observations.
- The atmosphere is constrained by ERA5's winds, temperature, specific humidity, ozone and surface pressure.
- Replay makes use in incremental analysis update (IAU) where the difference between the model forecast and an existing reanalysis is nudged in over a period of 6-hours to minimize initialization shock.
- Valid 1/1/1994-12/31/2023, history is saved every 3-hours for the atmosphere, and every 6-hours for the ocean.
- NetCDF data are publicly available at https://noaa-ufs-gefsv13replay-pds.s3.amazonaws.com/index.html
- Limited fields are available in Zarr format at (must have a google account) https://console.cloud.google.com/storage/browser/noaa-ufs-gefsv13replay

The 20th Century Reanalysis (20CR) provides a global, 200-year history of sub-daily weather by assimilating *only* surface pressure observations into a modern weather model



NOAA-CIRES-DOE 20th Century Reanalysis Version 3

- Estimates temperature, wind, precipitation, pressure, humidity, & other variables, from the ground to the top of the atmosphere
- Prescribed sea surface temperature, sea ice concentration, and radiative forcing
- Global 75km grid
- 3-hourly resolution
- Spans 1836-2015 [1806-1835 experimental]
- Data assimilation: Ensemble Kalman Filter with 80 ensemble members to quantify uncertainty
- Publicly available: https://go.usa.gov/XTd

Slivinski et al (2021)

Future of 20CR – Possibilities

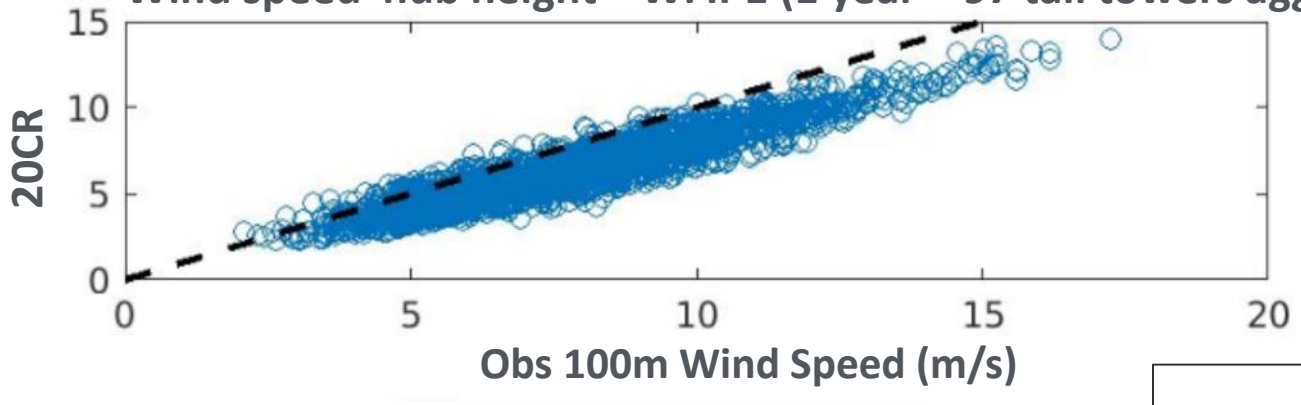
- Extend 20CRv3 to near-present
- Coupled ocean-atmosphere
- Data-driven models
  - Linear inverse model in ocean and/or trained AI model in atmosphere

More information:

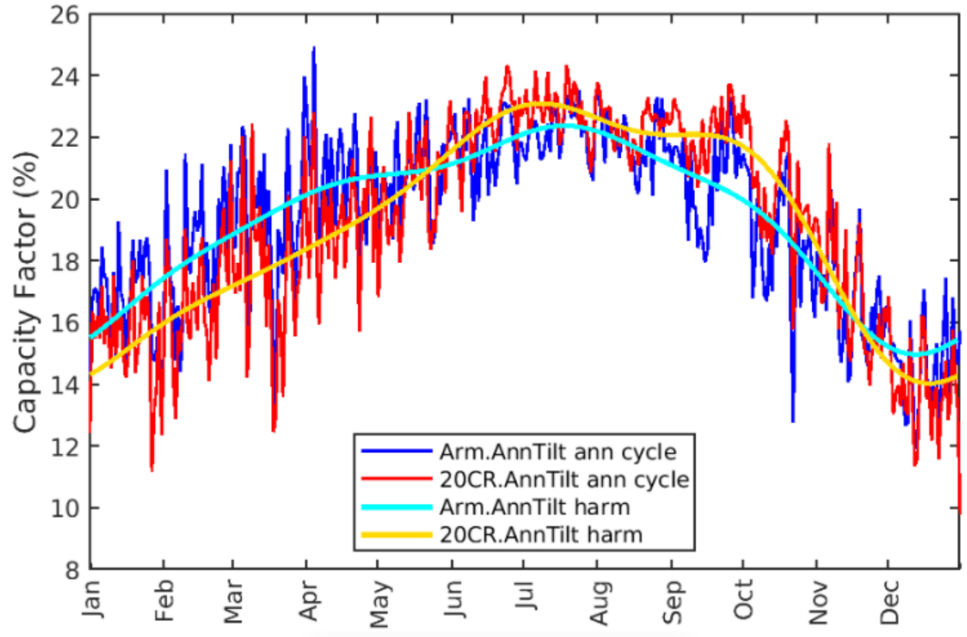
- Compo, G.P., et. al. (2011) The Twentieth Century Reanalysis Project. *Q.J.R. Meteorol. Soc.*, 137: 1-28. https://doi.org/10.1002/qj.776
- Slivinski, L.C., et. al. (2019) Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. *Quarterly Journal of the Royal Meteorological Society*, 145: 2876– 2908. https://doi.org/10.1002/qj.3598
- Slivinski, L.C., et. al. (2021) An Evaluation of the Performance of the Twentieth Century Reanalysis Version 3. *Journal of Climate*, 34(4): 1417-1438. https://doi.org/10.1175/JCLI-D-20-0505.1

20CR Applied to Wind and Solar Energy

Wind speed hub height WFIP1 (1 year – 97 tall towers aggregate)



Solar CF 20CR vs DOE ARM-SGP aggregate (17 years)



- For wind speed, 20CR has larger biases and RMSE, and smaller correlations than ERA5.
- For solar CF, 20CR has larger RMSE and smaller correlations than ERA5.
- Considering it only assimilates surface pressure, 20CR does surprisingly well.
- Fatal flaw was lack of summer clouds in SW U.S.

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

Wilczak, J.M., et al. Energies 2024, 17, 1667. https://doi.org/10.3390/en17071667

Novel Aspects:

1) Over U.S., wind & solar
2) Correction Methods
3) Severe drought events

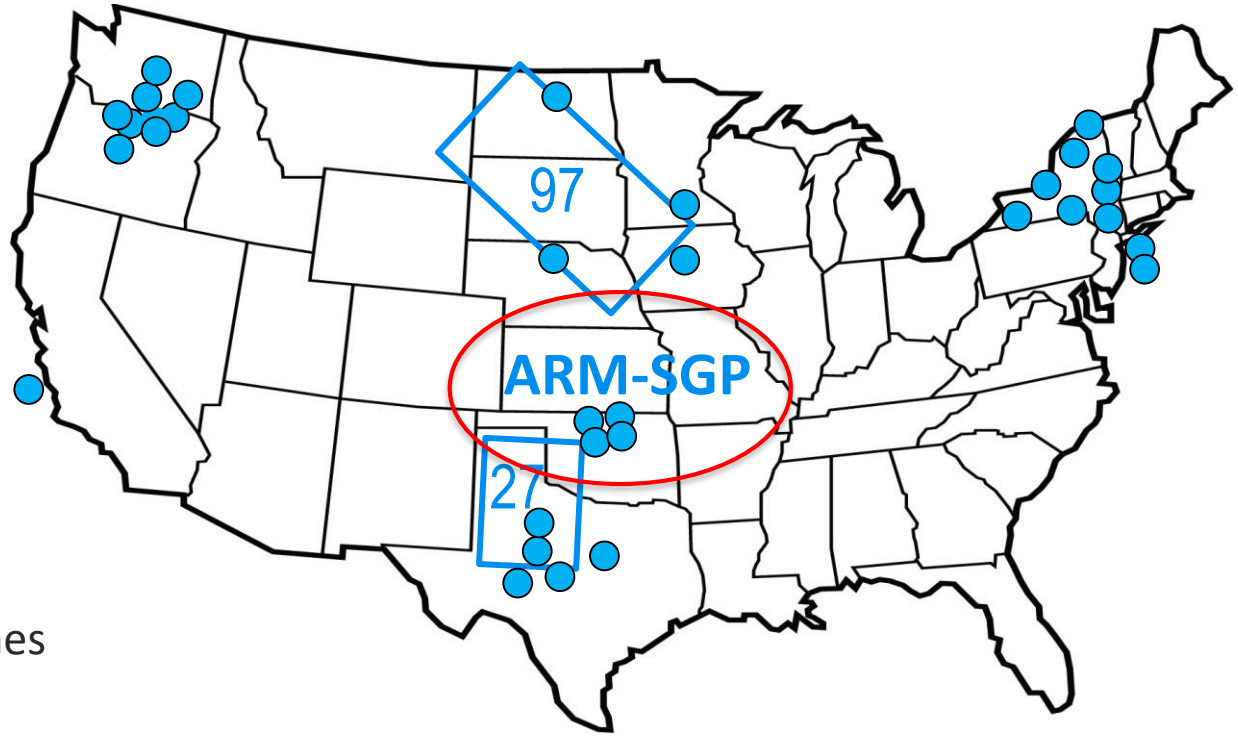
Wind Observations used for ERA5 Evaluation

Emphasis is placed on quality of observations over quantity

- Adequate meta data for sites
- Observations span at least one full year

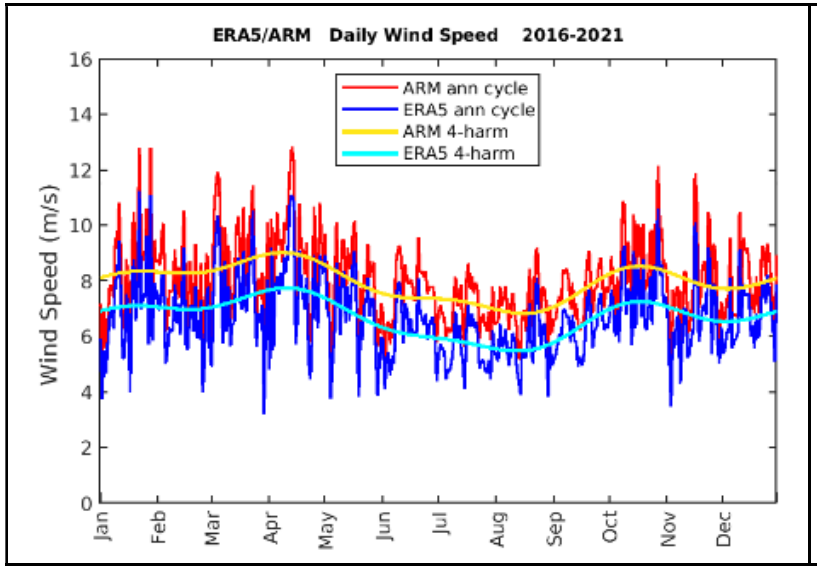
Wind Observations:

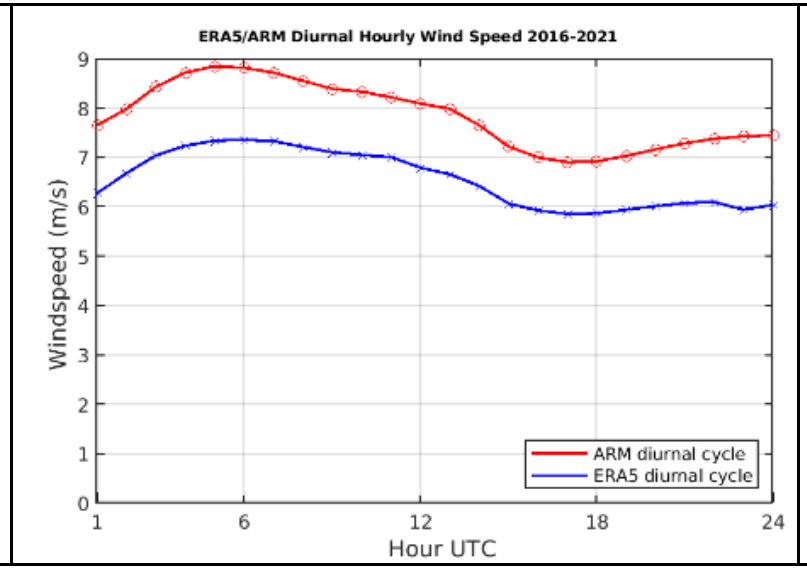
- Towers: booms in opposite or orthogonal directions to avoid tower shadowing
- Towers: checked for icing conditions
- Avoided stations in very complex terrain or near coastlines where ERA5 gid cells would use a mix of land and ocean tiles

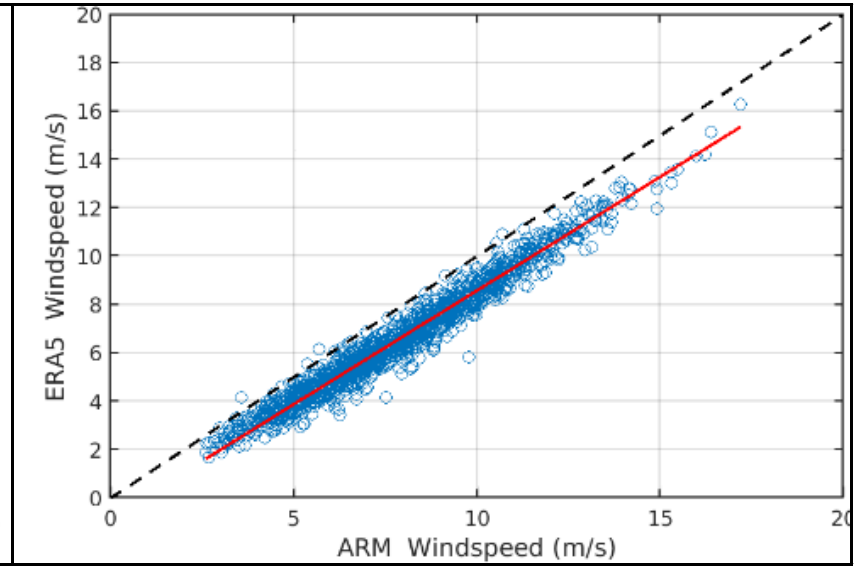


Wind observation sites (157):
Tall towers (124), lidars(16), sodars (14)
Wind speed, direction

Wind Speed (100m), ARM-SGP 4 lidar average (2016-2022): ERA5 Errors







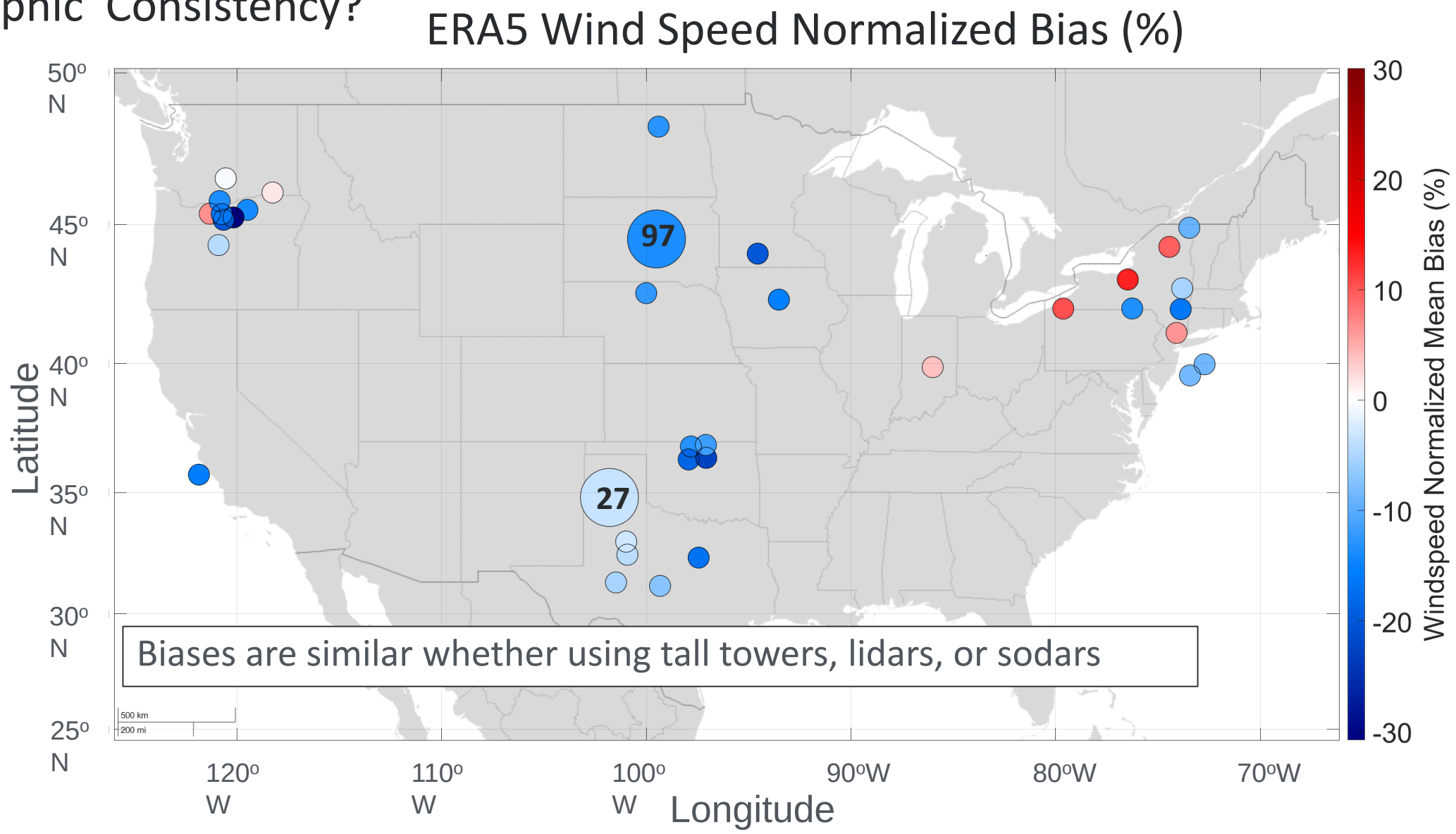
Annual Cycle

Diurnal Cycle

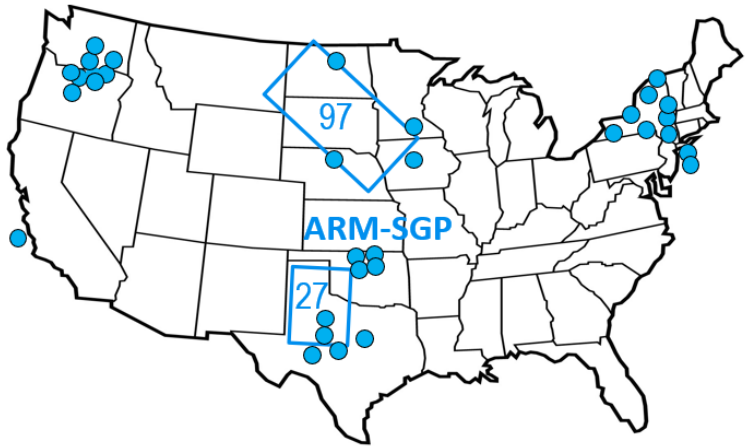
Scatter Plot of Daily Wind Speeds

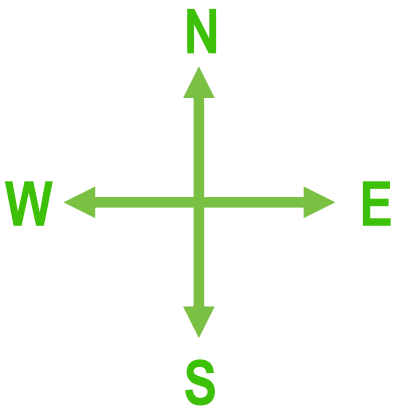
Daily-averaged wind speeds are used to reduce over-inflation of the corrected ERA5 variances arising from the use of point observations to corrected ERA5 grid cell values.

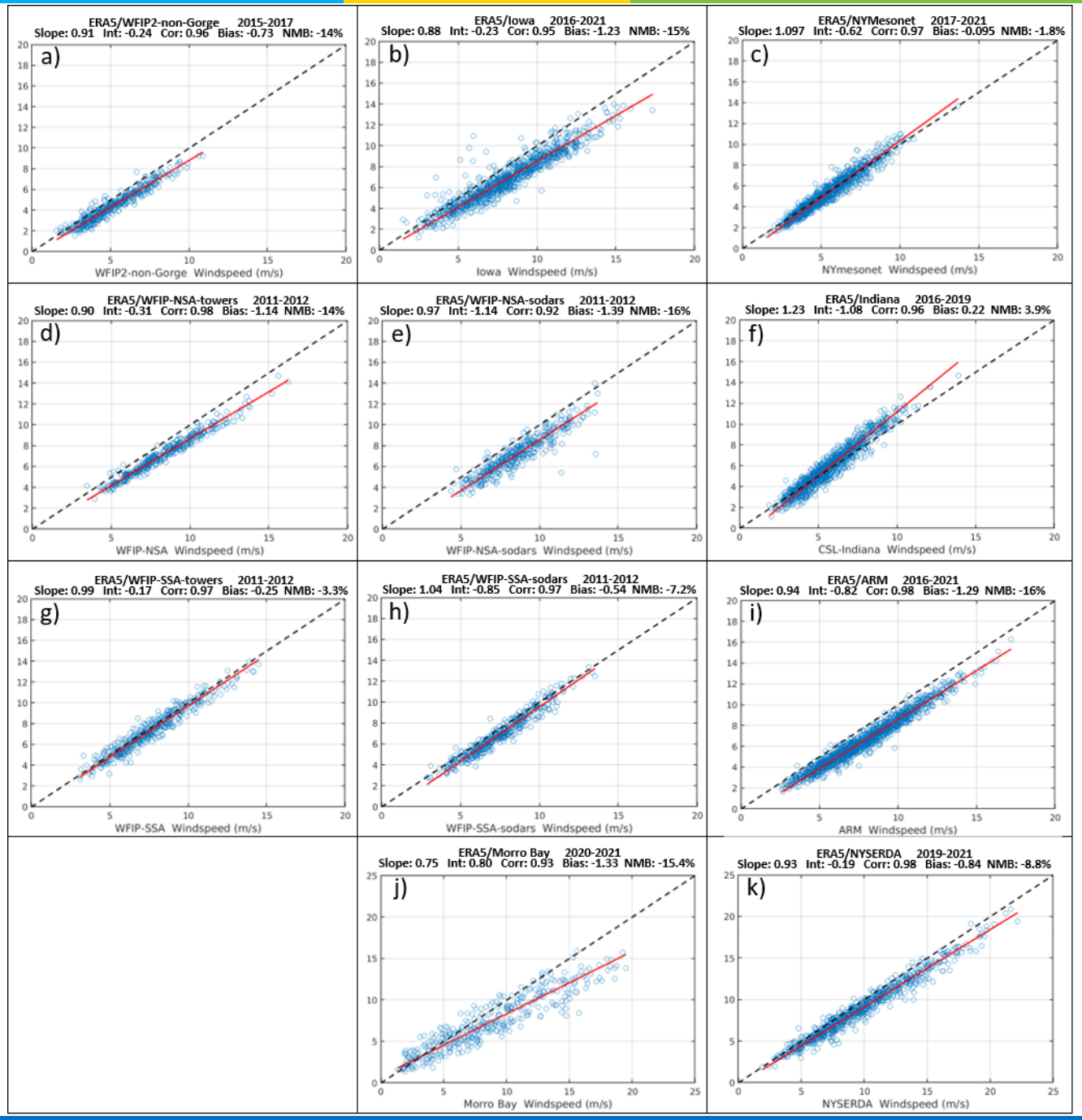
Geographic Consistency?



Wind Speed Regressions by region

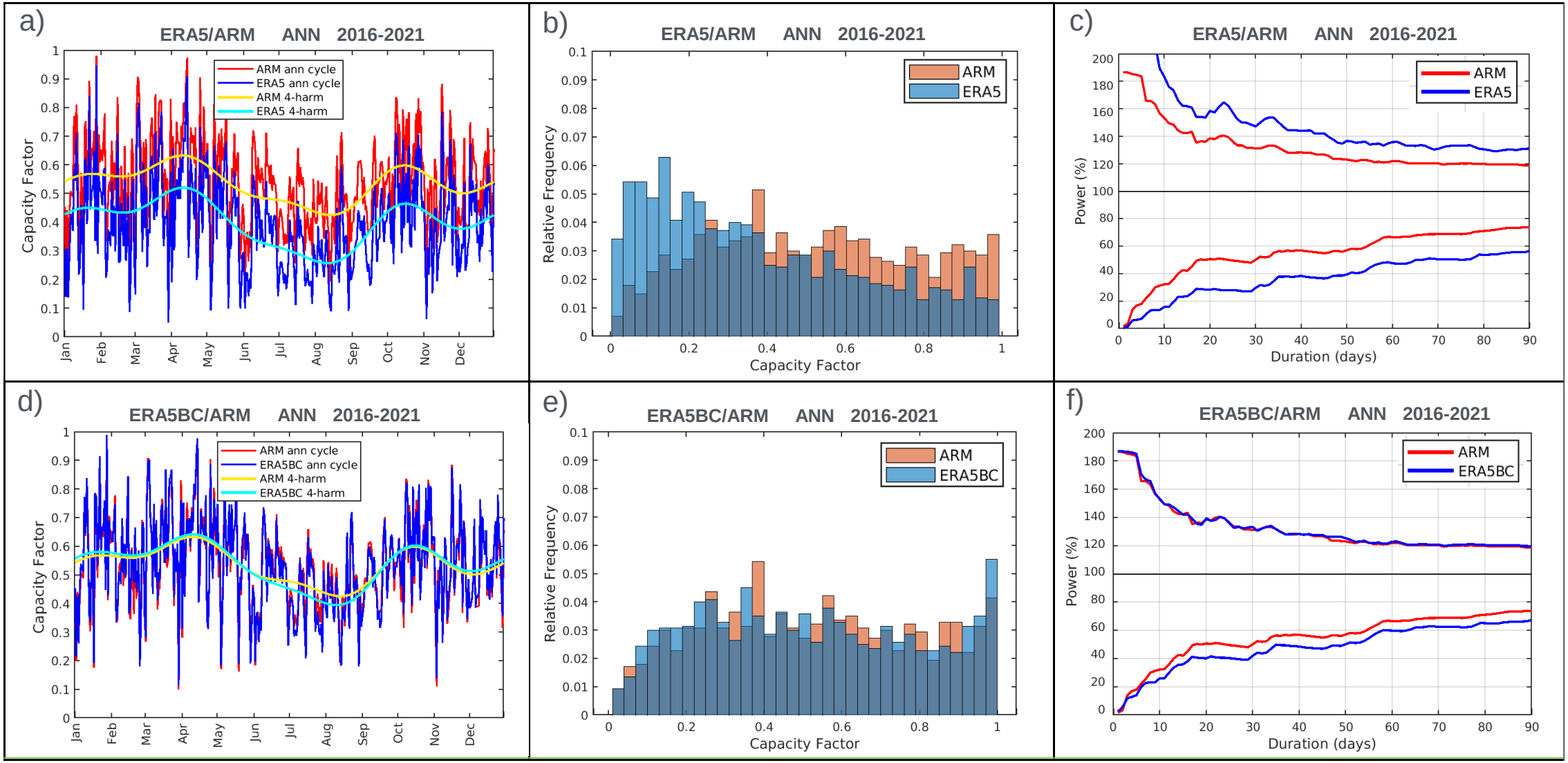






Daily Wind Capacity Factors, ARM-SGP 4 lidar average (2016-2022): Effect of Correction

DOE Wind ToolKit Power curves used, 3 on land, 1 offshore



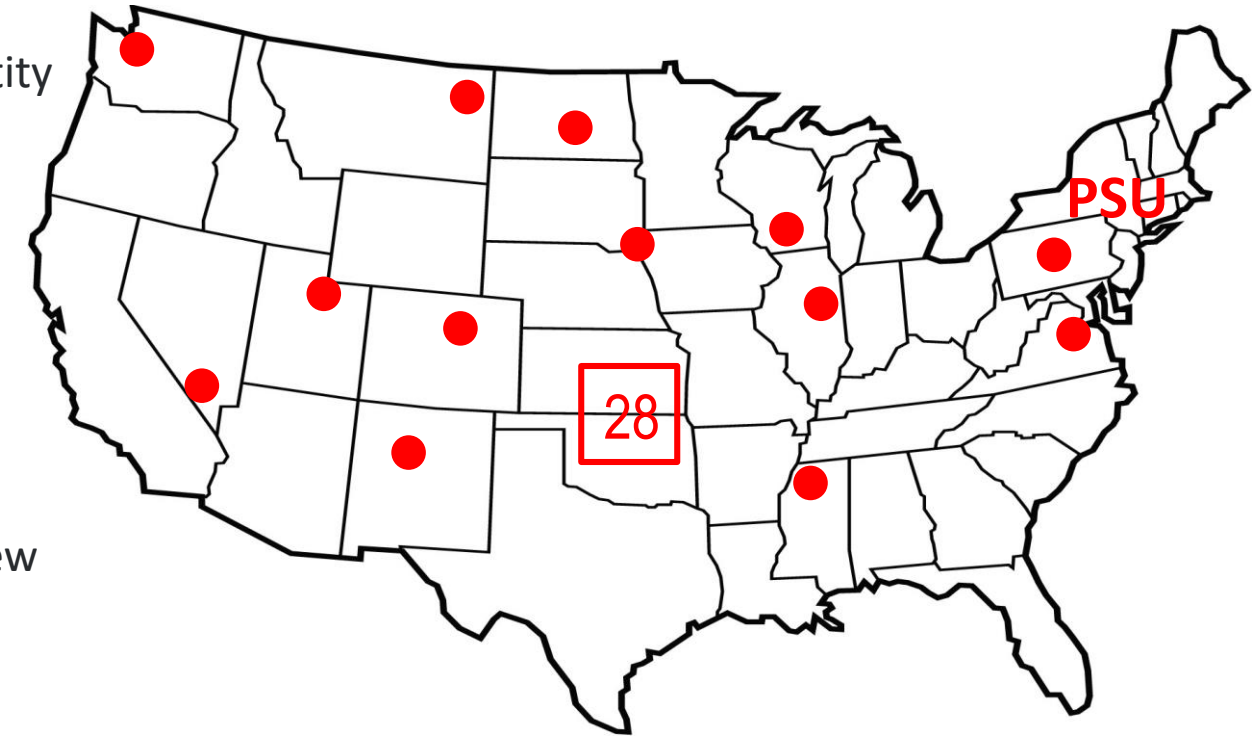
Solar Observations used for ERA5 Evaluation

Emphasis is placed on quality of observations over quantity

- Good meta data for sites
- Observations span at least one full year

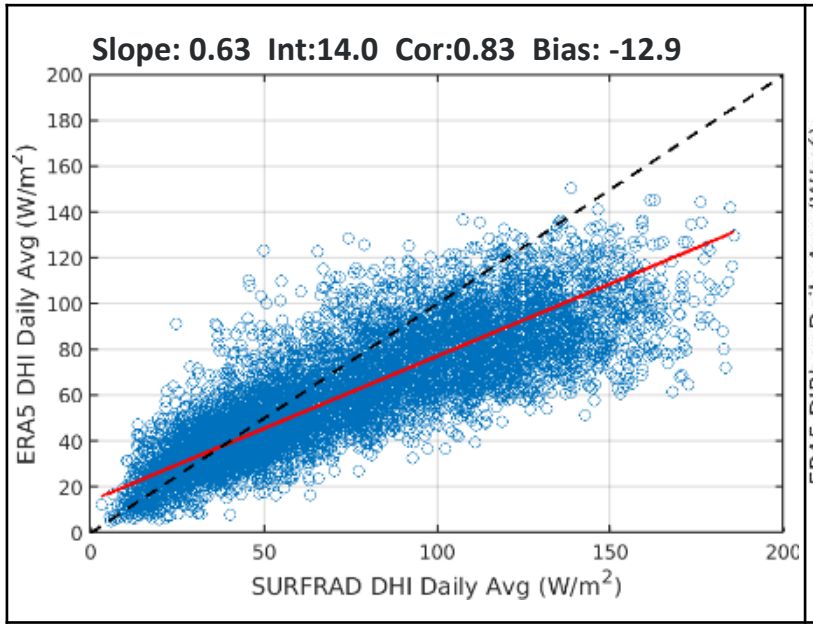
Irradiance observations:

- Frequent cleaning
- Heated sensors to minimize impacts of snow, rain, dew

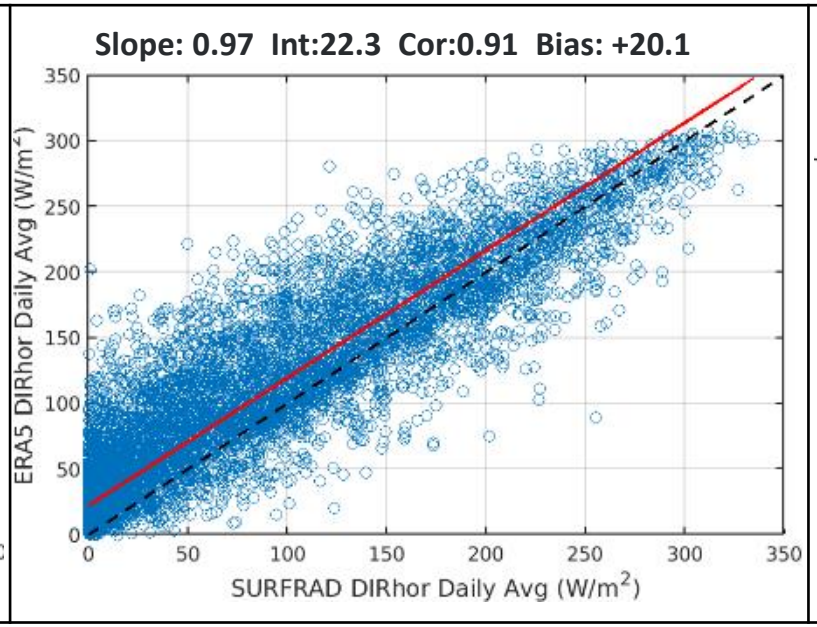


Solar irradiance observation sites (41):
NOAA SURFRAD & SOLRAD, DOE ARM-SGP
Direct, Diffuse irradiances (1998-2022)

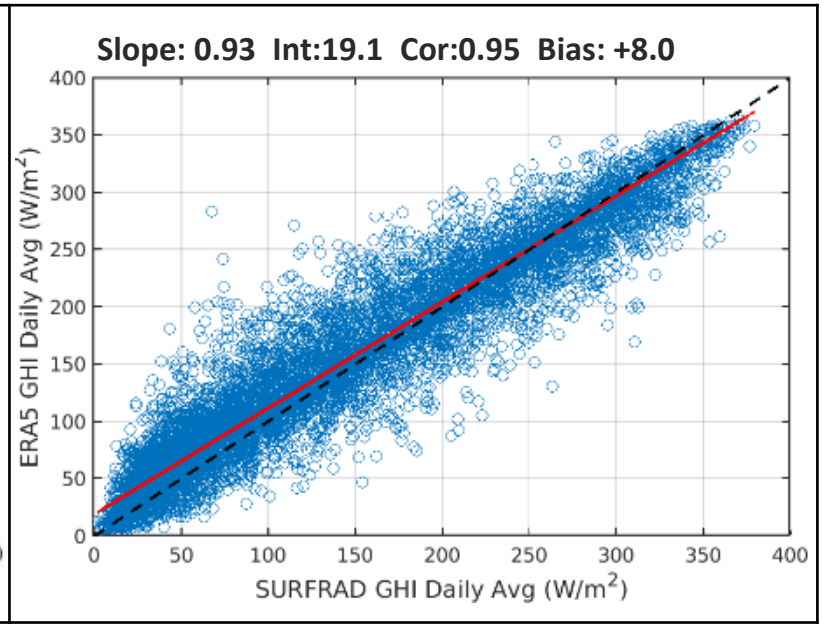
Daily Averaged Irradiances: NOAA SURFRAD site=PSU vs ERA5 (1998-2022)



Diffuse Horizontal Irradiance



Direct Horizontal Irradiance

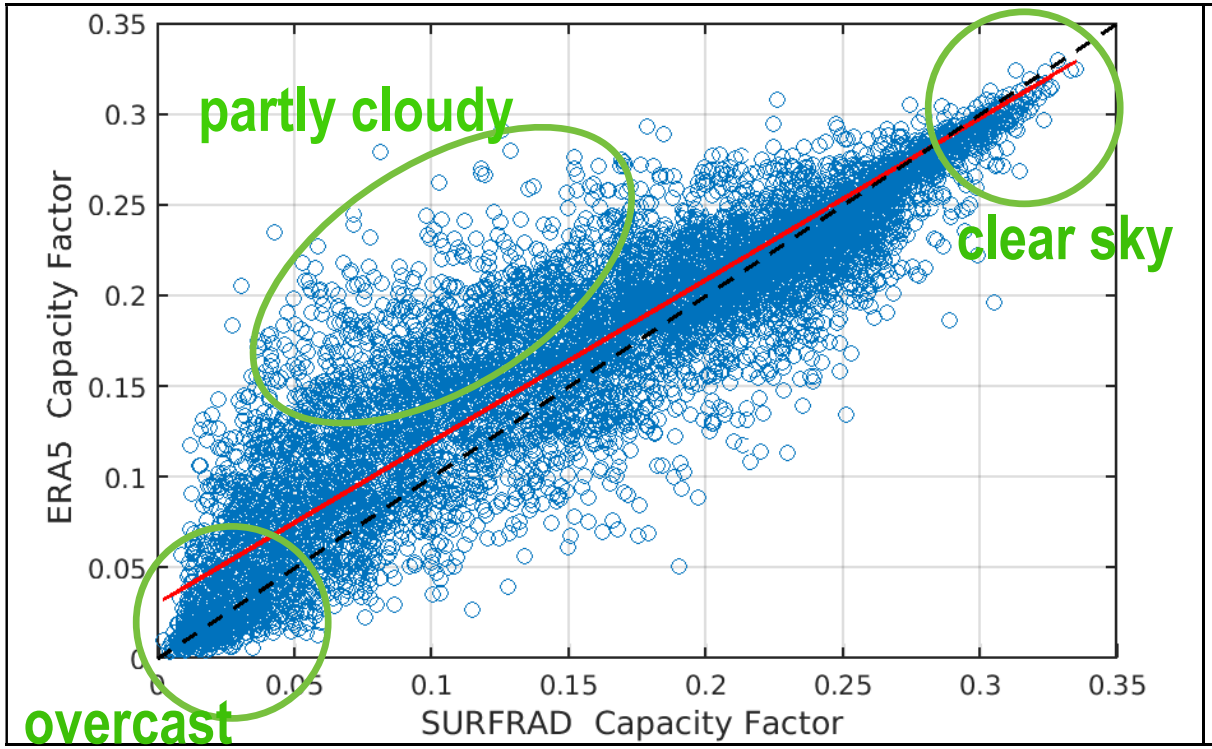


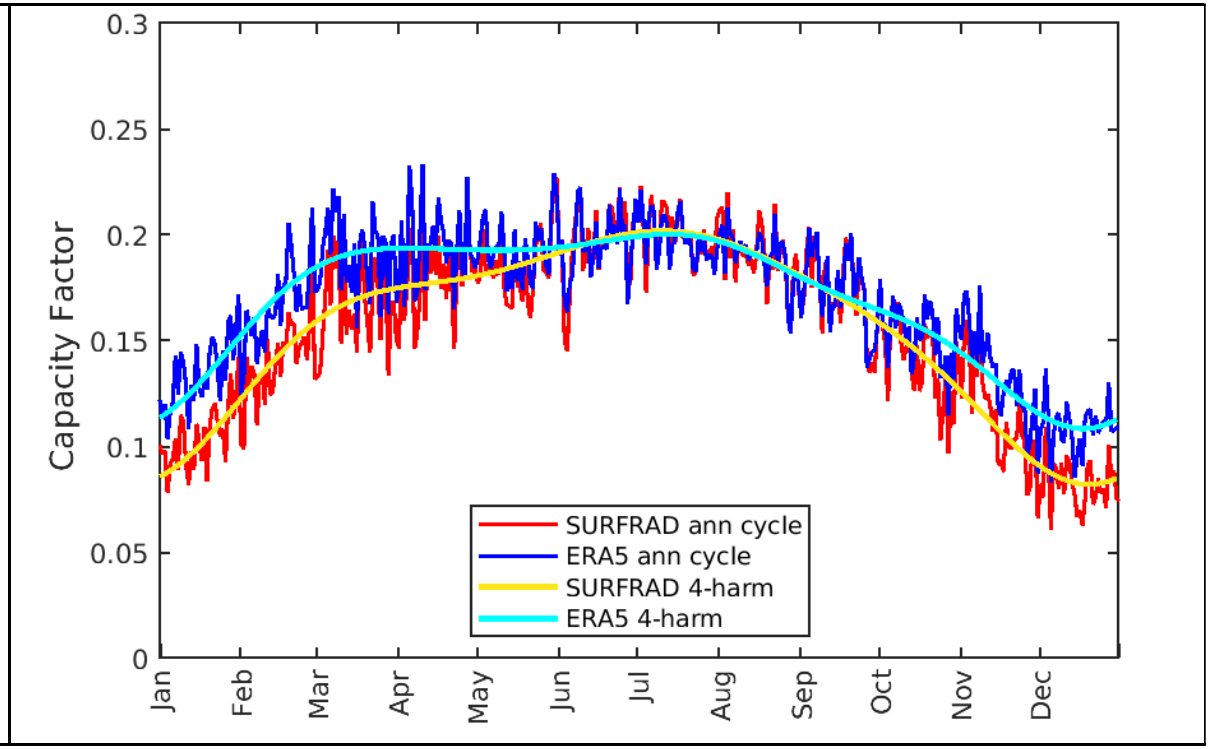
Global Horizontal Irradiance

Solar panels tilted towards the sun use more of the direct beam, less of diffuse → ERA5 high bias

Daily Solar Capacity Factors: SURFRAD site=PSU vs ERA5-derived (1998-2022)

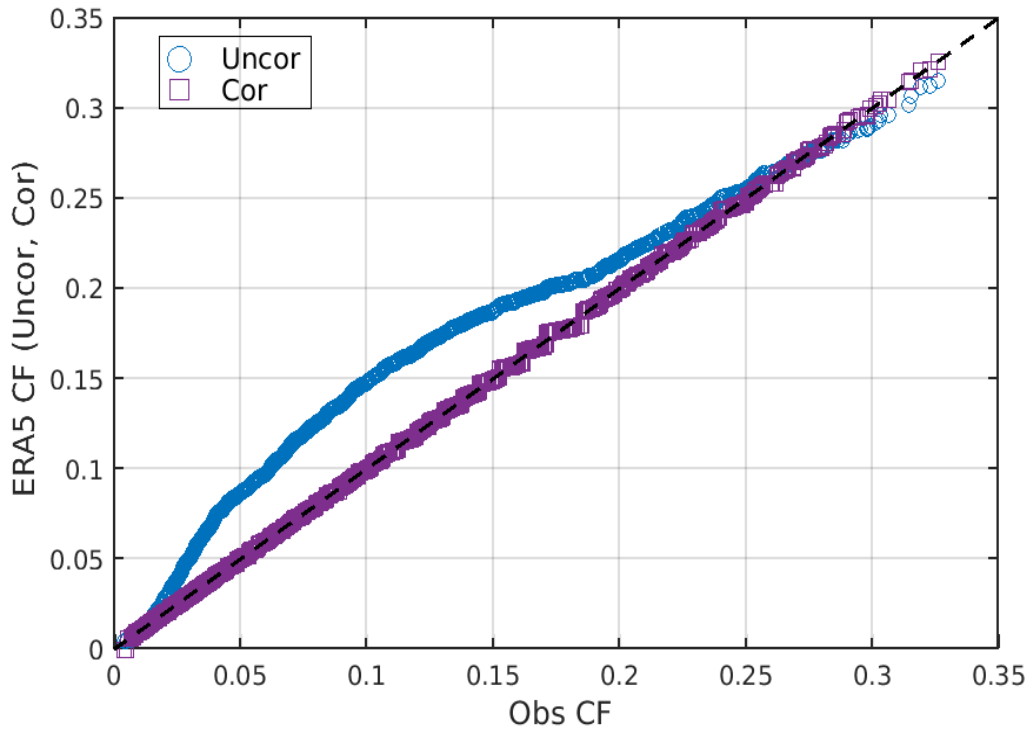
ERA5 ERRORS



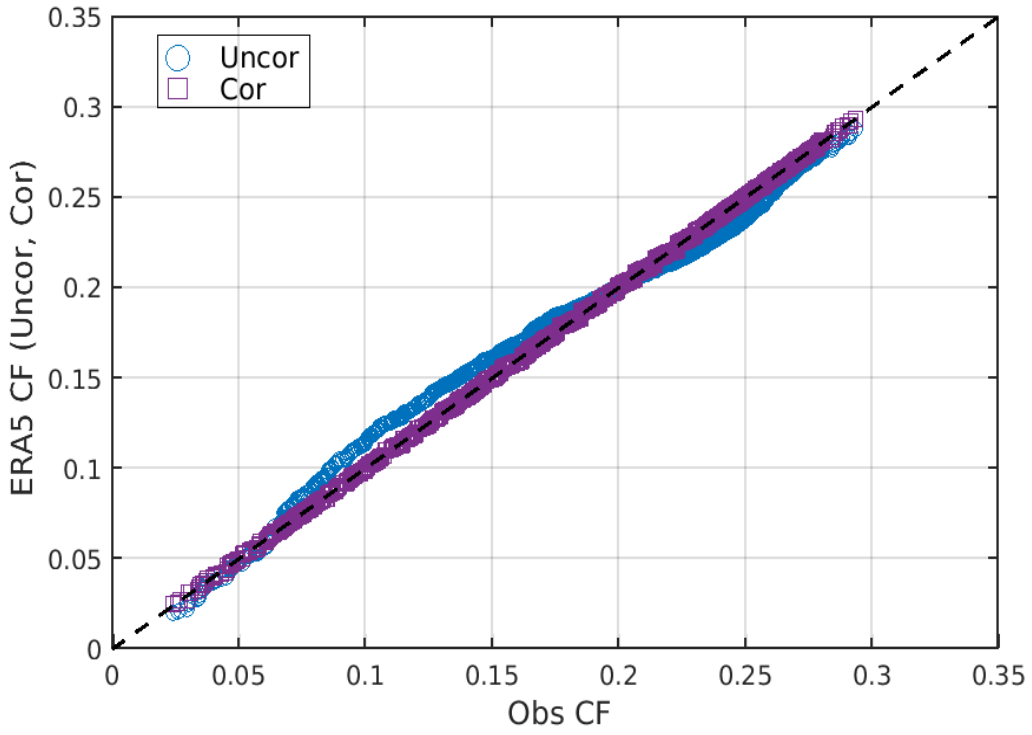


- Hourly ERA5 direct & diffuse irradiances → solar CF (pvlib), fixed tilts → daily values
- ERA5 errors small for overcast & clear skies, biased high when partly cloudy
- Annual cycle ERA5 errors largest in winter, disappear in summer

Daily Solar Capacity Factor Quantile-Quantile plots:
NOAA SURFRAD site=PSU vs ERA5-derived



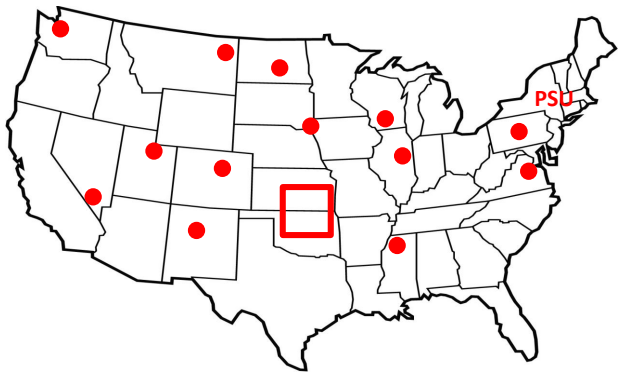
January

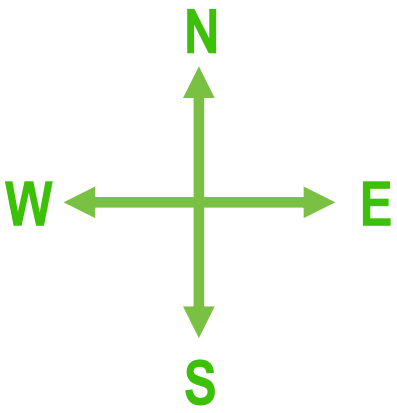


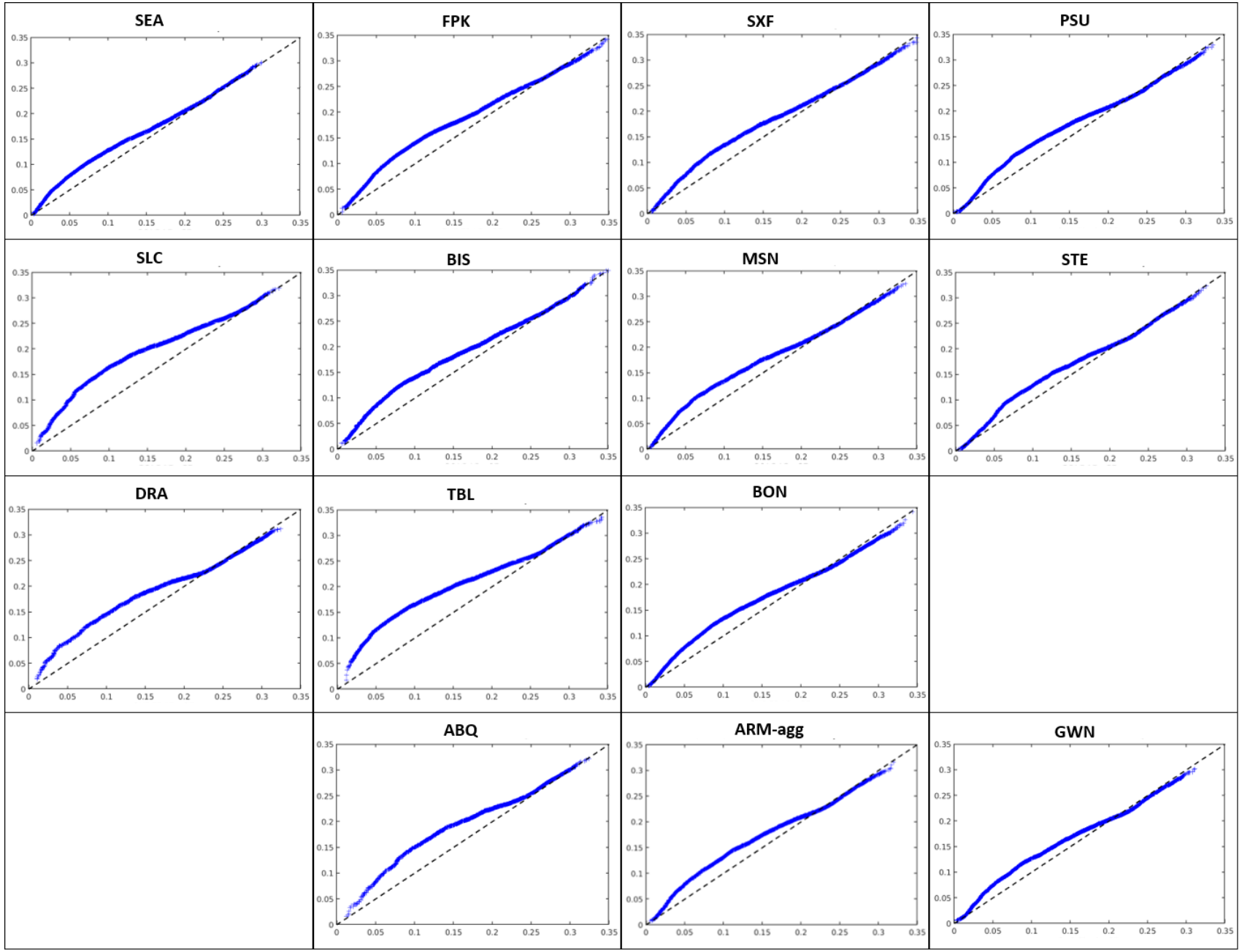
July

Q-Q corrections are made independently for each month of the year

Are ERA5-derived solar CF errors geographically consistent?







Summary

- ERA5-derived wind CFs are biased low by ~20% across most of U.S., while solar CFs are biased high by ~25% in winter.

- Quantile-quantile correction for solar, and linear regression for wind provides much more accurate solar and wind power estimates.

- Corrected solar and wind CFs provide an accurate representation of the most severe wind solar drought events

Biases in previous studies

Wind Speed

Author	Observations	Location	Wind speed bias
Dorenkamper	291 tall towers	Europe	-1.5m/s
Jourdier	7 tall towers	France	-0.5 to -1.7 m/s
Brune	14 tall towers	Europe	-0.2 to 0 m/s
Pronk	3 lidars	U.S.	-0.8 to -1.5 m/s
Gualtieri	4 tall towers	Europe, Iran, S. Africa	-0.08 to -2.25 m/s
Wilczak	157 sites (tall towers, lidars, sodars)	U.S.	-1.00 m/s

Solar Irradiances or CF

Author	Observations	Location	Diffuse Hor bias	Direct Hor bias	Solar CF NMB
Wu	17 sites, Dif	China	~-15 W/m2	NA	
Jiang	39 sites, Dif, Dir	China	-43 W/m2	+74 W/m2	
Li	14 sites, Dif, Dir	China	<0	>0	
Mathews	6 sites, Dif, Dir	Australia, Ireland			+15%
Wilczak	41 sites, Dif, Dir	U.S.	-12.1 W/m2	+21.2 W/m2	+23%

Questions to consider

1) Will next-generation reanalyzes be accurate enough that correction of systematic errors is not needed?

2) What is the best way to determine the characteristics of the systematic errors?
   a. Using meteorological observations at (limited) sites?
   b. Using wind and solar generation information, i.e. the Ninja approach of Staffell and Pfenninger (2016)?

3) If using point meteorological observations to compare to reanalysis grid cell values, what are the best ways to avoid over-inflation of the reanalysis variances?

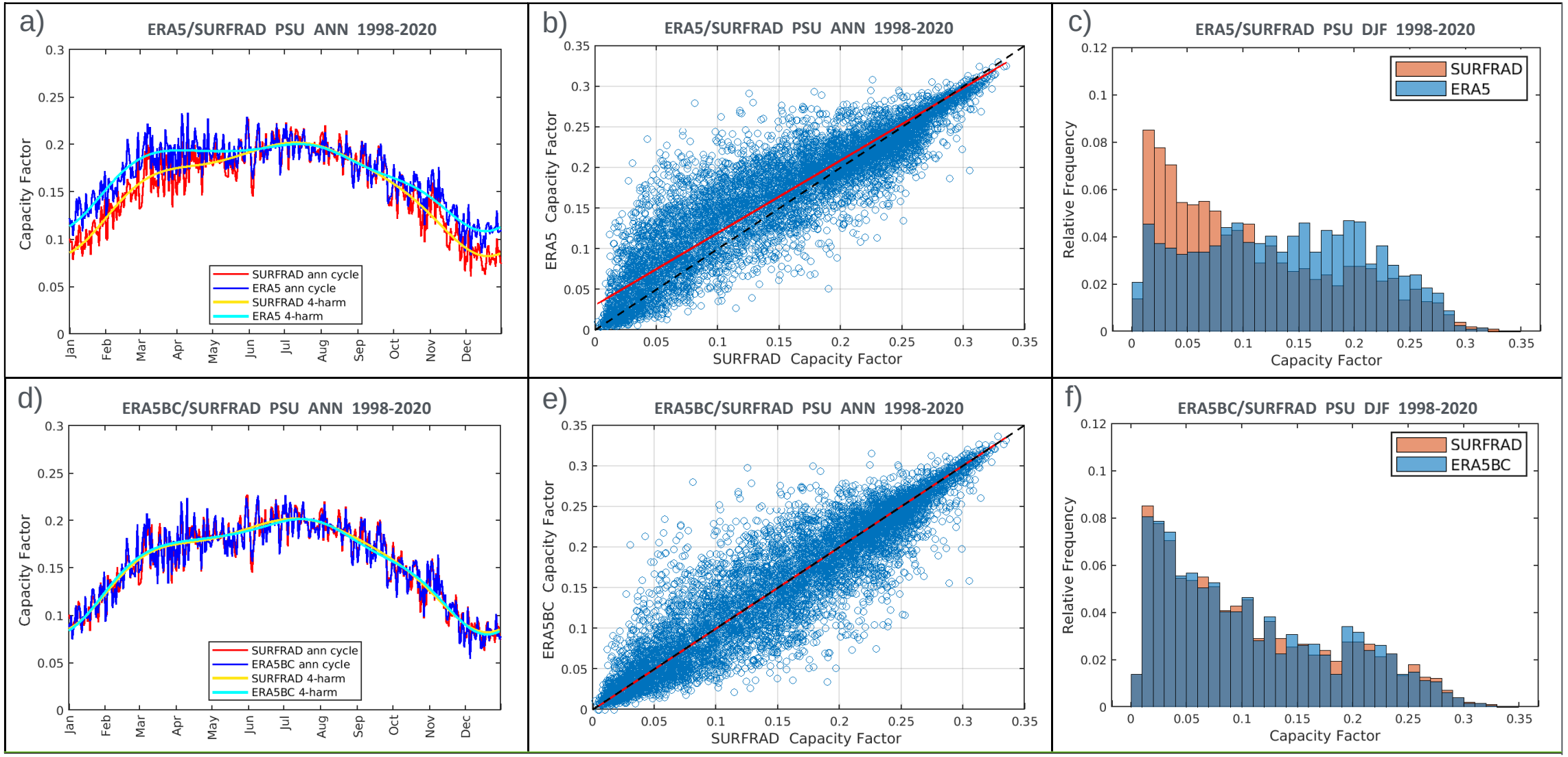
4) If using the meteorological observation approach, how does one account for sub-grid scale terrain height variations in the wind observations?

5) Does the Ninja approach provide sufficient information to inform reanalysis developers on how to improve the reanalyzes?

Thanks!

Extra slides

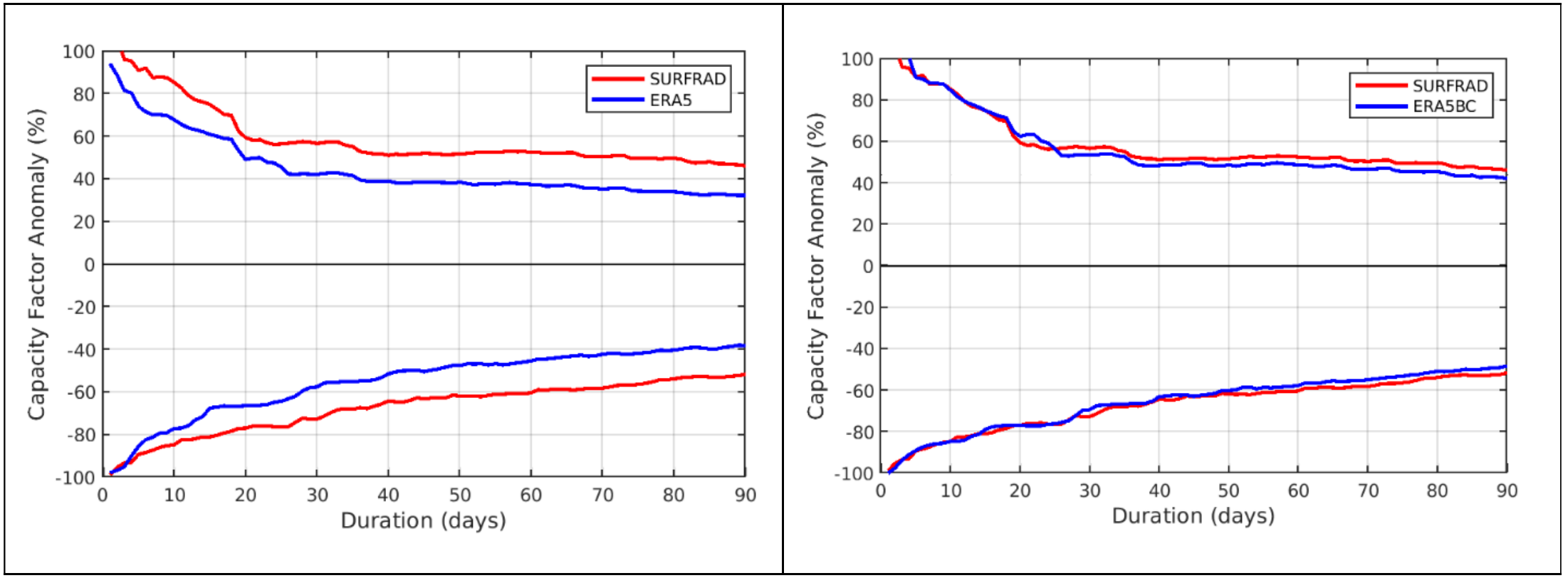
Daily Solar Capacity Factors: SURFRAD site=PSU vs ERA5-derived: Effect of Correction



ERA5

ERA5BC

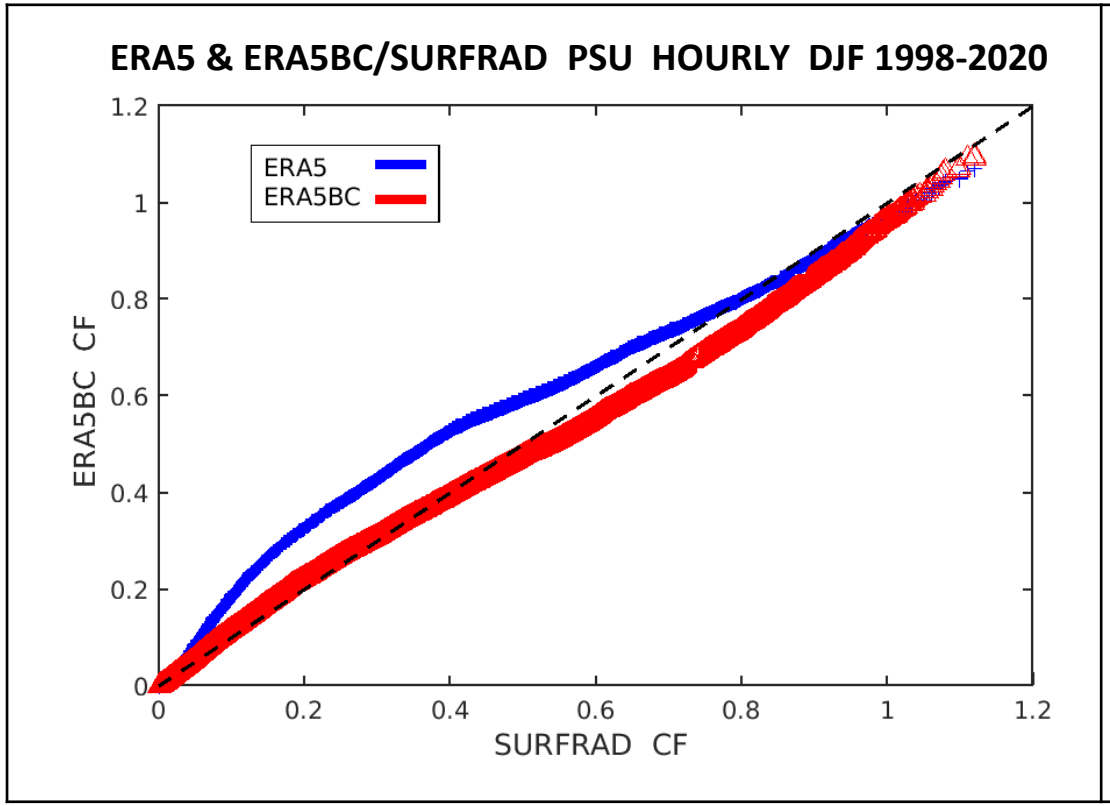
Intensity-Duration Curves: NOAA SURFRAD site=PSU vs ERA5-derived

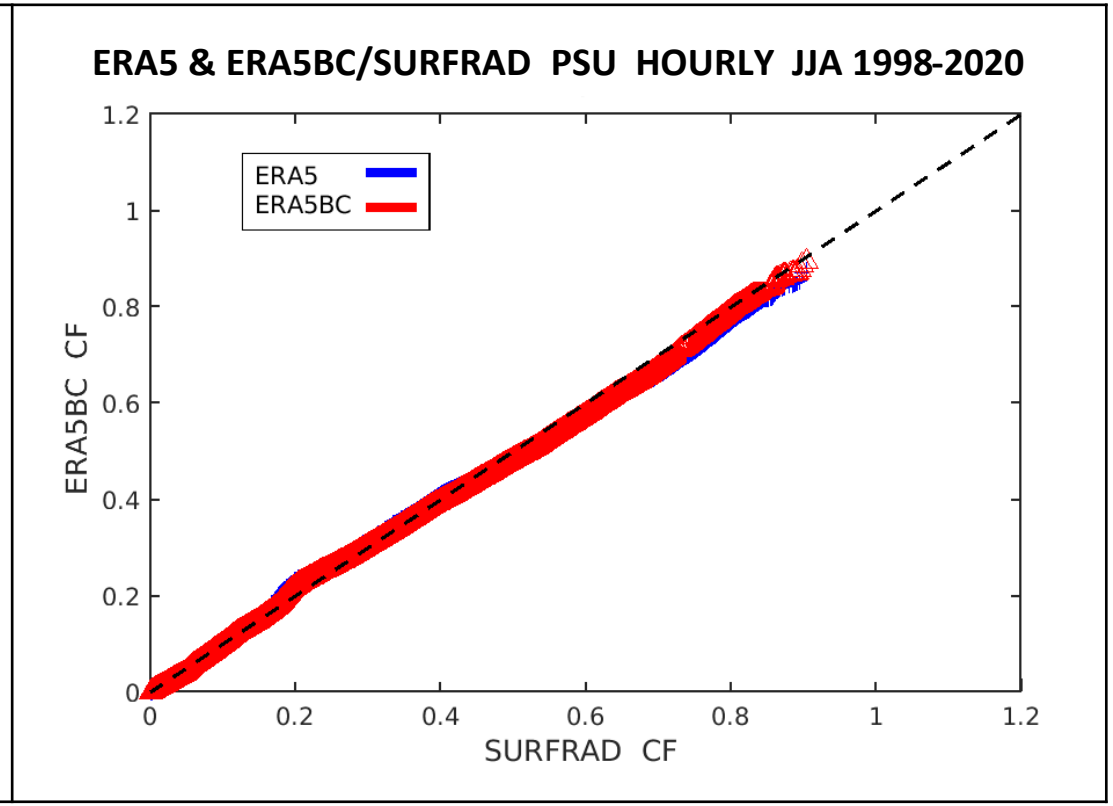


ERA5

ERA5BC (Bias Corrected)

Solar Capacity Factor Quantile-Quantile plots:
HOURLY NOAA SURFRAD site=PSU vs ERA5-derived





DJF **JJA**

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3. Gualtieri, G. Reliability of ERA5 Reanalysis Data for Wind Resource Assessment: A Comparison against Tall Towers. *Energies* **2021**, *14*, 4169. https://doi.org/10.3390/en14144169.
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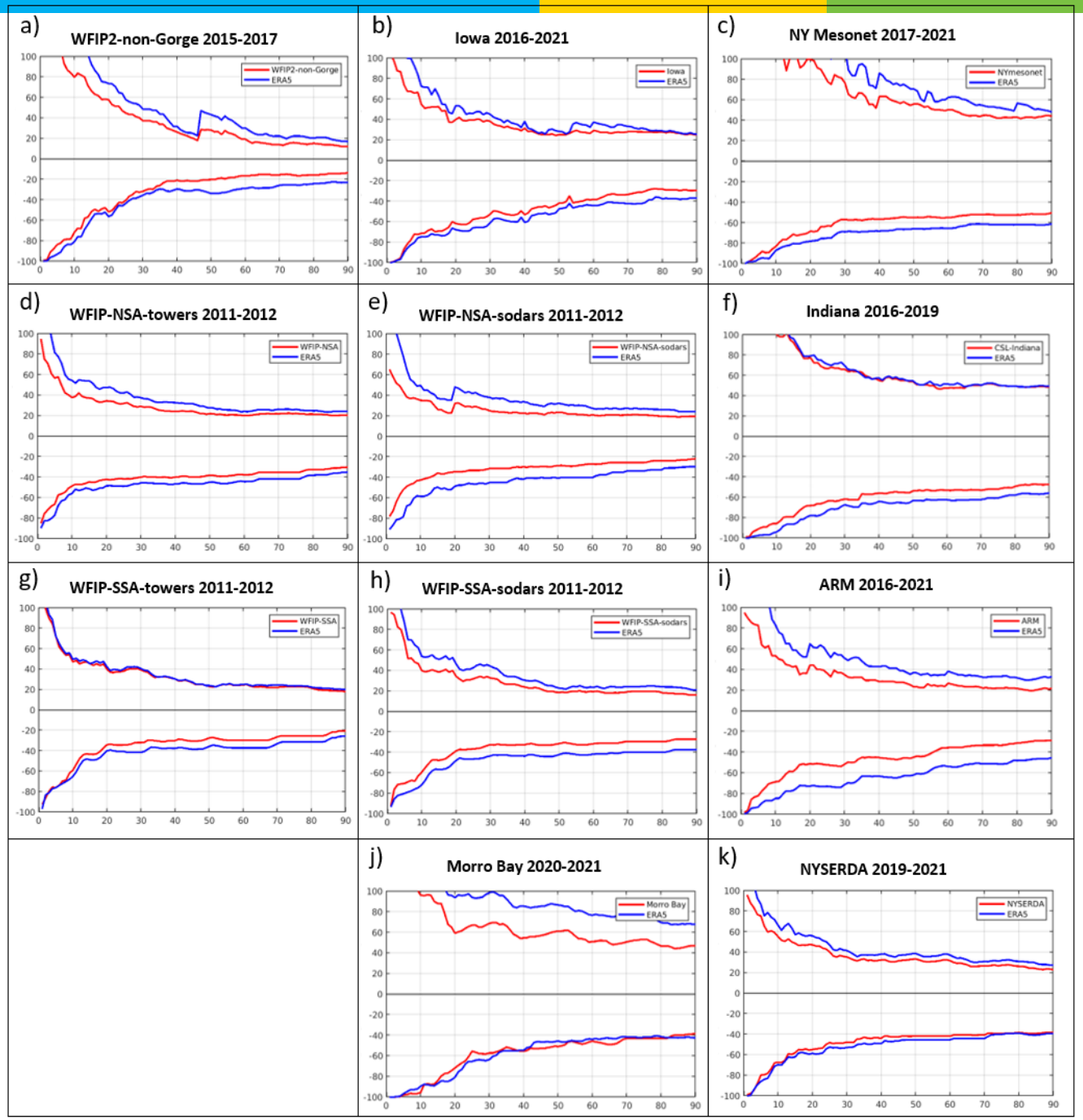
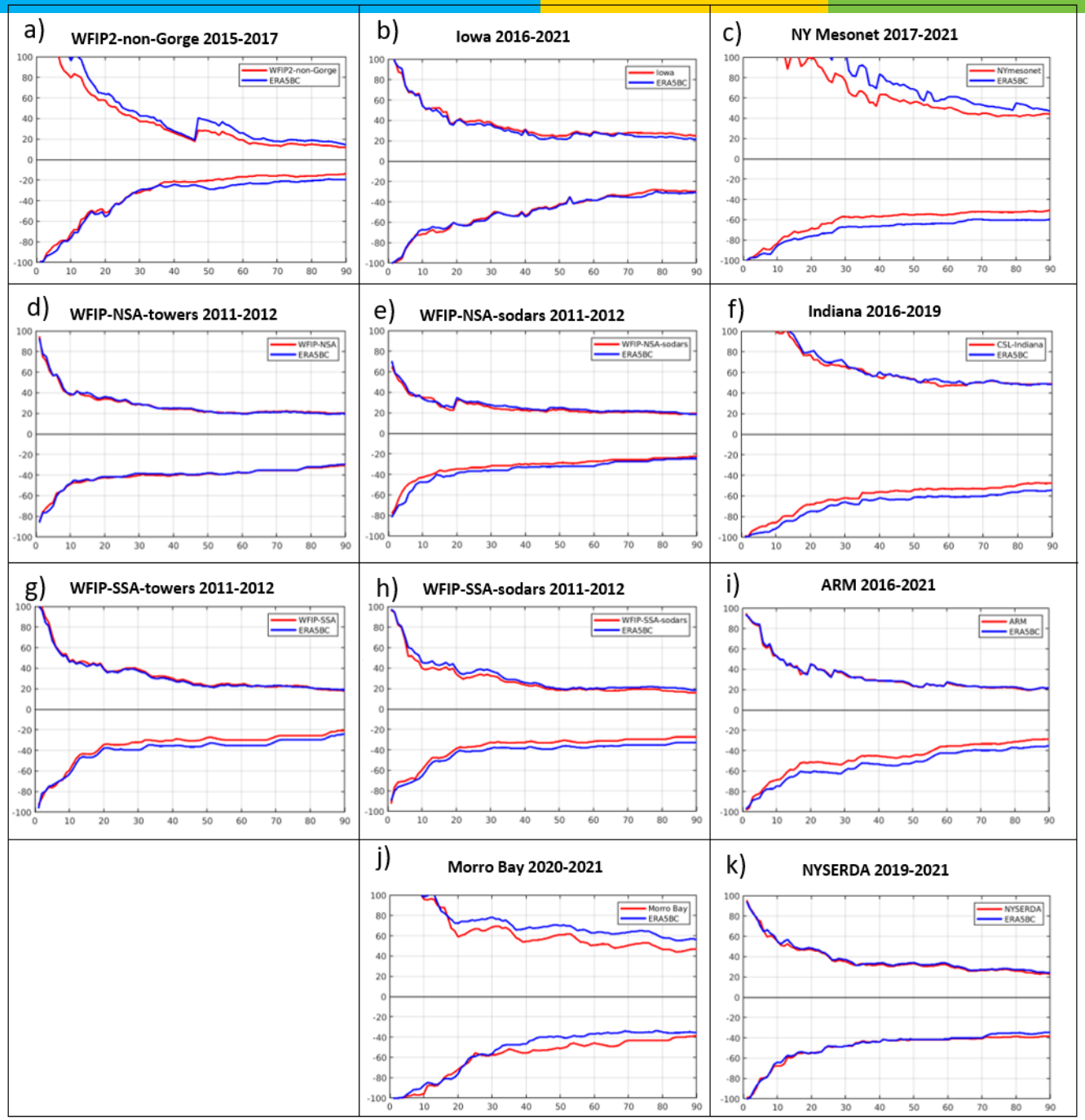
1. Wu, J.Y.; Fang, H.J.; Qin, W.M.; Wang, L.C.; Song, Y.; Su, X.; Zhang, Y.J. Constructing High-Resolution (10 km) Daily Diffuse Solar Radiation Dataset across China during 1982-2020 through Ensemble Model. *Remote Sens.* **2022**, *14*, 3695. https://doi.org/10.3390/rs14153695.
2. Jiang, H.; Yang, Y.P.; Bai, Y.Q.; Wang, H.Z. Evaluation of the Total, Direct, and Diffuse Solar Radiations From the ERA5 Reanalysis Data in China. *IEEE Geosci. Remote Sens.* **2020**, *17*, 47–51. https://doi.org/10.1109/Lgrs.2019.2916410.
3. Li, Z.G.; Yang, X.; Tang, H. Evaluation of the hourly ERA5 radiation product and its relationship with aerosols over China. *Atmos. Res.* **2023**, *294*, 106941. https://doi.org/10.1016/j.atmosres.2023.106941.
4. Mathews, D.; Gallachóir, B.O.; Deane, P. Systematic bias in reanalysis-derived solar power profiles & the potential for error propagation in long duration energy storage studies. *Appl. Energy* **2023**, *336*, 120819. https://doi.org/10.1016/j.apenergy.2023.120819.

Wind speed



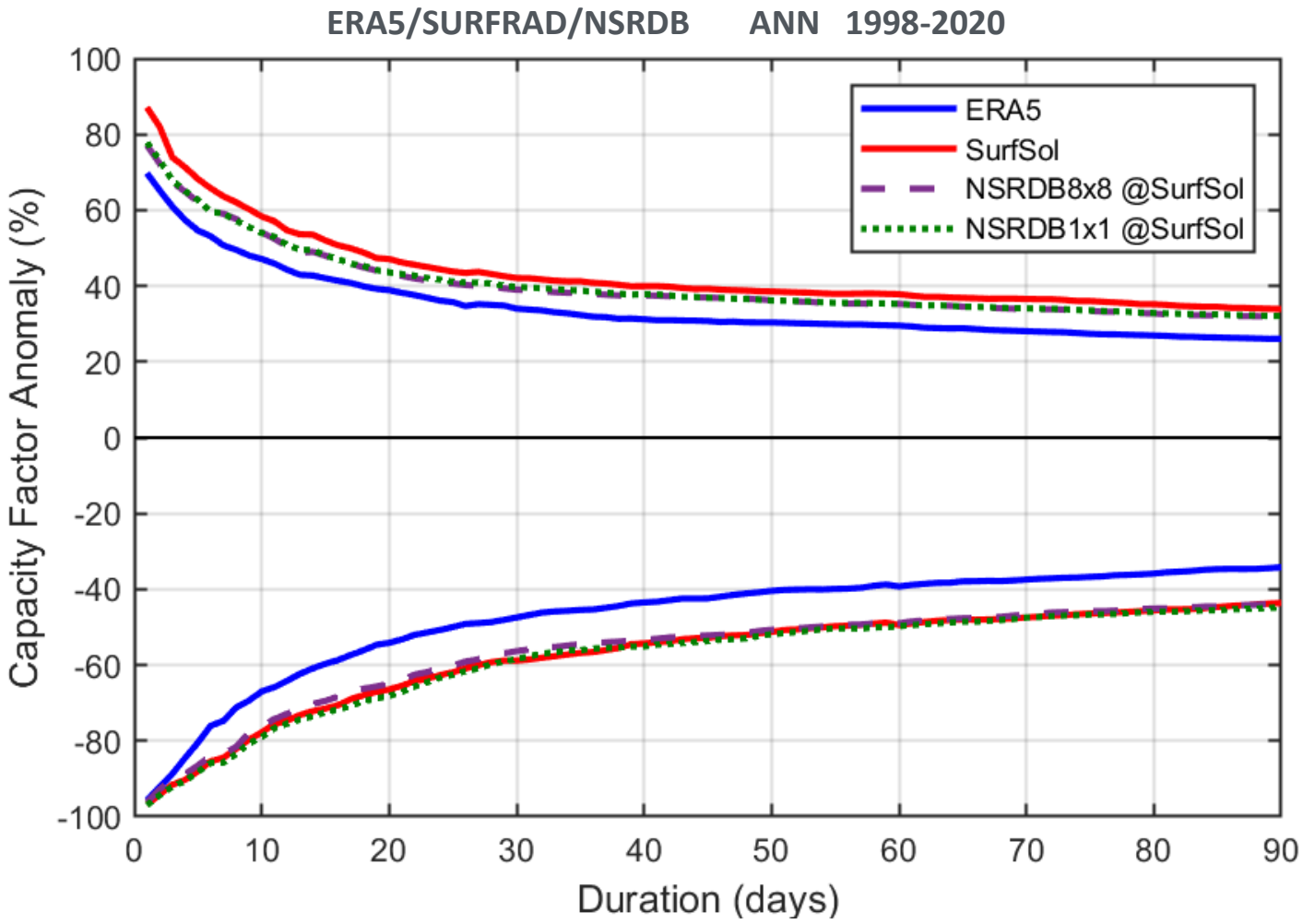
ERA5

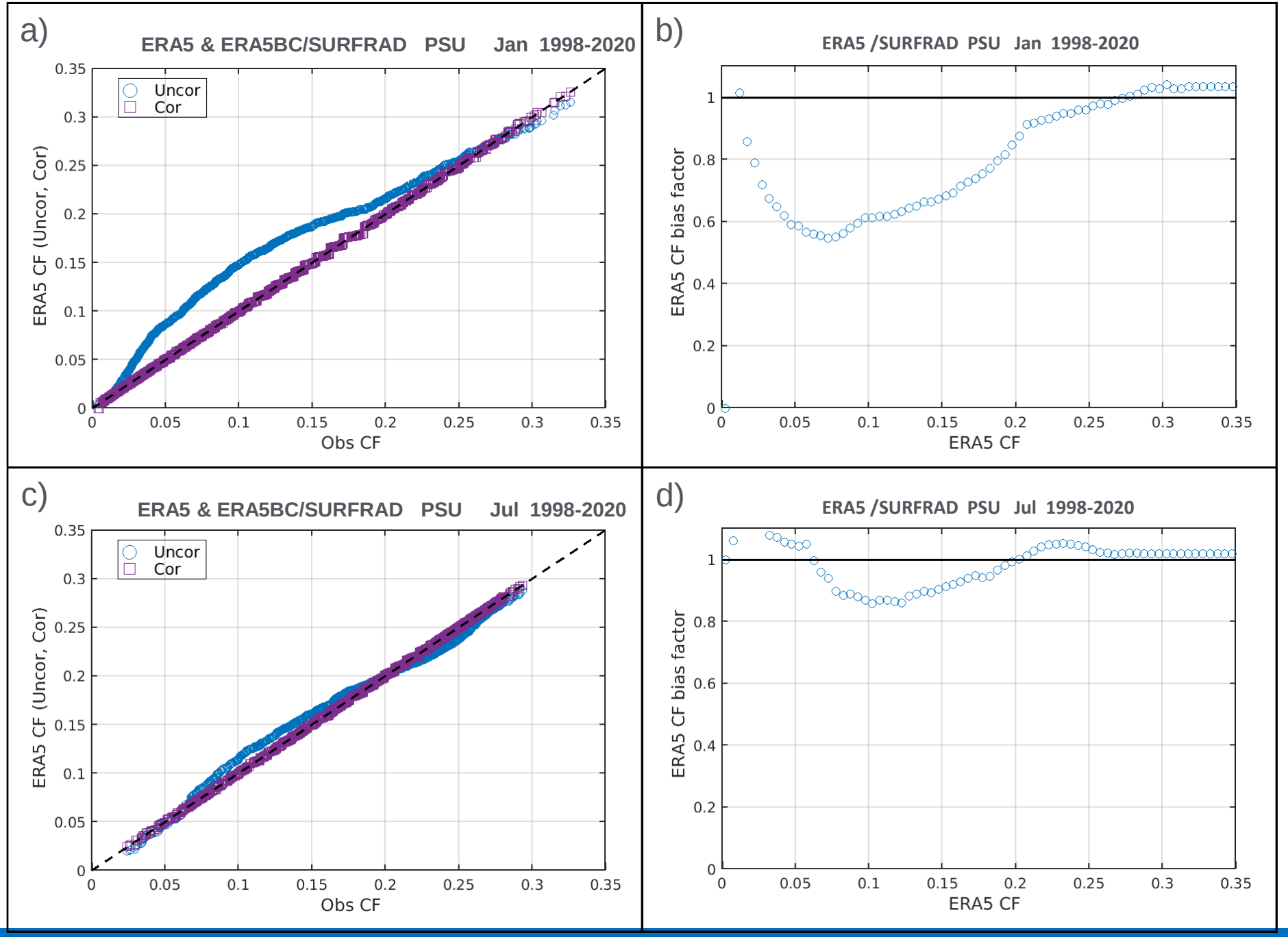
Wind speed

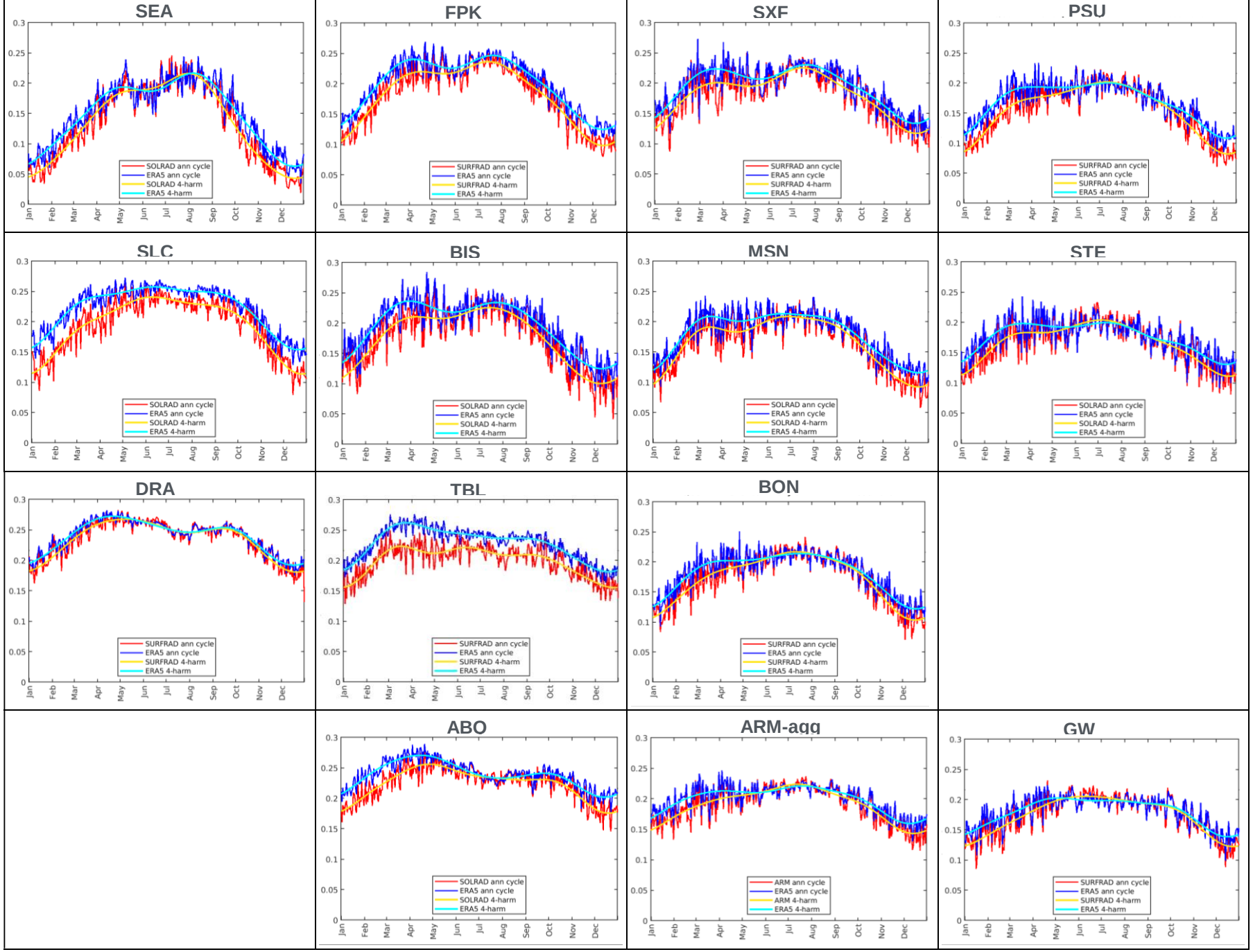


ERA5BC

Does the use of daily averaged solar CF values sufficiently reduce any potential over-inflation of the ERA5 variances?




a)
ERA5 & ERA5BC/SURFRAD PSU Jan 1998-2020
Uncor
Cor
ERA5 CF (Uncor, Cor)
Obs CF
b)
ERA5 /SURFRAD PSU Jan 1998-2020
ERA5 CF bias factor
ERA5 CF
c)
ERA5 & ERA5BC/SURFRAD PSU Jul 1998-2020
Uncor
Cor
ERA5 CF (Uncor, Cor)
Obs CF
d)
ERA5 /SURFRAD PSU Jul 1998-2020
ERA5 CF bias factor
ERA5 CF


SEA
SOLRAD ann cycle
ERA5 ann cycle
SOLRAD 4-harm
ERA5 4-harm
FPK
SURFRAD ann cycle
ERA5 ann cycle
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SXF
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ERA5 4-harm
PSU
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SLC
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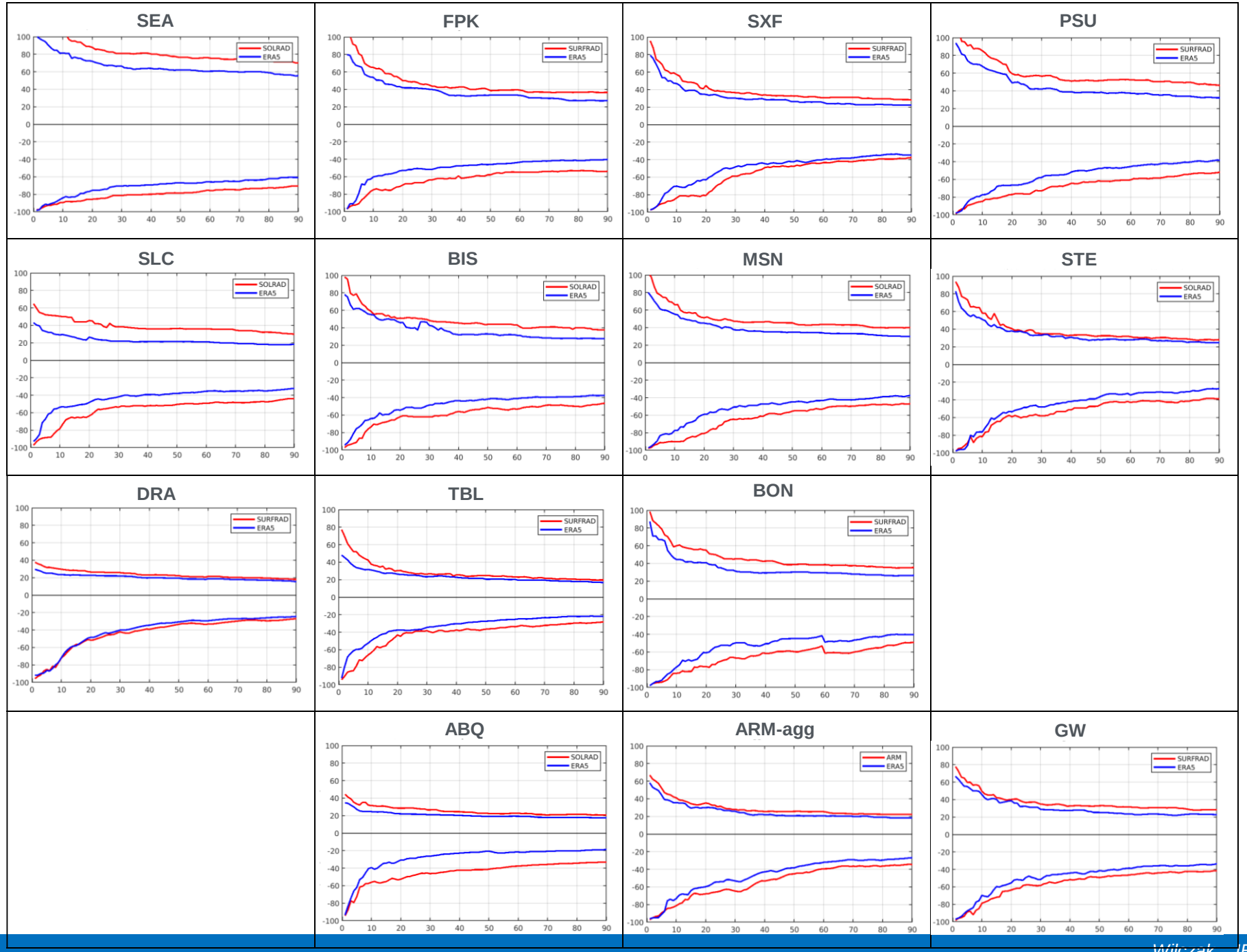
SURFRAD ann cycle
ERA5 ann cycle
SURFRAD 4-harm
ERA5 4-harm
ABO
SOLRAD ann cycle
ERA5 ann cycle
SOLRAD 4-harm
ERA5 4-harm
ARM-agg
ARM ann cycle
ERA5 ann cycle
ARM 4-harm
ERA5 4-harm
GW
SURFRAD ann cycle
ERA5 ann cycle
SURFRAD 4-harm
ERA5 4-harm
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 0.05 0.1 0.15 0.2 0.25 0.3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SOLRAD
ERA5
BIS
SOLRAD
ERA5
MSN
SOLRAD
ERA5
STE
SOLRAD
ERA5
DRA
SURFRAD
ERA5
TBL
SURFRAD
ERA5
BON
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ARM-agg
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ERA5
GW
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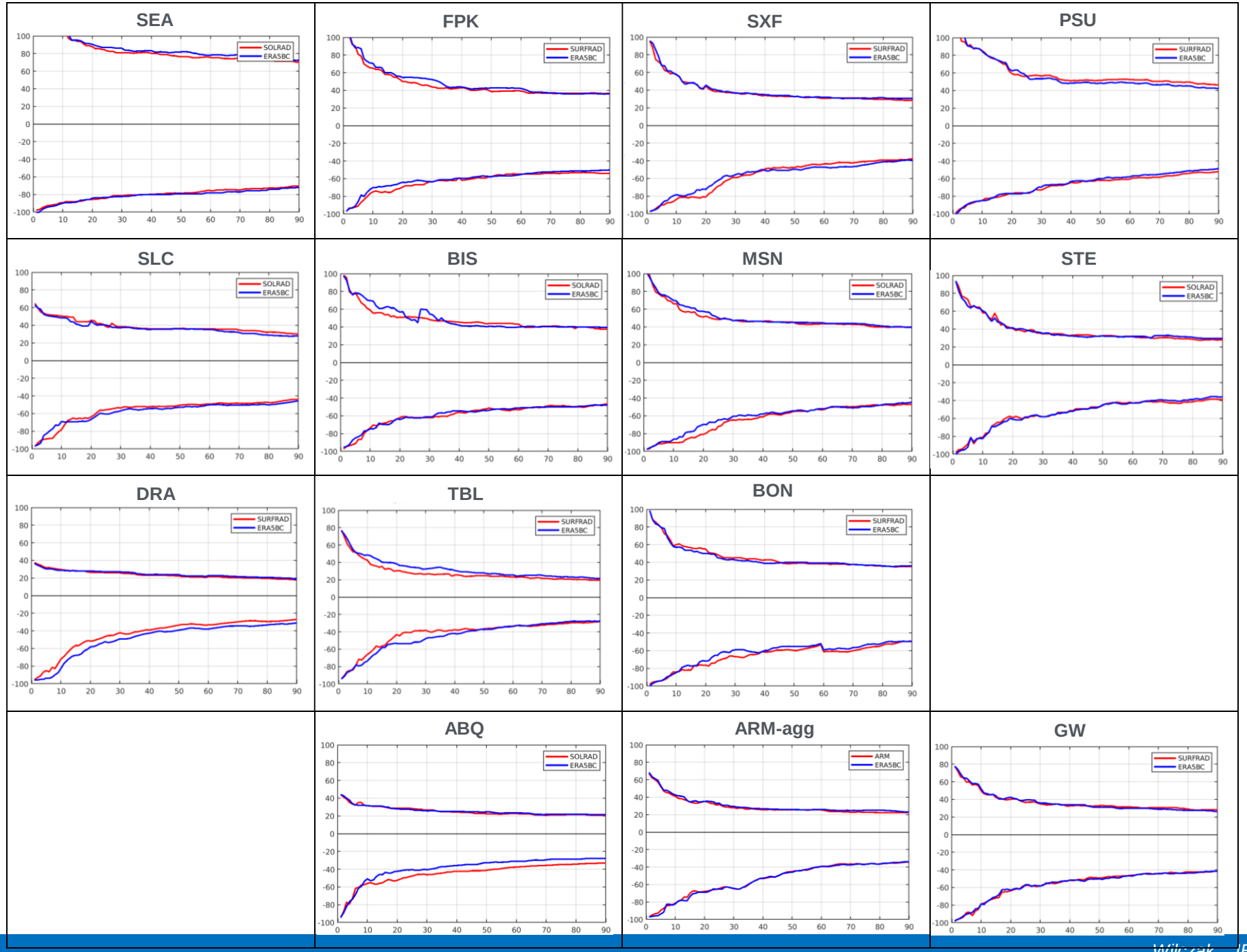
ERA5

ERA5


SEA
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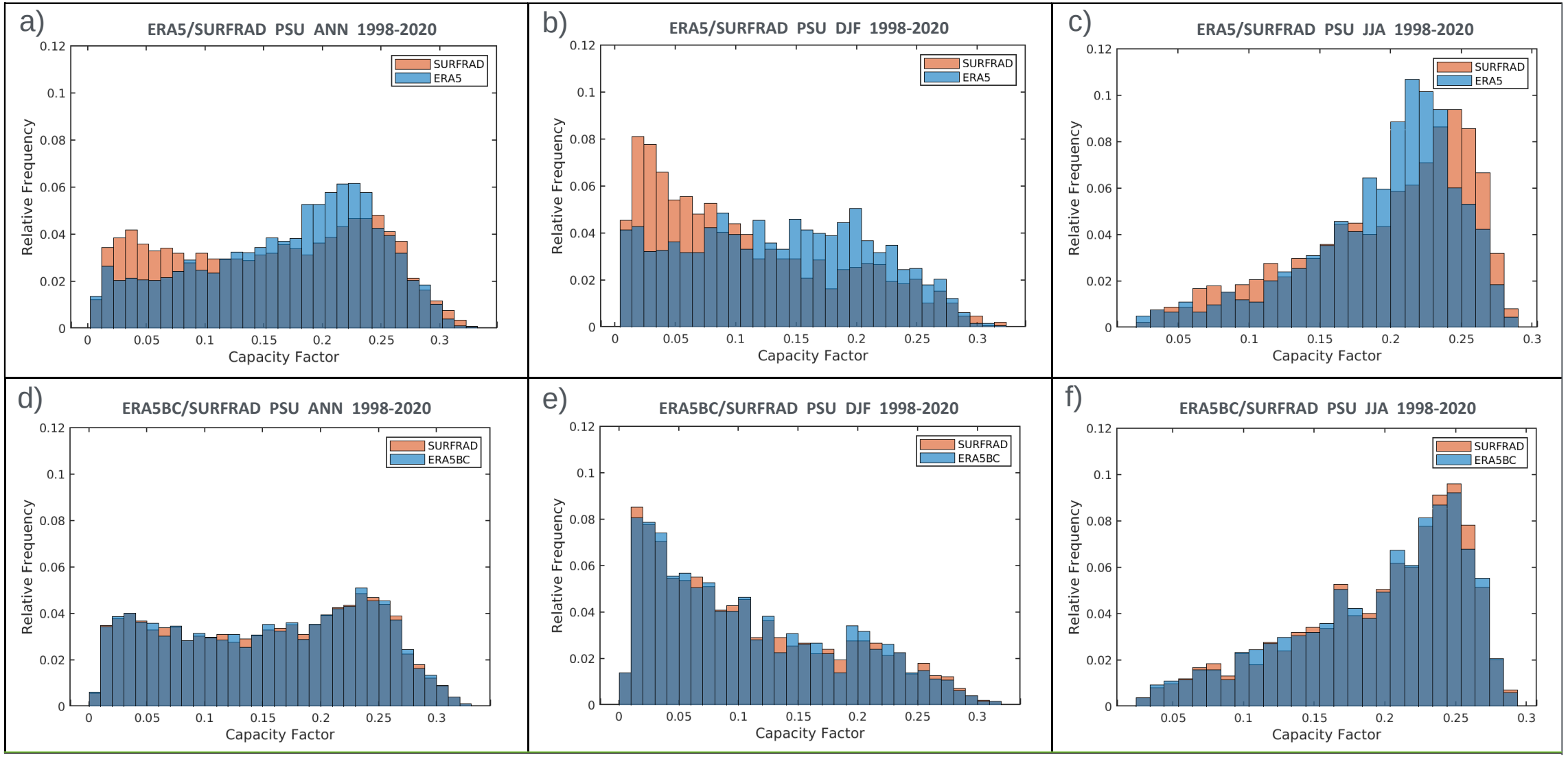
ARM
ERA5BC

ERA5BC

Solar Capacity Factors: NOAA SURFRAD site=PSU vs ERA5-derived



ERA5

ERA5BC