The WRF-Solar Ensemble Prediction System for Probabilistic Solar Forecasts

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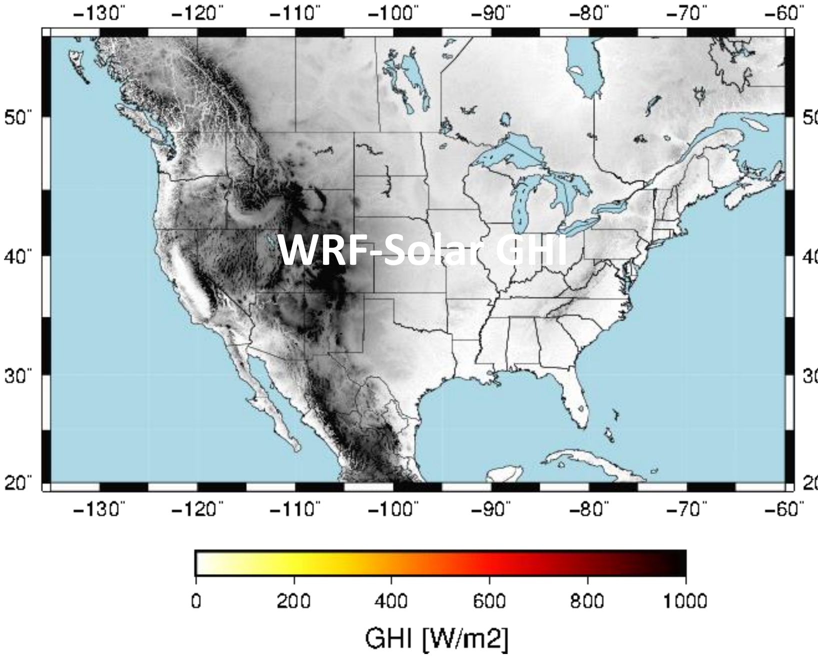
Objectives of the Project

Develop ensemble prediction system based on WRF-Solar that-

- Provides probabilistic forecasts for the grid with ensemble members tailored for solar forecasts.
- Delivers calibrated forecasts that -
  - Produce unbiased estimation of irradiance. **Goal: GHI bias < 5%; DNI Bias < 10%**
  - Improve the current-state-of-art solar forecasts and reduces uncertainty by **50% from current levels**.

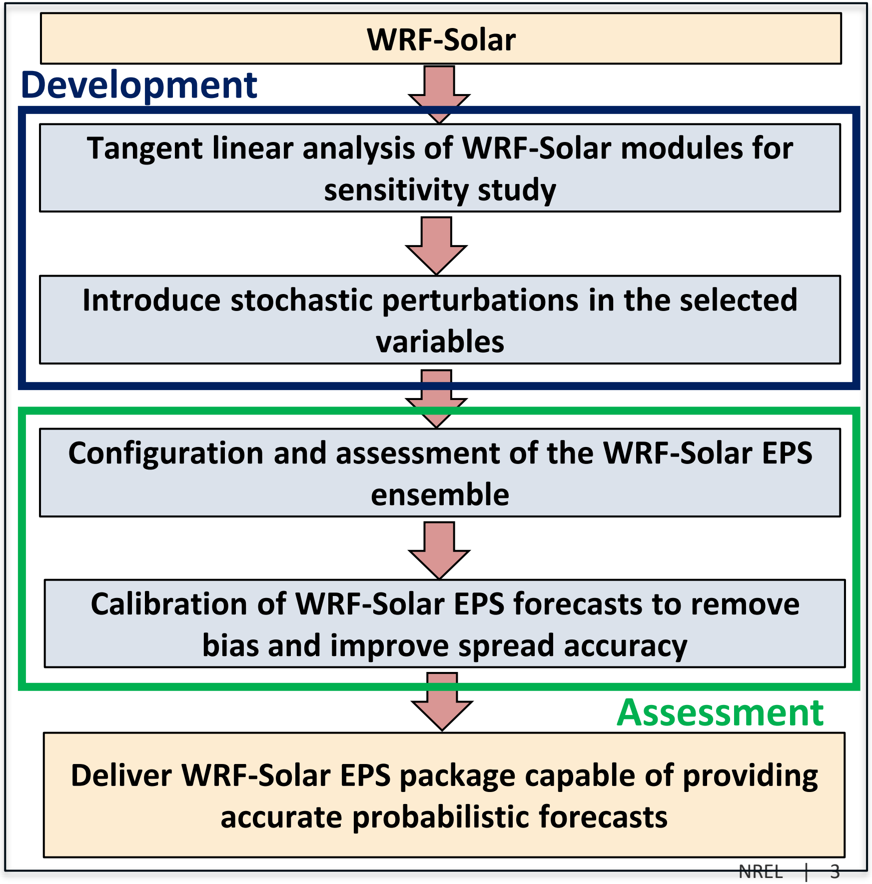
Deliver a publicly available model.



Approach

- Identify variables that significantly influence the formation and dissipation of clouds and solar radiation through a **tangent linear analysis** of WRF-Solar modules that influence cloud processes.
- Introduce stochastic perturbations in the variables identified in previous step to develop **WRF-Solar ensemble prediction system (WRF-Solar EPS).**
- **Calibrate WRF-Solar EPS** using observations to ensure that the forecasts' trajectories are unbiased and provide accurate estimates of forecast uncertainties under a wide range of meteorological regimes.
- **Demonstrate the improvements from WRF-Solar EPS.**
- Incorporate WRF-Solar EPS in the WRF-Solar community model as an open-source probabilistic framework: https://ral.ucar.edu/solutions/products/wrf-solar-eps

WRF-Solar EPS is the first NWP ensemble model specifically designed to provide probabilistic irradiance forecast.



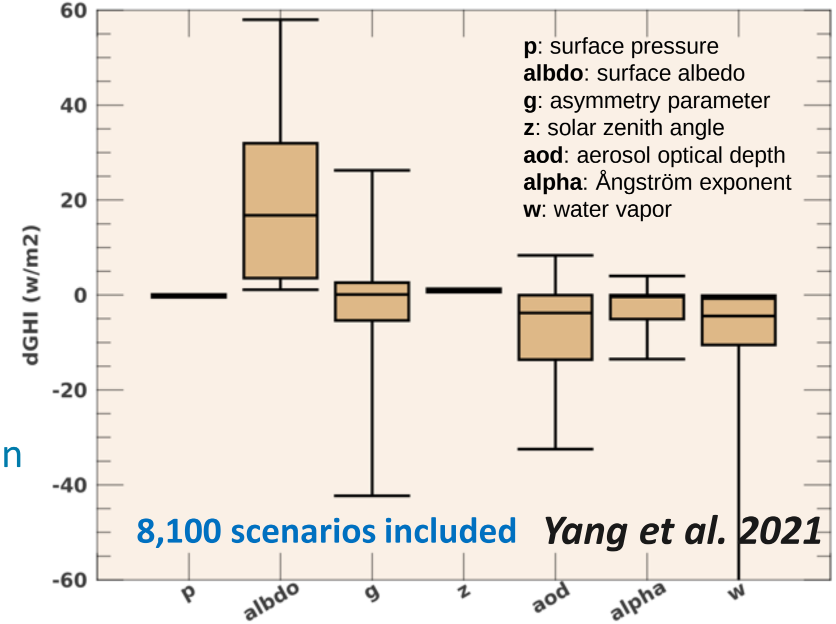
Selecting variables for WRF-Solar EPS

Developed tangent linear (TL) models to quantify the impact of the uncertainty of input variables on the output when forecasting clouds and irradiance.

WRF-Solar parameterizations selected:

- Fast All-sky Radiation Model for Solar applications
- Thompson microphysics
- Mellor–Yamada–Nakanishi–Niino (MYNN) for PBL
- Deng shallow cumulus system
- Unresolved clouds parameterization module based on relative humidity (CLD3)
- Noah land surface model (Noah LSM)

Impact of uncertainty of FARMS input variables on GHI in clear-sky



Innovative approach that can cover all possible ranges of input parameters efficiently.

Yang, J., J.H. Kim, P.A. Jimenez, M. Sengupta, J. Dudhia, Y. Xie, A. Golnas and R. Giering, 2021: An Efficient Method to Identify Uncertainties of WRF-Solar Variables in Forecasting Solar Irradiance Using a Tangent Linear Sensitivity Analysis. *Solar Energy*, Vol. 220, pp.509-522. (**Best paper award from *Solar Energy* Journal**).

Development of WRF-Solar EPS

Selected 14 WRF-Solar variables to be stochastically perturbed to generate ensemble members for solar forecasts

#	Variable Name	σ	λ (m)	τ (s)
1	Albedo	0.1	100000	86400
2	Aerosol optical depth	0.25	100000	3600
3	Ångström wavelength exponent	0.1	100000	3600
4	Asymmetry factor	0.05	100000	3600
5	Water vapor mixing ratio	0.05	100000	3600
6	Cloud water mixing ratio	0.1	100000	3600
7	Ice mixing ratio	0.1	100000	3600
8	Snow mixing ratio	0.1	100000	3600
9	Ice number concentration	0.05	100000	3600
10	Potential temperature	0.001	100000	3600
11	Turbulent kinetic energy	0.05	80000	600
12	Soil moisture content	0.1	80000	21600
13	Soil temperature	0.001	80000	21600
14	Vertical velocity	0.1	80000	21600

Characteristics of the perturbation
σ: Standard deviation which is used as tunning parameter to control the amplitude of the perturbation
λ: Length scale [m]
τ: Time scale [s]

$\underbrace{\sigma \quad \lambda \quad \tau}$

Main parameters to control WRF-Solar EPS

A user-friendly interface

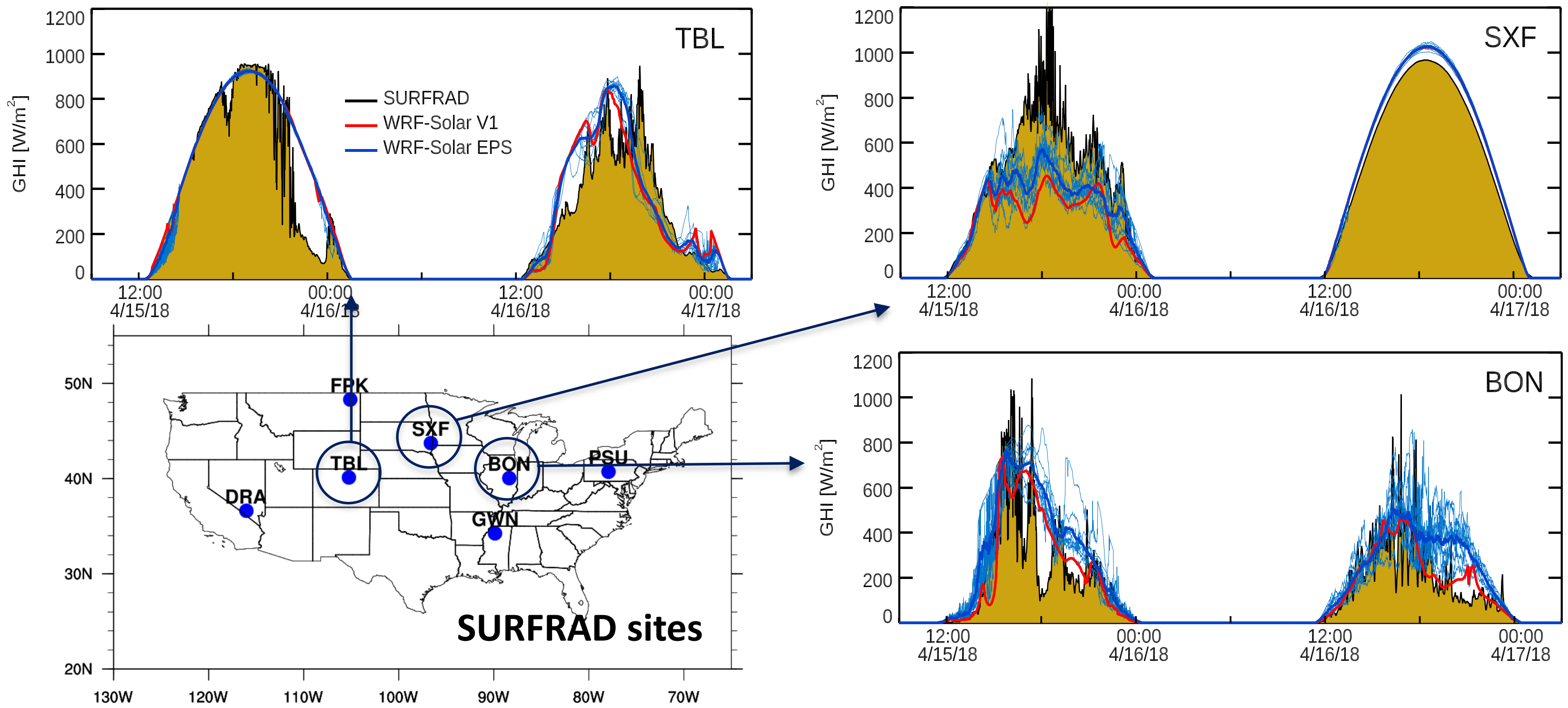
```
&stoch
multi_perturb                     = 1
num_ensemble                      = 10

pert_farms                        = .true.
pert_farms_albedo                 = 1.0
pert_farms_aod                    = 1.0
pert_farms_angexp                 = 1.0
pert_farms_aerasy                 = 1.0
pert_farms_qv                     = 1.0
pert_farms_qc                     = 1.0
pert_farms_qs                     = 1.0
```

- **We specify the characteristics of the stochastic perturbations for each variable using a configuration file.**
- **Preliminary user's guide for WRF-Solar EPS: https://ral.ucar.edu/projects/wrf-solar-eps**

Testing of WRF-Solar EPS

Timeseries of predicted GHI from the WRF-Solar EPS

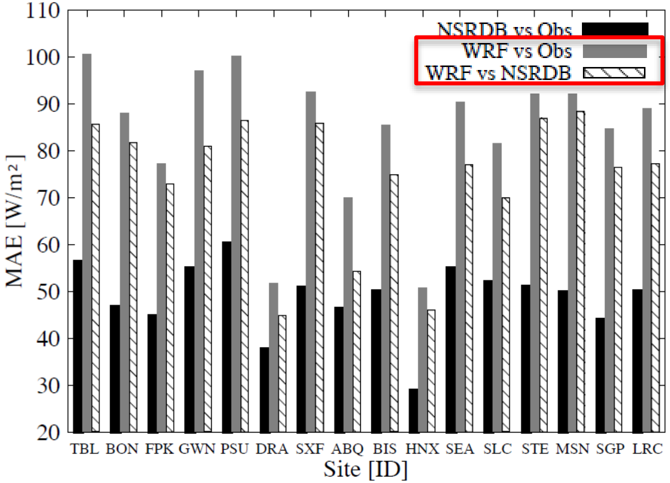


The impact of perturbations on 10 ensemble members is pronounced in cloudy-sky.

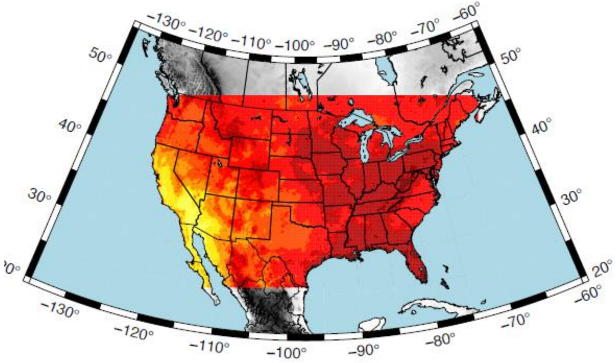
Satellite-derived Datasets for Validation

NSRDB compared with surface observations and deterministic WRF-Solar day ahead forecasts (2018).

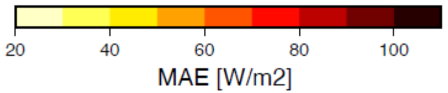
MAE comparison of WRF-Solar, NSRDB, and ground Obs.



MAE of WRF-Solar GHI calculated with NSRDB.



MAE of WRF-Solar GHI calculated with ground Obs.



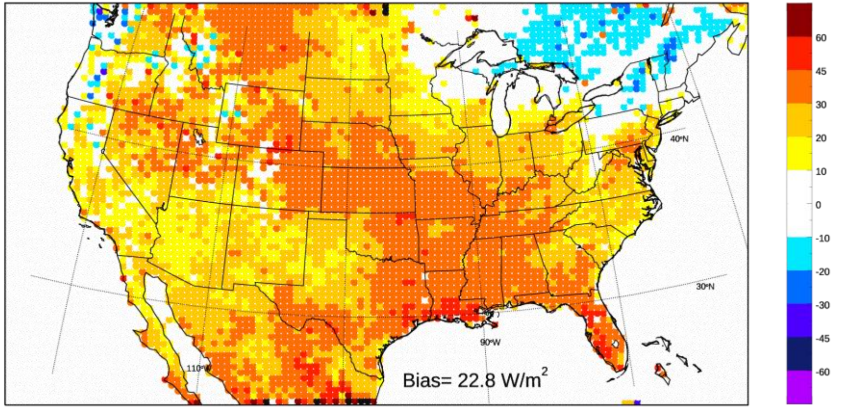
The MAE calculated with NSRDB is within ~10% of high-quality ground observations and reproduces the spatial variability of the error (r = 0.96).

Accuracy of NSRDB is sufficient for WRF-EPS validation.

Jimenez, P.A., Yang, J., Kim, J.H., Sengupta, M. and Dudhia, J., 2021, [Assessing the WRF-Solar Model Performance Using Satellite-derived Irradiance from the National Solar Radiation Database](), *Journal of Applied Meteorology and Climatology.*

WRF-Solar EPS Assessment and Calibration

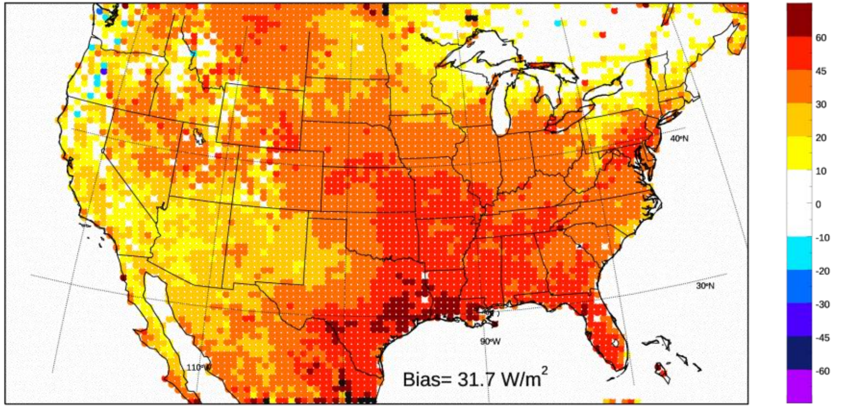
WRF-Solar V1 Bias



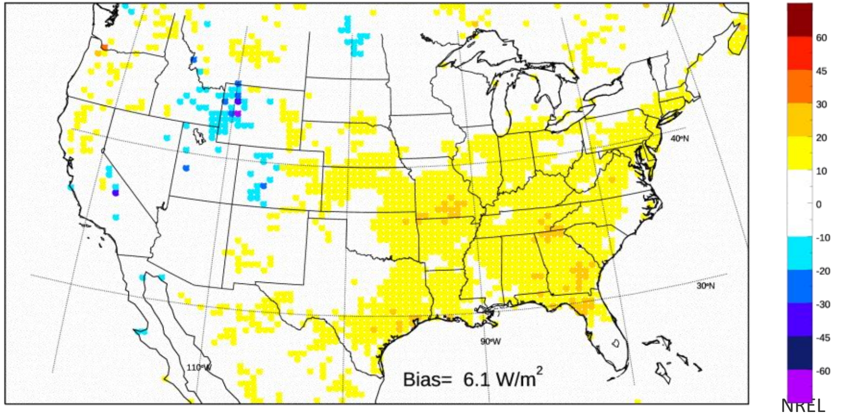
2018 evaluation

WRF-Solar EPS slightly increases positive bias in the day ahead GHI forecasts from WRF-Solar reference configuration, but the calibration largely suppresses the bias.

WRF-Solar EPS Bias



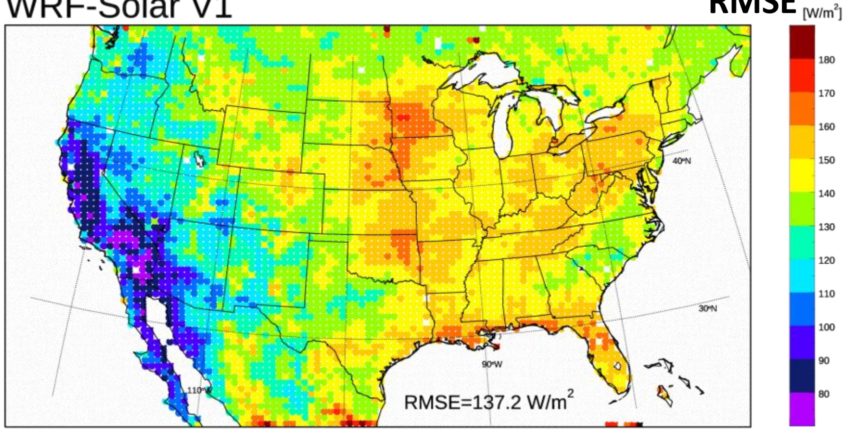
Calibrated WRF-Solar EPS Bias



WRF-Solar EPS Assessment and Calibration

WRF-Solar V1

RMSE

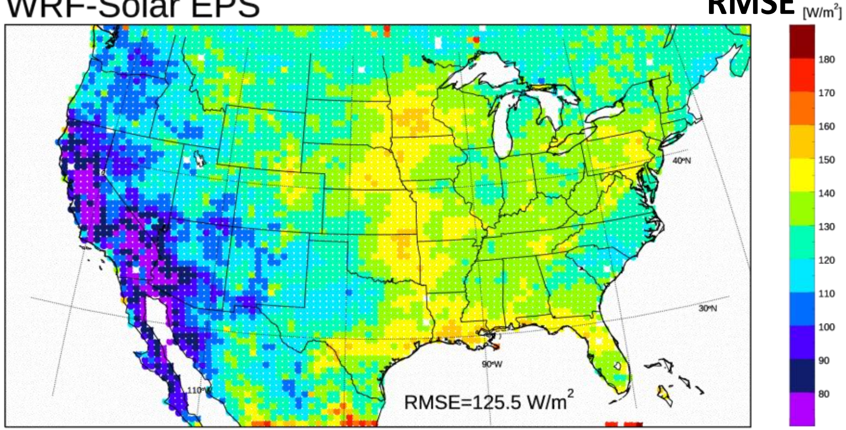


2018 evaluation

The calibrated **WRF-Solar EPS reduces the errors** in the day ahead GHI forecasts from WRF-Solar reference configuration **by 14 %.**

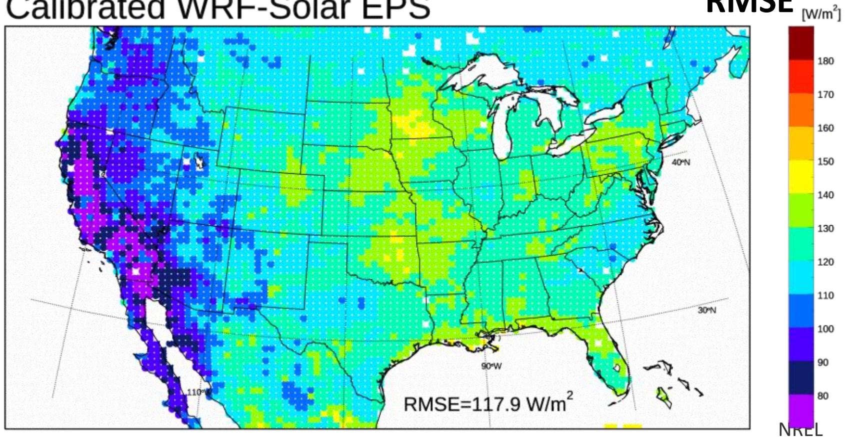
WRF-Solar EPS

RMSE

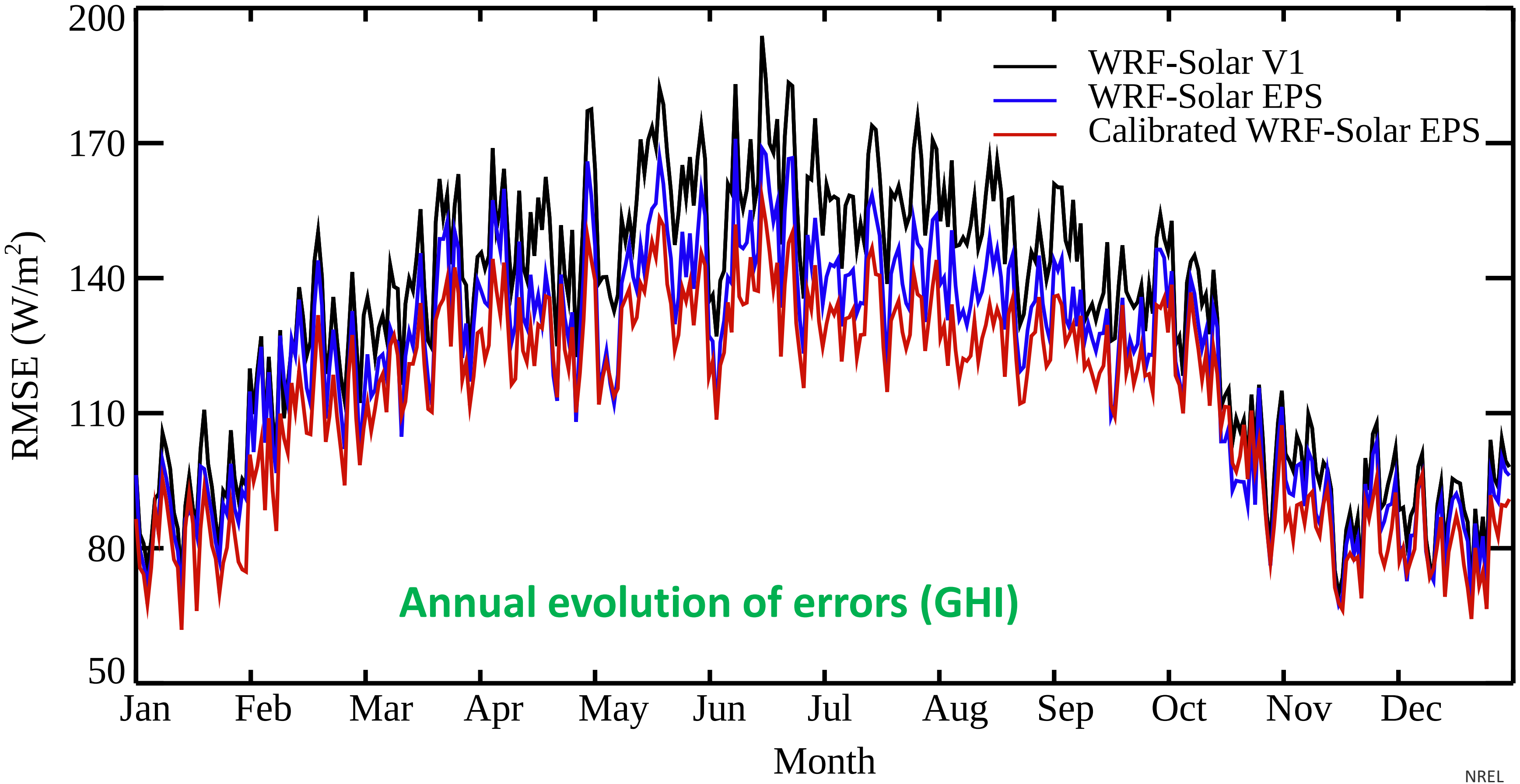


Calibrated WRF-Solar EPS

RMSE

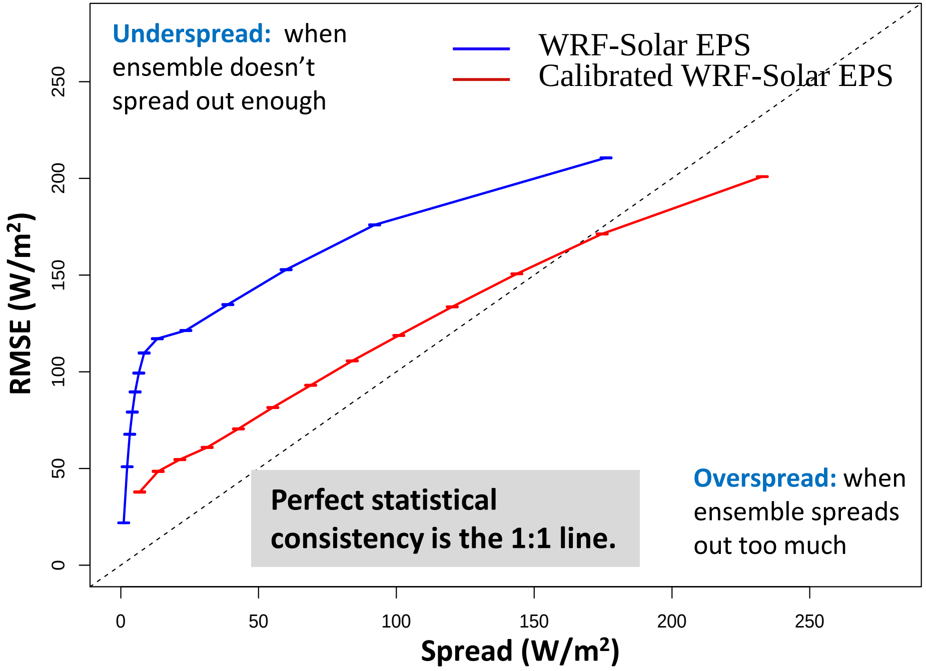


WRF-Solar EPS Assessment and Calibration

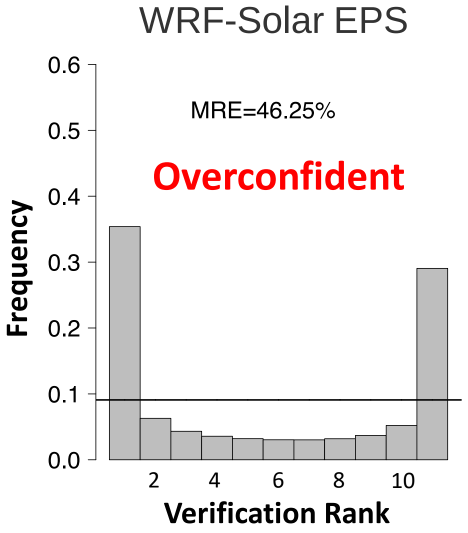


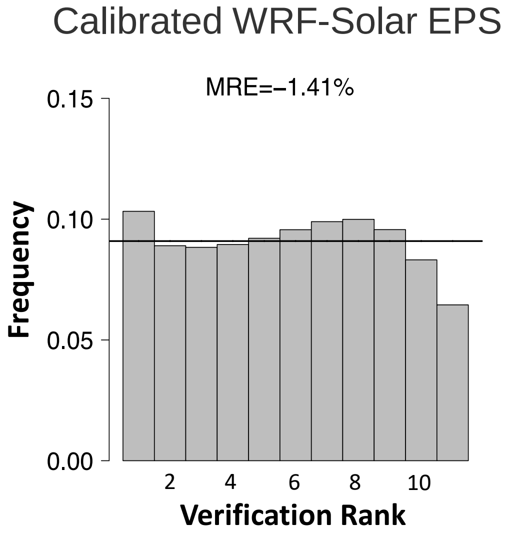
Evaluation of Probabilistic Forecasts

Binned spread-skill plot (for uncertainty)



Rank Histogram (for consistency)



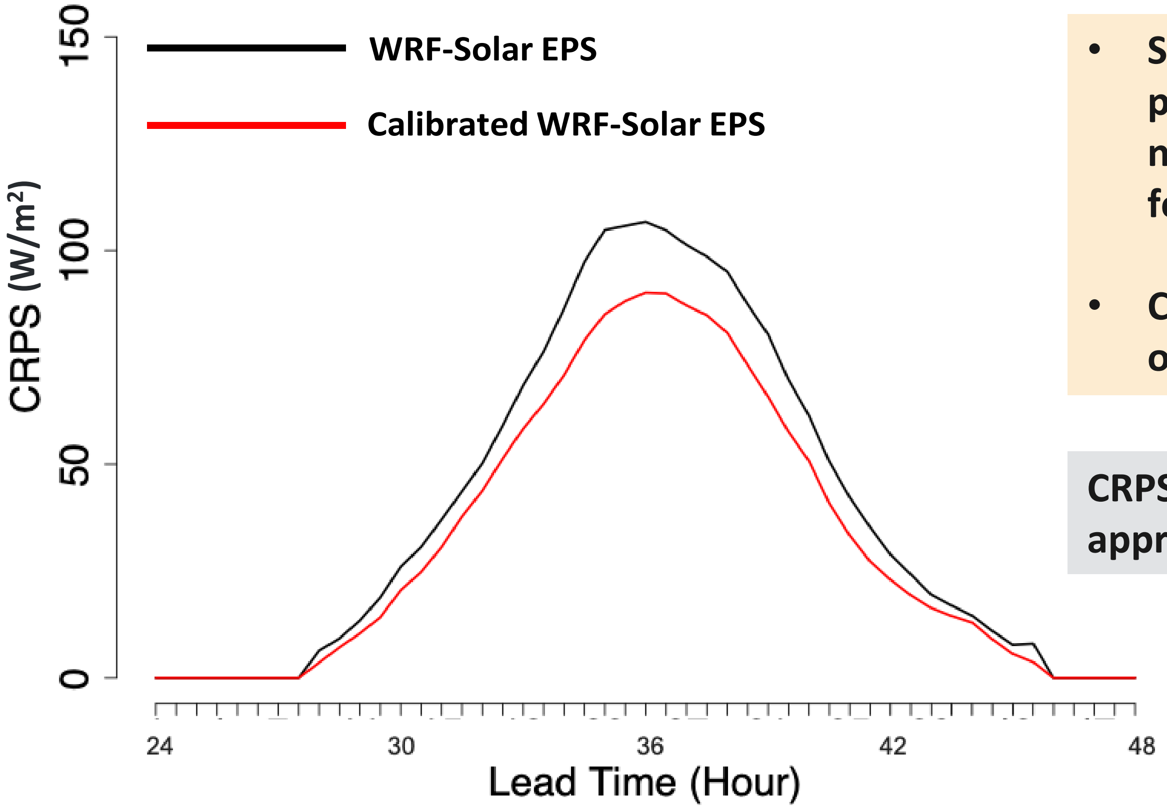


The black line indicates perfect, uniform probability of for the 10 ensemble members.

- **Calibrated ensemble (red) exhibits improved spread-skill relationship compared to uncalibrated ensemble.**
- **The uncertainty of day-ahead forecast was reduced by >50%**
- **The flatter rank histogram (reduction in MRE by nearly 100%) after calibration demonstrates the improvement in the consistency of the results.**

Evaluation of Probabilistic Forecasts

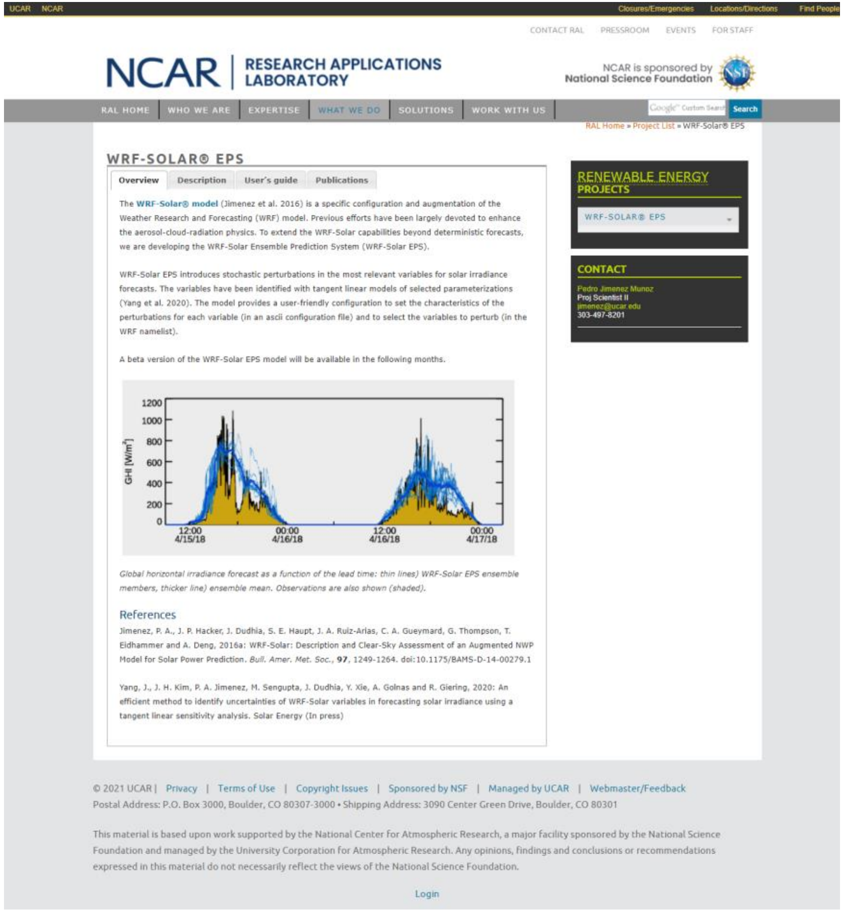
Continuous Rank Probability Score (CRPS)



- **Statistical metrics for deterministic prediction such as RMSE and MAE are not directly applicable to probabilistic forecasts.**
- **CRPS generalizes the MAE to the case of probabilistic forecasts.**

CRPS of GHI was improved by 18% approximately.

WRF-Solar EPS Website and Distribution



- **We have created the website for WRF-Solar EPS (https://ral.ucar.edu/projects/wrf-solar-eps).**
- **This website includes an overview of WRF-Solar EPS:**

✓ **Description of WRF-Solar EPS**
✓ **User's guide**
✓ **Publications**

WRF-Solar EPS is publicly available from https://github.com/wrf-model/WRF/pull/1547 until it is integrated into the next major WRF release.

Summary

- The WRF-Solar ensemble prediction system (WRF-Solar EPS) has been developed.
- First NWP model with an ensemble capability tailored for solar energy applications.
- Project objectives were met - Day-Ahead Forecast Bias < 5%. Uncertainty reduced by > 50%.
- WRF-Solar EPS will be part of the next WRF major release.

Publications

Conference paper:

Yang, J., Sengupta, M., Xie, Y., Jimenez, P.A. and Kim, J.H., 2019, Adjoint Sensitivity of FARMS to the Forecasting Variables of WRF-Solar. In *36th European Photovoltaic Solar Energy Conference and Exhibition.*

Kim, J.H., Jimenez, P.A., Dudhia, J., Yang, J., Sengupta, M., Xie, Y., 2020, Probabilistic Forecast of All-sky Solar Radiation Using Enhanced WRF-Solar, In *37th European Photovoltaic Solar Energy Conference and Exhibition.*

Yang, J., Kim, J.H., Sengupta, M., Jimenez, P.A. and Xie, Y., 2021, Assessment of Cloud Mask Forecasts from the WRF-Solar Ensemble Prediction System, *In 38th European Photovoltaic Solar Energy Conference and Exhibition.*

Journal paper:

Yang, J., J.H. Kim, P.A. Jimenez, M. Sengupta, J. Dudhia, Y. Xie, A. Golnas and R. Giering, 2021: An Efficient Method to Identify Uncertainties of WRF-Solar Variables in Forecasting Solar Irradiance Using a Tangent Linear Sensitivity Analysis. *Solar Energy*, Vol. 220, pp.509-522.

Kim, J.H, Jimenez, P.A, Sengupta, M., Yang, J., Dudhia, J., Alessandrini, S., Xie, Y., 2021, The WRF-Solar Ensemble Prediction System To Provide Solar Irradiance Probabilistic Forecasts, *IEEE Journal of Photovoltaics*.

Jimenez, P.A., Yang, J., Kim, J.H., Sengupta, M. and Dudhia, J., 2021, Assessing the WRF-Solar Model Performance Using Satellite-derived Irradiance from the National Solar Radiation Database, *Journal of Applied Meteorology and Climatology*.

+ 6 presentations at AMS Annual Meetings in 2019-2021.

Papers in final stage of preparation:

- The Impact of Stochastic Perturbations in Physics Variables on Predicting Surface Solar Irradiance.
- Evaluating Cloud Forecasts from the WRF-Solar Ensemble Prediction System with Satellite Derived Dataset.

Thank you

www.nrel.gov

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