Enhancing WRF-Solar to provide solar irradiance probabilistic forecasts

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Outline

1. **Overview of WRF-Solar probabilistic forecasts**
2. **TL/AD Sensitivity test for WRF-Solar modules**
   - Methodology
   - Application to FARMS
   - Application to Thompson microphysics scheme
3. **Summary**

WRF-Solar probabilistic forecasts

Limitations of deterministic forecasts

1. Deterministic forecast can potentially result in incorrectly predicting clear sky (day 5)

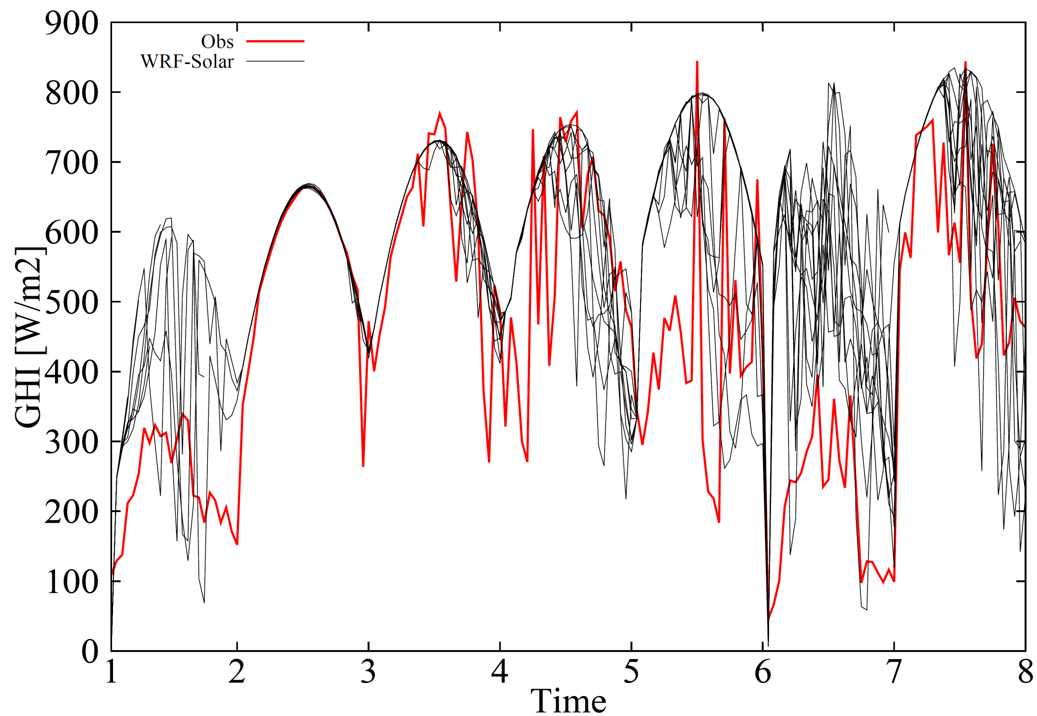
2. Deterministic forecast does not inform us about how confident we are on the predictions

- **What do we need**

1. Ensemble based probabilistic forecast

2. Careful selection of relevant variables to perturb the ensembles

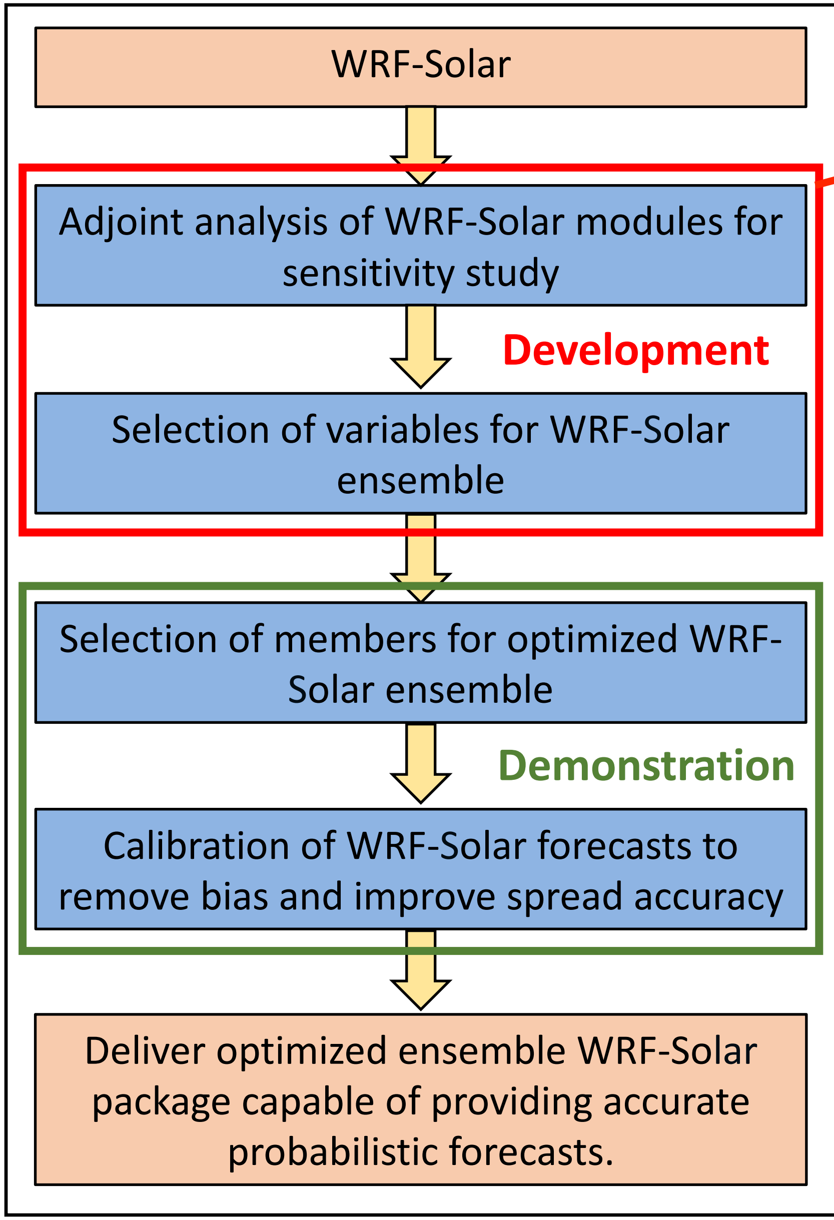
3. Calibration to provide unbiased forecasts with accurate ensemble spread



The ensemble perturbs temperature and winds which is not the optimal for solar irradiance forecasting

Pedro et al., 2019 (AMS)

Approach



Pedro et al., 2019 (AMS)

1. Developing stand alone version for five independent physics schemes
    - **FARMS radiation scheme**
    - NOAH LSM
    - **Thompson microphysics scheme**
    - MYNN boundary layer scheme
    - Deng shallow cumulus scheme

2. Developing TL/AD codes for five independent physics schemes by TAF

3. Verify standalone TL/AD derivatives against finite difference approximations

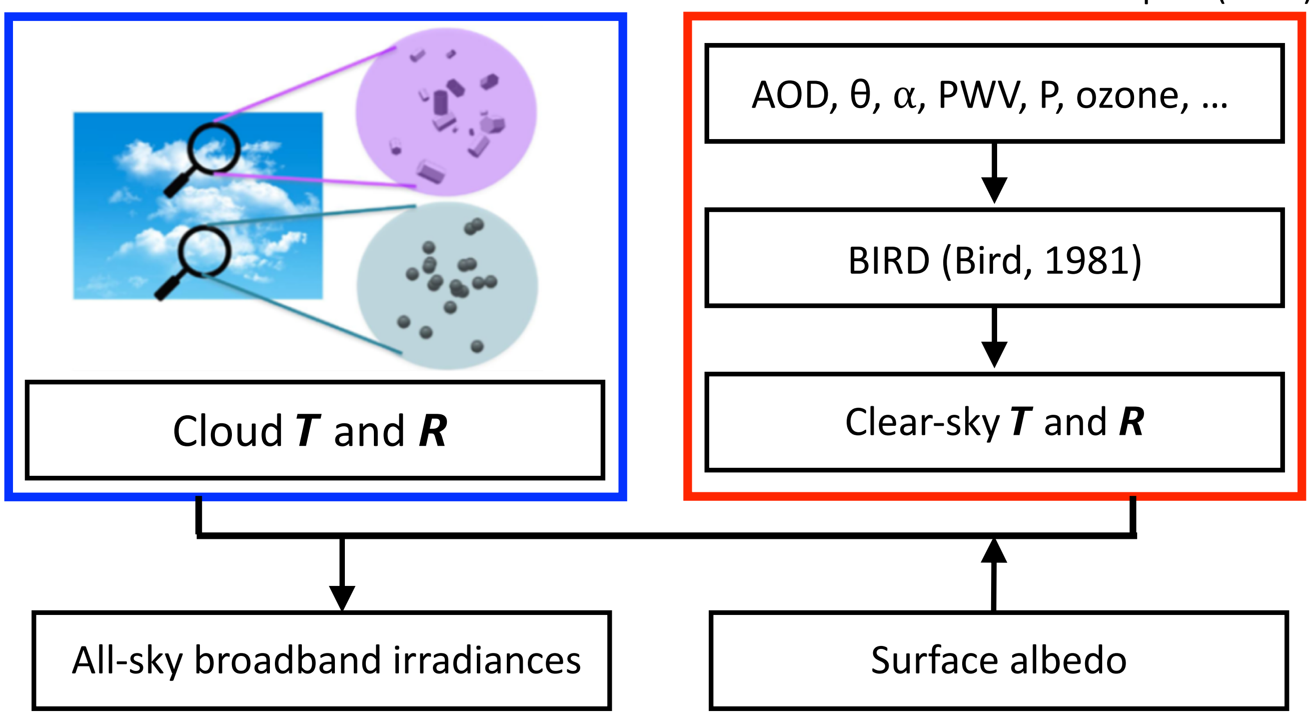
4. Adjoint sensitivity test

"Identify variables that significantly influence the formation and dissipation of clouds and solar radiation"

FARMS (Fast-All-sky Radiation Model for Solar applications)

- New option for approximating solar radiation at the land surface with minimal loss of accuracy at high speed
- Using simplified clear-sky RT model (BIRD) and parameterized LUTs of cloud transmittances (***T***) and reflectances (***R***) from RRTM by functions of θ and cloud microphysical and optical properties
- ***Xie et al. (2016)***

NREL report (2016)



Concept of TL/AD model

- Tangent linear model, $\mathbf{M} = dY/dX$
- Adjoint model, $\mathbf{M}^{\mathrm{T}}$

- Tangent linearity test

[Xiao et al., 2008 and Zhang et al., 2013]

$$\Phi(\lambda) = \frac{\|f(\mathbf{x}+\lambda) - f(\mathbf{x}))\|}{\lambda\,\|\mathbf{M}\_f(\mathbf{x})\|},\ \lim_{\lambda\to 0}\Phi(\lambda) = 1$$

- Adjointness test

[Errico, 2007]

$$\langle \mathbf{Mx}, \mathbf{y} \rangle = \left\langle \mathbf{x}, \mathbf{M}^{\mathrm{T}}\mathbf{y} \right\rangle$$

$$\langle \boldsymbol{M}d\boldsymbol{X}, d\boldsymbol{Y} \rangle = \left\langle d\boldsymbol{X}, \boldsymbol{M}^{T} d\boldsymbol{Y} \right\rangle$$

$$\langle d\boldsymbol{Y}, d\boldsymbol{Y} \rangle = \left\langle d\boldsymbol{X}, \boldsymbol{M}^{T} \boldsymbol{M}d\boldsymbol{X} \right\rangle$$

TLM output

TL/AD test results for FARMS

$$\Phi(\lambda) = \frac{\|f(\mathbf{x}+\lambda) - f(\mathbf{x}))\|}{\lambda\,\|\mathbf{M}\_f(\mathbf{x})\|}, \lim_{\lambda\to 0}\Phi(\lambda) = 1$$

1. Linearity test

perturbation	p_pa	albdo	g	z	aod	alpha	w
0.1000000000000000	0.9999982364046653	1.0188647732770281	0.9917049740714006	1.0042335622745637	0.8462754438249935	1.0129788969255637	0.9983380765501092
0.0100000000000000	0.9999998236404184	1.0018158916543432	0.9991672863045974	1.0003264890200507	0.9781597802865119	1.0012874995463447	0.9998334652066911
0.0010000000000000	0.9999999823640414	1.0001809300768514	0.9999166964076329	1.0000315676203267	0.9977030097580280	1.0001286466470811	0.9999833430872762
0.0001000000000000	0.9999999982364041	1.0000180864602585	0.9999916693184228	1.0000031458224640	0.9997690757944912	1.0000128636322218	0.9999983342743847
0.0000100000000000	0.9999999998236404	1.0000018085805947	0.9999991669286187	1.0000003144727223	0.9999768952220578	1.0000012863528950	0.9999998334270950
0.0000010000000000	0.9999999999823640	1.0000001808574052	0.9999999166928296	1.0000000314461768	0.9999976893985263	1.0000001286351833	0.9999999833427060
0.0000001000000000	0.9999999999982364	1.0000000180857339	0.9999999916692826	1.0000000031446067	0.9999997689386168	1.0000000128635144	0.9999999983342705
0.0000000100000000	0.9999999999998236	1.0000000018085733	0.9999999991669283	1.0000000003144605	0.9999999768938504	1.0000000012863485	0.9999999998334270
0.0000000010000000	0.9999999999999824	1.0000000001808573	0.9999999999166928	1.0000000000314460	0.9999999976893861	1.0000000001286319	0.9999999999833427
0.0000000001000000	0.9999999999999982	1.0000000000180857	0.9999999999916693	1.0000000000031446	0.9999999997689515	1.0000000000128602	0.9999999999983343
0.0000000000100000	1.0000000000000000	1.0000000000018086	0.9999999999991669	1.0000000000003145	0.9999999999769068	1.0000000000012831	0.9999999999998334

perturbation	tau_qv	tau_qi	tau_qs	re_qcloud	re_qice	re_qsnow	all
0.1000000000000000	0.9997621196466283	1.0112169317719268	0.9970413686052752	0.0005459268851194	0.0004176341818085	0.0000034232401077	0.0032491446762745
0.0100000000000000	0.9999250625671401	1.0011786617347218	0.9997033980921332	0.0054592688511941	0.0041763418180853	0.0000342324010777	0.0034578655844038
0.0010000000000000	0.9999941841740992	1.0001184526051330	0.9999703324018598	0.0545926885119413	0.0417634181808530	0.0003423240107771	0.0036797444681094
0.0001000000000000	0.9999994352462062	1.0000118511420059	0.9999970331660927	0.5459268851194133	0.4176341818085303	0.0034232401077709	0.0097356469201613
0.0000100000000000	0.9999999436929583	1.0000011851730327	0.9999997033158683	0.9944871048739917	1.0584638226107561	0.0342324010777093	0.0527578433172523
0.0000010000000000	0.9999999943709793	1.0000001185178916	0.9999999703315794	0.9994451811011804	1.0056955543051338	0.3423240107770930	0.3484416093477078
0.0000001000000000	0.9999999994371148	1.0000000118517950	0.9999999970331578	0.9999444825306623	1.0005680853326386	1.0000205362750230	1.0001230674173293
0.0000000100000000	0.9999999999437116	1.0000000011851795	0.9999999997033157	0.9999944478969836	1.0000567938695239	1.0000020552558749	1.0000123112856492
0.0000000010000000	0.9999999999943712	1.0000000001185179	0.9999999999703315	0.9999994447861372	1.0000056792403521	1.0000002055418651	1.0000012311739880
0.0000000001000000	0.9999999999994371	1.0000000000118518	0.9999999999970332	0.9999999444785781	1.0000005679225692	1.0000000205543492	1.0000001231178530
0.0000000000100000	0.9999999999999437	1.0000000000011852	0.9999999999997033	0.9999999944478574	1.0000000567922422	1.0000000020554365	1.0000000123117898

2. Adjointness test

Val_TL 177428010441.853279159389844692656
Val_AD 177428010441.853279159389844692656

$$\langle dY, dY \rangle = \langle dX, M^T M dX \rangle$$

- Tangent linear forecast approximates well the derivative of the nonlinear model solution as the perturbations decreased and approach zero.
- Adjoint code is developed correctly with the tangent linear code.

Sensitivity test for FARMS

$$\frac{\partial \mathrm{GHI}}{\partial X} \cdot \Delta\ \mathrm{X} = \Delta\ GHI$$

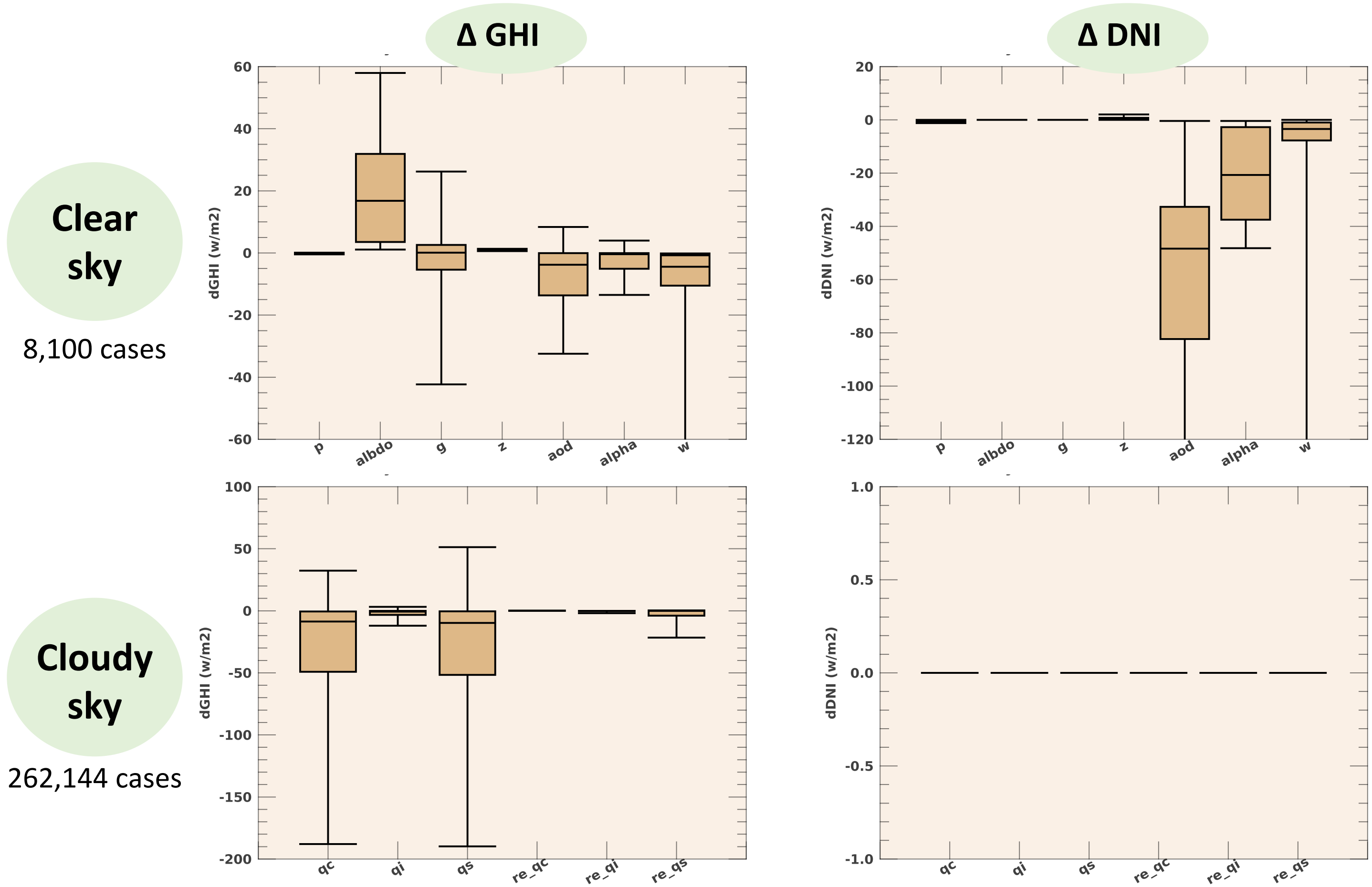
Tangent linear model gives the derivative of forecast variables w.r.t. model state variables.

The error of each model-state variable

The error of GHI w.r.t each model-state variable

P_ERROR = 1000.0, ALBEDO_ERROR = 0.1,
Z_ERROR = 0.001, AOD_ERROR = 0.1,
ALPHA_ERROR = 0.5, W_ERROR = 10.,
TAU_QC_ERROR = 37.8, TAU_QI_ERROR = 2.0,
TAU_QS_ERROR = 31.6, RE_QC_ERROR = 4.2828965E-06,
RE_QI_ERROR = 1.8598472E-05, RE_QS_ERROR = 2.1256968E-04

Sensitivity test result for FARMS



- In clear sky, GHI is sensitive to albedo, aod, w, and g and less sensitive to p and DNI is very sensitive to aod and alpha (Ångström wavelength exponent).
- In cloudy sky, GHI is sensitive to cloud optical depth and less sensitive to effective radius. DNI shows small sensitivity to cloud variables, because DNI tends to attenuate fast if there is a cloud.

Thompson microphysics scheme

- Processes controlling formation of cloud droplets and ice crystals, and their growth and fallout as a surface precipitation
- Thompson et al. (2004) (2008)
- **Important outputs**
  - Hydrometeors mixing ratio **Qv Qc Qr Qi Qs Qg**
  - Number concentration **Ni Nr**
  - Effective radius **Re_qc Re_qi Re_qs**

- <u>**Tangent linearity test result**</u>

perturbation	pii	p	qv	ni	nr	th
0.1000000000000000	29.12026251452843614	1.00000080868057415	0.88252174368814363	0.99999805785627547	0.99999497867708051	1.00128868656308209
0.0100000000000000	4.63732994181417238	1.00000008086788871	4221.80608905632988580	0.99999980546347224	0.99999949774467703	1.00010906271534277
0.0010000000000000	1.39942238411864841	1.00000000808678378	45186.75732615917270445	0.99999998054313366	0.99999994977323686	1.00001081974271796
0.0001000000000000	0.99967320622910260	1.00000000080867493	144196.24922916645081677	0.99999999805428124	0.99999999497731138	1.00000108110223898
0.0000100000000000	0.99996519006617278	1.00000000008086406	13426.90232938601181683	0.99999999980542780	0.99999999949773101	1.00000010810149680
0.0000010000000000	0.99999649722187581	1.00000000000808297	0.99873757368969613	0.99999999998054278	0.99999999994977310	1.00000001081006235
0.0000001000000000	0.99999964950387523	1.00000000000080486	0.99987345683297629	0.99999999999805428	0.99999999999497731	1.00000000108100531
0.0000000100000000	0.99999996494820387	1.00000000000007705	0.99998734266891684	0.99999999999980543	0.99999999999949773	1.00000000010810047
0.0000000010000000	0.99999999649479849	1.00000000000000427	0.99999873423673883	0.99999999999998054	0.99999999999994977	1.00000000001081000
0.0000000001000000	0.99999999964947957	0.99999999999999699	0.99999987342337234	0.99999999999999805	0.99999999999999498	1.00000000000108095
0.0000000000100000	0.99999999996494789	0.99999999999999626	0.99999998734233422	0.99999999999999981	0.99999999999999950	1.00000000000010805
0.0000000000010000	0.99999999999649473	0.99999999999999622	0.99999999873423339	0.99999999999999998	0.99999999999999995	1.00000000000001076

perturbation	qc	qr	qi	qs	qg
0.0000000000100000000000	1.00000273019470091743457	1.00000784252376445529653	0.99981157525696905115314	37.10524982069591782772204	239256243.40504912474784572891045
0.0000000000010000000000	1.00000000021344899935915	0.99999982279203363897683	0.99998115889208196461107	0.99964139927448519287004	0.99427010326095451218421
0.0000000000001000000000	1.00000000002134138495380	0.99999998227919636322747	0.99999811590209594349521	0.99996411296642087964673	0.99942094530561036044225
0.0000000000000100000000	1.00000000000213062351526	0.99999999822791956631603	0.99999981159033854263204	0.99999641102672648559782	0.99994203299382740560471
0.0000000000000010000000	1.00000000000020954737205	0.99999999982279195593155	0.99999998115903514381686	0.99999964109997318679654	0.99999420268311420799683
0.0000000000000001000000	1.00000000000001743978490	0.99999999998227919558432	0.99999999811590352727758	0.99999996410997032375629	0.99999942026214783280643
0.0000000000000000100000	0.99999999999999822894251	0.99999999999822791955865	0.99999999981159035285760	0.99999999641099676242597	0.99999994202615311172572
0.0000000000000000010000	0.99999999999999630944905	0.99999999999982279194006	0.99999999998115903529840	0.99999999964109967353838	0.99999999420261464193263
0.0000000000000000001000	0.99999999999999613783073	0.99999999999998227924355	0.99999999999811590364896	0.99999999996410996731257	0.99999999942025810306582
0.0000000000000000000100	0.99999999999999595632141	0.99999999999999822606518	0.99999999999981159156856	0.99999999999641099646883	0.99999999994197961872795
0.0000000000000000000010	0.99999999999999611421704	0.99999999999999995704902	0.99999999999998117134816	0.99999999999964109050174	0.99999999999369346852715
0.0000000000000000000001	1.00000000000001816866288	1.00000000000000086362292	0.99999999999999843364601	0.99999999999996404606414	0.99999999999399672578662

Tangent linearity test for Thompson scheme

$$\Phi(\lambda) = \frac{\|f(\mathbf{x}+\lambda) - f(\mathbf{x}))\|}{\lambda\,\|\mathbf{M}\_f(\mathbf{x})\|}, \lim_{\lambda \to 0} \Phi(\lambda) = 1$$

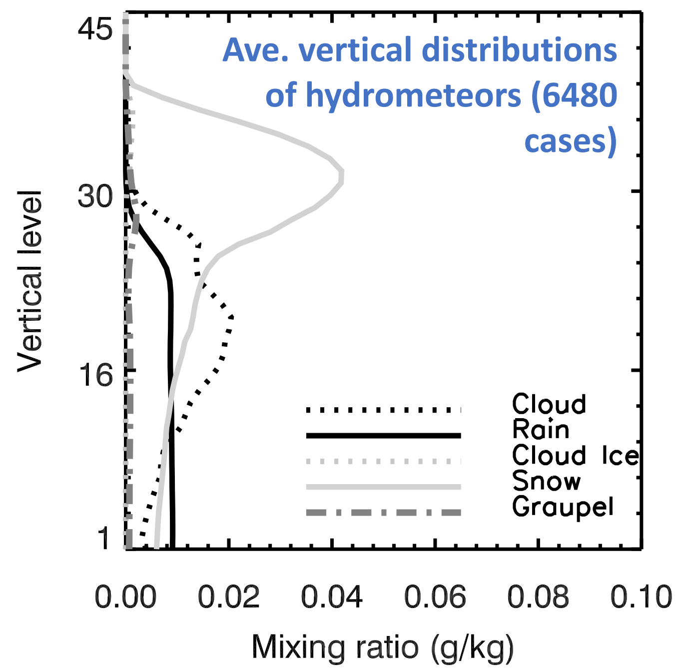
perturbation	pii	p	qv	ni	nr	th
0.1000000000000000	29.12030523556387637	1.00000080868272916	0.88252219607973746	0.99999805778299295	0.99999497867754053	1.00128845923923615
0.0100000000000000	4.63733555290297041	1.00000008086810423	4221.80833022473431091	0.99999980545616871	0.99999949774472302	1.00010906120903525
0.0010000000000000	1.39942289284096050	1.00000000808680533	45186.78117493344075776	0.99999998054240355	0.99999994977324146	1.00001081959714770
0.0001000000000000	0.99967319690782009	1.00000000080867708	144196.32538407285628561	0.99999999805420823	0.99999999497731184	1.00000108108773024
0.0000100000000000	0.99996518924224179	1.00000000008086427	13426.90942341354219545	0.99999999980542050	0.99999999949773106	1.00000010810004641
0.0000010000000000	0.99999649714037468	1.00000000000808299	0.99873757342351134	0.99999999998054205	0.99999999994977310	1.00000001080991732
0.0000001000000000	0.99999964949573388	1.00000000000080486	0.99987345680685796	0.99999999999805420	0.99999999999497731	1.00000000108099081
0.0000000100000000	0.99999996494738983	1.00000000000007705	0.99998734266631015	0.99999999999980542	0.99999999999949773	1.00000000010809902
0.0000000010000000	0.99999999649471708	1.00000000000000427	0.99999873423647821	0.99999999999998054	0.99999999999994977	1.00000000001080985
0.0000000001000000	0.99999999964947143	0.99999999999999699	0.99999987342334628	0.99999999999999805	0.99999999999999498	1.00000000000108094
0.0000000000100000	0.99999999996494708	0.99999999999999626	0.99999998734233161	0.99999999999999981	0.99999999999999950	1.00000000000010805
0.0000000000010000	0.99999999999649464	0.99999999999999622	0.99999999873423313	0.99999999999999998	0.99999999999999995	1.00000000000001076
0.0000000000001000	0.99999999999964940	0.99999999999999607	0.99999999987342331	1.00000000000000004	1.00000000000000000	1.00000000000000103
0.0000000000000100	0.99999999999996488	1.00000000000000197	0.99999999998734233	1.00000000000000031	1.00000000000000007	1.00000000000000006
0.0000000000000010	0.99999999999999642	0.99999999999998714	0.99999999999873423	0.99999999999999412	1.00000000000000096	0.99999999999999994
0.0000000000000001	0.99999999999999958	0.99999999999882345	0.99999999999987342	1.00000000000001514	0.99999999999998794	1.00000000000000002
0.0000000000000000	0.99999999999999990	0.99999999999552101	0.99999999999998734	0.99999999999987412	1.00000000000007701	1.00000000000000283

perturbation	qc	qr	qi	qs	qg	all
0.1000000000000000	281.34456142445849957	2.19384750267052879	0.01155896842249986	0.00007252360161562	0.64451134823791261	0.42439858362708435
0.0100000000000000	285.97351077066334983	0.18030861218548039	0.01962119499487456	0.00016194838274708	6.41388513857499314	0.43116791714569173
0.0010000000000000	7.01276622189808159	0.10590235623146618	0.46592783694438773	0.00092599355963521	6.46600229774844385	11.40722340930796670
0.0001000000000000	1.22939532370324930	0.28109304050254447	0.36232576571379455	0.00118431146783223	10.53809087584880070	35.24932022568506997
0.0000100000000000	1.01705652312390459	0.47164075033815304	0.23392497022670649	0.00205343008589638	34.23268992810648346	3.56390895313794714
0.0000010000000000	1.00486681475522106	0.55338043995902427	0.10126584533535047	0.00625424963418540	0.00636956549368435	0.01291551336322019
0.0000001000000000	1.10127365042464094	0.99790315794997332	0.07712704232194833	0.03092310448595279	0.01681313348501246	0.03299373225120408
0.0000000100000000	1.00002134551779328	6.69528236582946477	0.52626318402452369	0.14225343371521997	0.04660269625648190	0.15339259214172173
0.0000000010000000	1.00000213453166396	0.99823565407643765	0.82915048689990875	0.41889089884757768	0.13094162244810964	0.42599349556284316
0.0000000001000000	1.00000021345296088	0.99982286898670179	0.98108518736584234	0.78868988323508999	0.34511667924968418	0.79138650865320306
0.0000000000100000	1.00000002134528967	0.99998227990163307	0.99811457668207070	0.96680649238488845	0.71099777998462236	0.96744208306705779
0.0000000000010000	1.00000000213452454	0.99999822792015984	0.99981157890917568	0.99644065249002359	0.94800422337681784	0.99675941884231901
0.0000000000001000	1.00000000021344805	0.99999982279131581	0.99998115917301595	0.99964139927177141	0.99427010324258760	0.99992655630504401
0.0000000000000100	1.00000000002134040	0.99999998227912447	0.99999811593019329	0.99996411296614925	0.99942094528733811	1.00024589065633193
0.0000000000000010	1.00000000000212964	0.99999999822791227	0.99999981159314832	0.99999641102669932	0.99994203297556467	1.00027785060379990
0.0000000000000001	1.00000000000020856	0.99999999982279112	0.99999998115931612	0.99999964109997047	0.99999420266485243	1.00028104686398169
0.0000000000000000	1.00000000000001645	0.99999999998227900	0.99999999811593162	0.99999996410997005	0.99999942024388615	1.00028136649265454

- Same perturbations were applied to all input variables. If hydrometeors are less than 1.e-12, we did not perturb that layer.
- When input values are much larger than perturbation (P, Ni, and Nr), it tends to reach model precision quickly.
- Tangent linear forecast approximates well the derivative of the nonlinear model solution as the perturbations decreased and approach zero.

Sensitivity test for Thompson scheme

- Cases are provided by WRF simulation (4/15 - 4/16 2018)
- 9 km horizontal resolution (600 x 354), 45 vertical layers



$$\frac{\partial Y}{\partial X} \cdot \Delta X = \Delta Y$$

1. Constant error - TH

2. Value of variable itself - Ni

3. Standard deviation of each variable on each layer

- Qc, Qi, Qr, Qs, Qg, Nr

- Qv, Pi, P

Comparing sensitivity

Input →

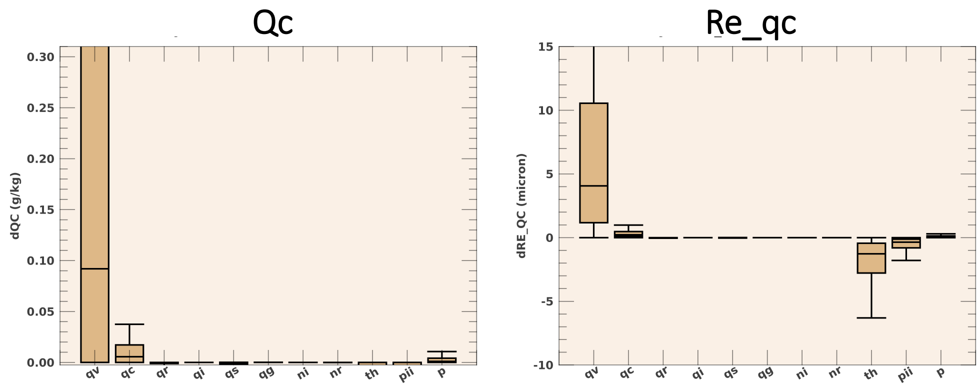
$$\left(\frac{\partial Y}{\partial X} \cdot \Delta X\right)_{median} / \bar{Y}$$

Output ↓

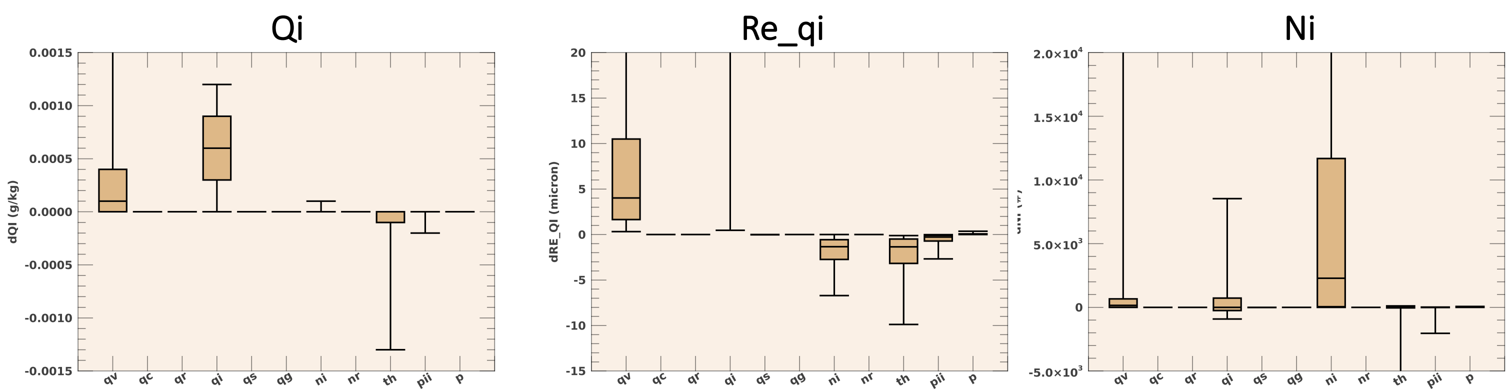
	QV	QC	QR	QI	QS	QG	NI	NR	TH	PII	P
QV	0.98	0	0	0	0	0	0	0	0	0	0
QC	**4.521**	0.276	0	0	0	0	0	0	**-1.323**	**-0.354**	0.054
QR	0	0	1.74	0	0	0	0	0.023	0	0	0
QI	0.258	0	0	**1.549**	0	0	0	0	0	0	0
QS	0.008	0	0	0	**1.734**	0	0	0	**-0.004**	0	0
QG	0	0	0	0	0	1.811	0	0	0	0	0
NI	0	0	0	0	0	0	**0.04**	0	0	0	0
NR	0	0	0	0	0	0	0	0.92	0	0	0
TH	0	0	0	0	0	0	0	0	0.01	0	0
REQC	**1.37**	0.08	0	0	0	0	0	0	**-0.43**	-0.12	0.02
REQI	**0.36**	0	0	**80.98**	0	0	-0.12	0	-0.12	-0.02	0
REQS	0.02	0	0	0	**329.16**	0	0	0	0	0	0
RAINNC	0	0	0.004	0	0	0	0	0	0	0	0

Sensitivity analysis

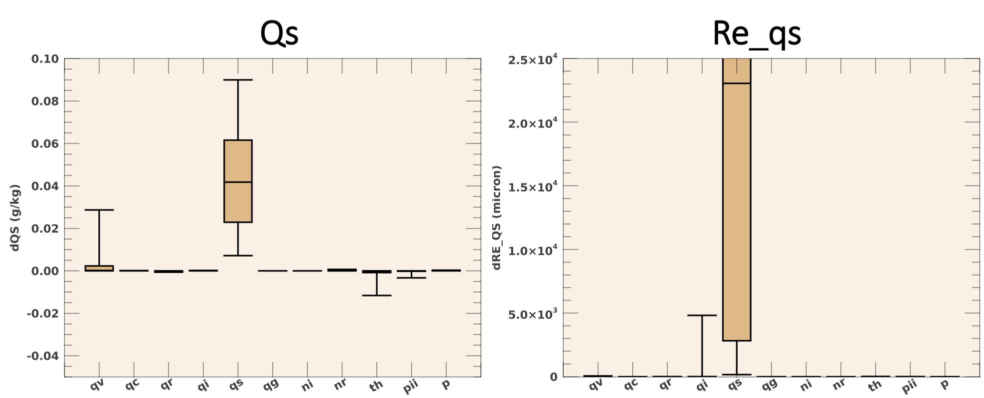
$$\left(\frac{\partial Y}{\partial X} \cdot \Delta X\right)$$



- Cloud water variables are sensitive to Qv, Qc, TH, and Pi.

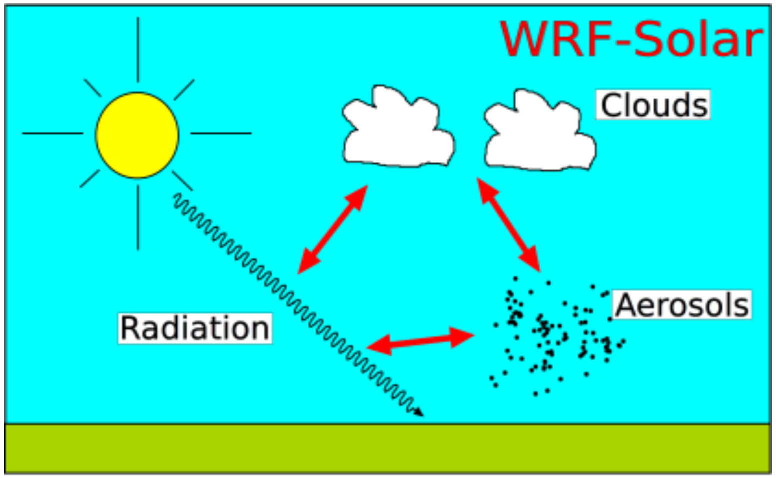


- Ice variables are sensitive to Qi, Qv, Ni, and TH.



- Snow variables are sensitive to Qs, Qv, and TH.

Summary



- WRF-Solar was the first NWP model specifically designed to provide solar irradiance forecast tailored for solar energy applications.

- New developments focused on improving the cloud-aerosol-radiation physics by ensemble based probabilistic forecasts.

- Adjoint sensitivity analysis of physics packages is used for finding key variables and parameters controlling the surface irradiance. In this study, it was applied to FARMS and Thompson schemes.

- This will lead to select optimal ensemble members and reduce forecast errors by providing more accurate probabilistic forecasts.