The WRF-Solar Ensemble Prediction System: Development, Test, and Validation

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1. INTRODUCTION

- A team from NREL and NCAR developed the WRF-Solar ensemble prediction system (WRF-Solar EPS) with funding from DOE SETO.
- The project goal was to develop ensemble prediction system based on WRF-Solar that-

1) Provided probabilistic forecasts for the grid with ensemble members tailored for solar forecasts.
2) Delivered calibrated forecasts that -
   - Produced unbiased estimation of irradiance. Goal: GHI bias < 5%; DNI bias < 10%
   - Improved the current-state-of-art solar forecasts and reduced uncertainty by 50% from current levels.
3) Delivered a publicly available model.

2. APPROACH

WRF-Solar

Development

Tangent linear analysis of WRF-Solar modules for sensitivity study

↓

Introduce stochastic perturbations in the selected variables

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Configuration and assessment of the WRF-Solar EPS ensemble

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Calibration of WRF-Solar EPS forecasts to remove bias and improve spread accuracy

Assessment

Deliver WRF-Solar EPS package capable of providing accurate probabilistic forecasts

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

REFERENCES

Delle Monache, L., Eckel, F.A., Rife, D.L., Nagarajan, B. and Searight, K., 2013. Probabilistic weather prediction with an analog ensemble. Monthly Weather Review, 141(10), pp.3498-3516.

Yang, J., Kim, J.H., Jiménez, P.A., Sengupta, M., Dudhia, J., Xie, Y., Golnas, A. and Giering, R., 2021. An efficient method to identify uncertainties of WRF-Solar variables in forecasting solar irradiance using a tangent linear sensitivity analysis. Solar Energy, 220, pp.509-522

Kim, J.H., Munoz, P.A.J., Sengupta, M., Yang, J., Dudhia, J., Alessandrini, S. and Xie, Y., 2021. The WRF-Solar Ensemble Prediction System to Provide Solar Irradiance Probabilistic Forecasts. IEEE Journal of Photovoltaics, 12(1), pp.141-144.

Jiménez, P.A., Yang, J., Kim, J.H., Sengupta, M. and Dudhia, J., 2022. Assessing the WRF-Solar model performance using satellite-derived irradiance from the National Solar Radiation Database. Journal of Applied Meteorology and Climatology, 61(2), pp.129-142.

3. DEVELOPMENT AND TEST

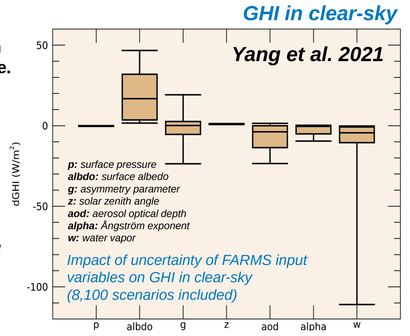
1) Selecting variables for WRF-Solar EPS

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 (FARMS)*
- *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)*

GHI in clear-sky



2) WRF-Solar EPS configuration

#	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 (Main parameters to control WRF-Solar EPS)
σ: Standard deviation which is used as tunning parameter to ***control the amplitude of the perturbation***
λ: Length scale [m]
τ: Time scale [s]

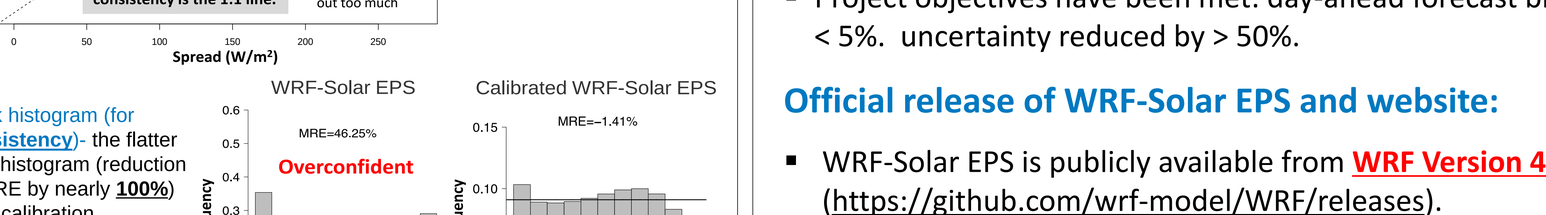
WRF-Solar EPS namelist

```
&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
```

- 14 selected WRF-Solar variables are stochastically perturbed to generate ensemble members for solar forecasts.
- 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

3) Testing of WRF-Solar EPS



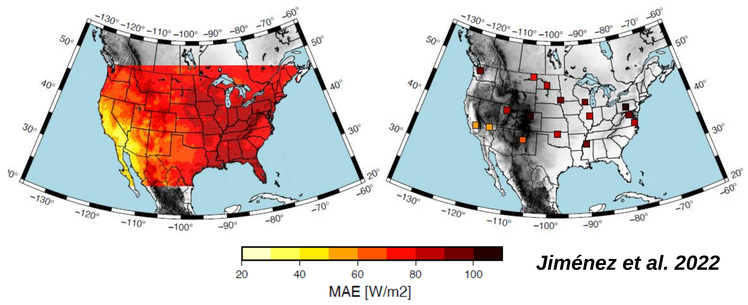
The impact of perturbations on 10 ensemble members is pronounced in cloudy-sky.

4. CALIBRATION AND VALIDATION

1) Satellite-derived datasets for validation

MAE of WRF-Solar GHI calculated with NSRDB

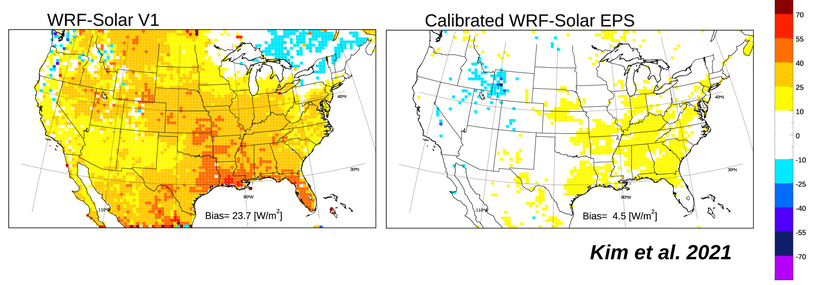
MAE of WRF-Solar GHI calculated with ground Obs.



Jiménez et al. 2022

- 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-Solar EPS validation.**

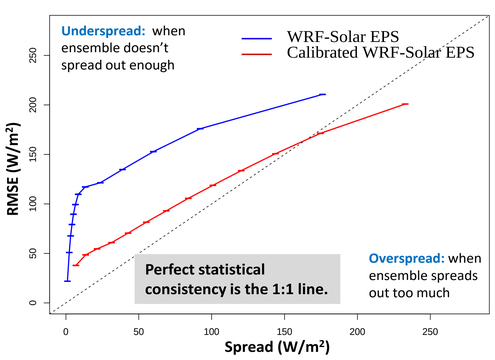
2) Ensemble calibration



Kim et al. 2021

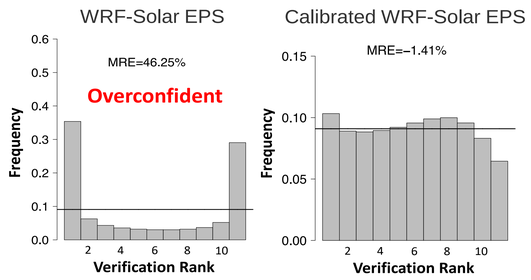
- We implemented an **analog technique** (Delle Monache et al. 2013) as an ensemble post-processing method to improve the performance of WRF-Solar EPS.
- **High-quality observations are essential to improve solar forecasts.**
- GHI bias was reduced by **81%** (calibrated WRF-Solar EPS versus WRF-Solar V1).
- The calibrated WRF-Solar EPS provides unbiased estimations of the solar irradiance within **1%** of the satellite observations of GHI.

3) Evaluation of probabilistic forecast



Binned spread-skill plot (for **uncertainty**)- calibrated ensemble (red) exhibits improved spread-skill relationship compared to uncalibrated ensemble (the uncertainty of day-ahead forecast was reduced by **>50%**).

Rank histogram (for **consistency**)- the flatter rank histogram (reduction in MRE by nearly **100%**) after calibration demonstrates the improvement in the consistency of the results.



5. 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 have been met: day-ahead forecast bias < 5%. uncertainty reduced by > 50%.

Official release of WRF-Solar EPS and website:

- WRF-Solar EPS is publicly available from **WRF Version 4.4** (https://github.com/wrf-model/WRF/releases).
- WRF-Solar EPS website:

https://ral.ucar.edu/projects/wrf-solar-eps

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