CERES Cloud Radiative Swath (CRS) Validation & Improvements to FLASHFlux via Machine Learning

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Spring 2021 CERES / Libera Science Team Meeting
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CERES CRS

- CERES observes TOA radiation – but to understand climate we also need surface & atmospheric fluxes
  - The current L2 Single Scanner Footprint (SSF) product estimates surface fluxes w/ simple parameterizations (Model B)
- The Cloud Radiative Swath (CRS) product – reintroduced at last STM – builds upon the SSF by calculating instantaneous instrument footprint-level irradiances using the NASA LaRC Fu-Liou radiative transfer model
  - SW↓↑ & LW↓↑ broadband flux profiles + Surface narrowband SW & LW, direct + diffuse SW↓, PAR, UV fluxes
  - How does CRS compare to Surface-Only Flux Algorithms (SOFA) Model B & other CERES flux products?

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- Here we update & extend our analysis from the last STM to cover an entire year (2019):

CRS vs (1) **CERES TOA observations**, (2) SSF Model B surface fluxes, (3) SYN1deg surface fluxes

	CERES CRS	CERES SSF Ed4A	FLASHFlux SSF v4A	CERES SYN1deg-Hr
L2 / L3	Instantaneous footprint	Instantaneous footprint	Instantaneous footprint	TISA gridded, hourly (L3)
Surface	Fu-Liou RT model	Model B parameterization	Model B parameterization	Fu-Liou RT model
TOA	Fu-Liou RT model	Observations	Observations	Fu-Liou & Observations

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- Can we use CRS to improve FLASHFlux low-latency surface fluxes for the applied science community?

(4) Preliminary development & evaluation of Machine Learning models to provide rapid & accurate surface radiative fluxes

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CERES CRS

Inputs

CERES SSF Ed4A
geolocated FOVs, etc.

GEOS 5.4.1
$T(z)$, $p(z)$, $q(z)$, $O_3(z)$
surface wind speed

MODIS
cloud properties (Ed4)
AOD (sometimes)
spectral albedo
land temp (clear)

MATCH hourly
aerosol profiles & AOD

IGBP surface type

albedo history
map (cloudy)

NASA Langley Fu-Liou
Radiative Transfer Model

SW↓↑

LW↓↑

~20-50 km

CERES Footprint / FOV
Terra FM1, Aqua FM3

Outputs

instantaneous vertical
profiles (6 levels) of
broadband flux &
spectrally-resolved fluxes
at the surface and TOA

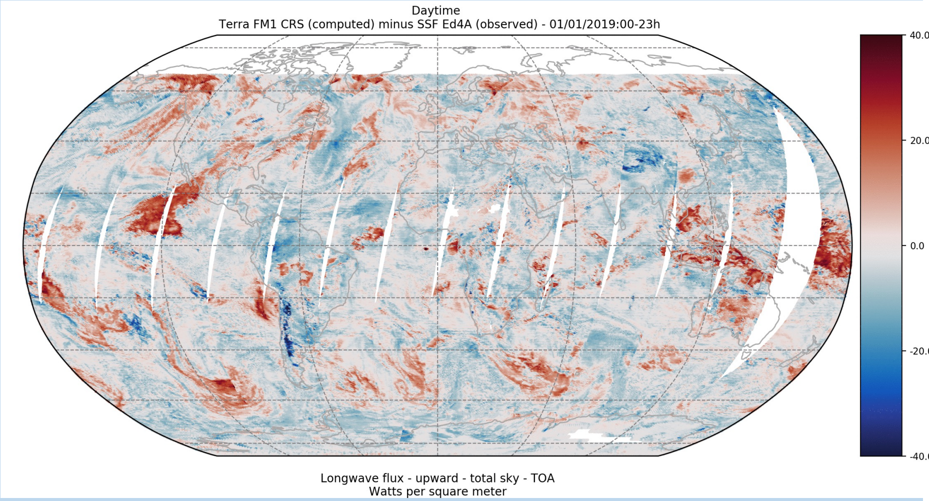
LW : 12 bands
SW : 14 bands

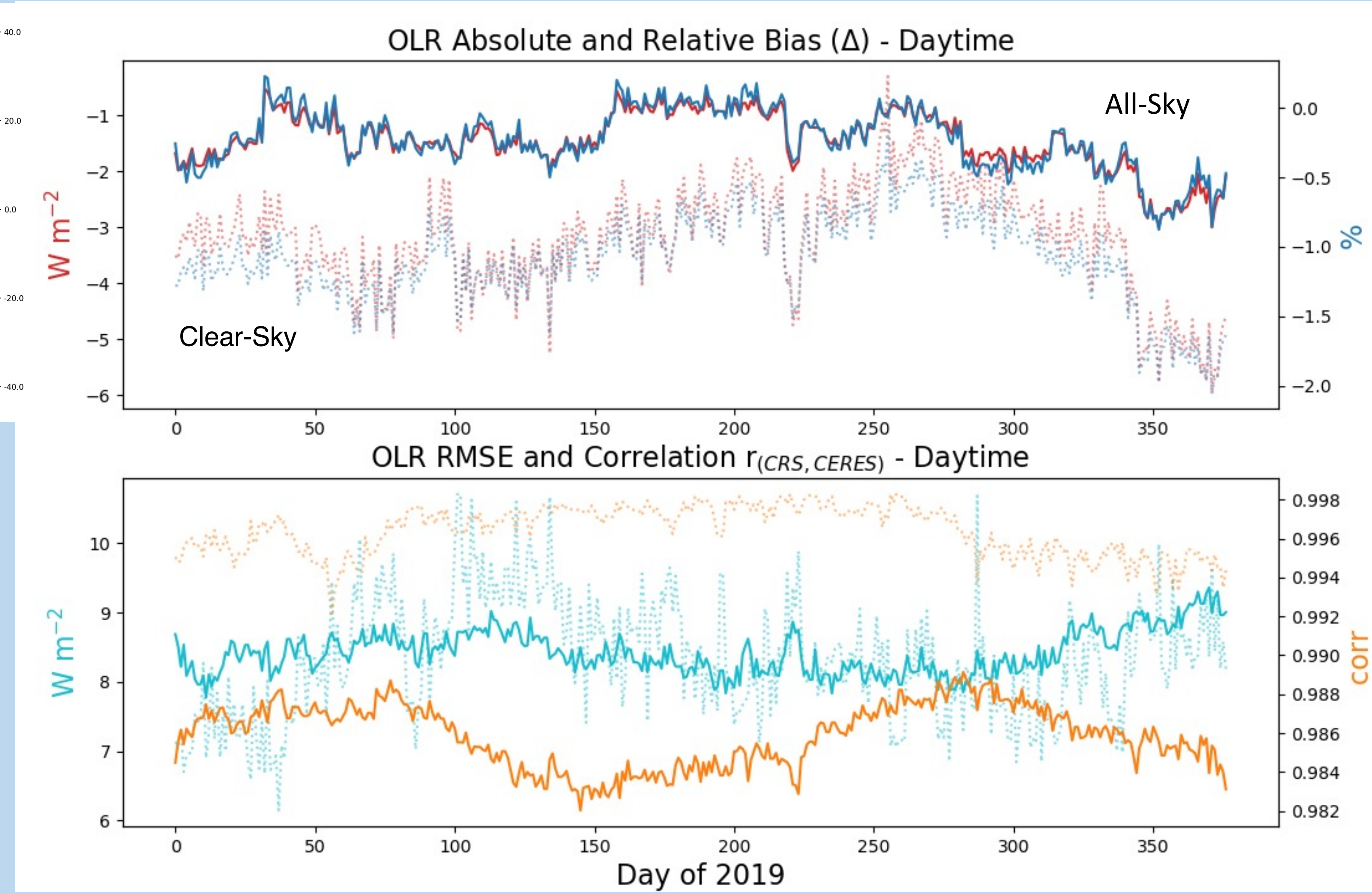
(surface, all-sky)
SW↓ direct + diffuse
PAR, UV fluxes

All-sky
Clear-sky
Pristine-sky
All-sky no aerosol

2-stream LW
4-stream SW

TOA CRS Computed LW↑ *vs* SSF Ed 4A Observations





- (↑) Daily, geographic ΔOLR variability
  - CRS minus CERES SSF observations
- (→) Time series of OLR validation stats
- Global statistics remain relatively stable throughout 2019
- All-sky bias within -1% (~ -1 to -2 W m^{-2})
- Negative clear-sky bias compensated by excessive OLR from high clouds
- ~ 7 W m^{-2} global RMSE w/ strong correlation of modeled & observed fluxes

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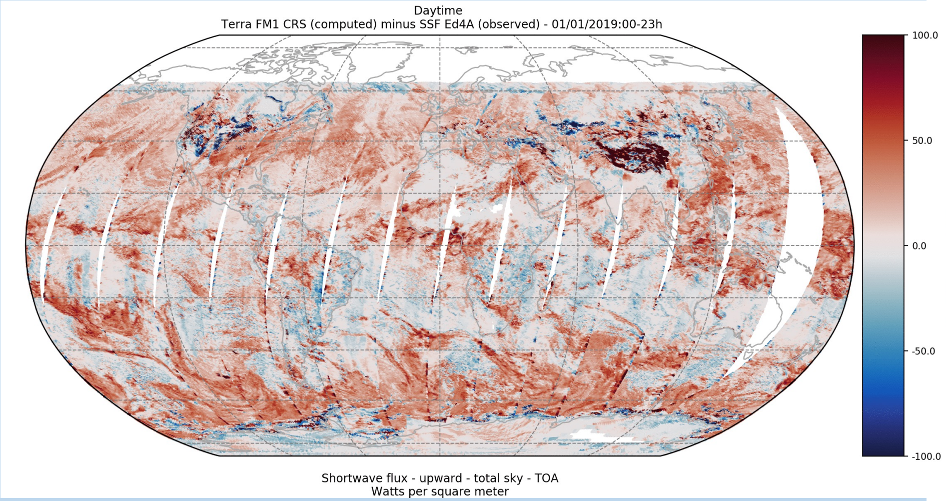
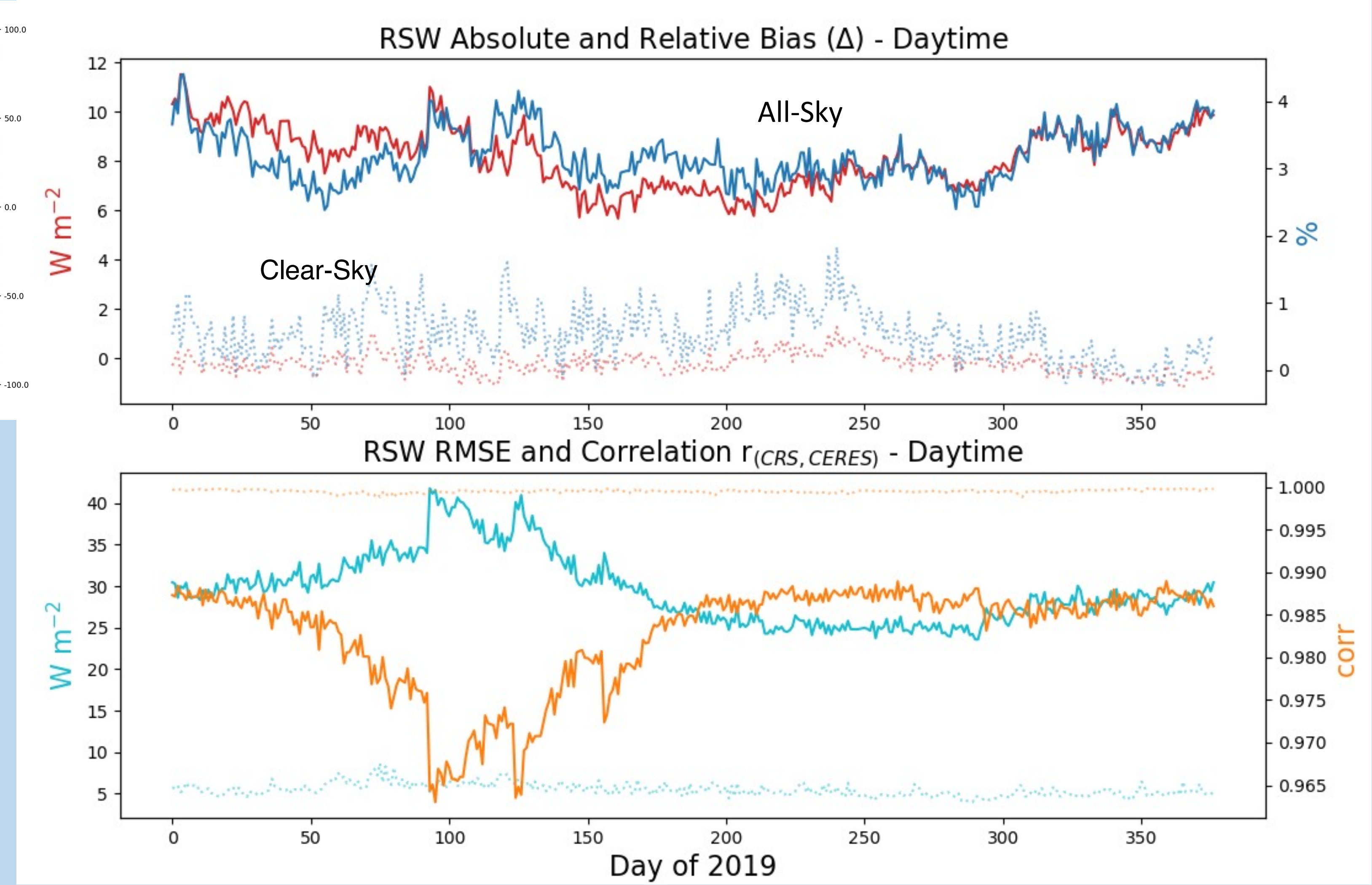
TOA CRS Computed SW↑ *vs* SSF Ed 4A Observations





- (↑) Daily, geographic ΔRSW variability
  - CRS minus CERES SSF observations
- (→) Time series of RSW validation stats
- Excessive reflection to space by clouds & occasionally the surface
  - ~ 3 - 4 % global mean all-sky bias
- Better clear-sky performance
  - ~ 0 - 1 % clear-sky relative bias
- Biases relatively stable through time
- RMS peak in boreal spring from surface albedo retrievals over NH continents

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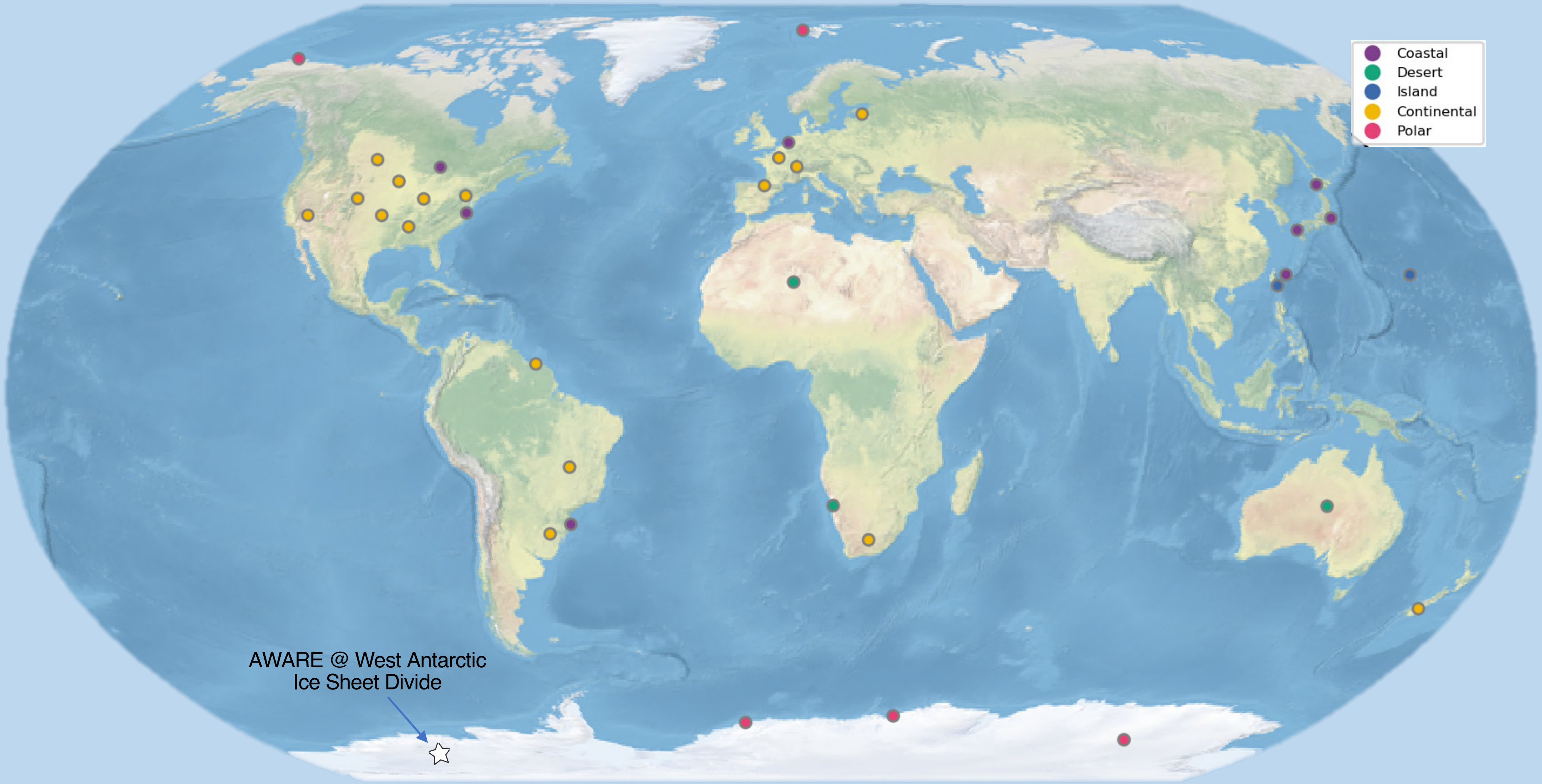
Surface Validation Sites



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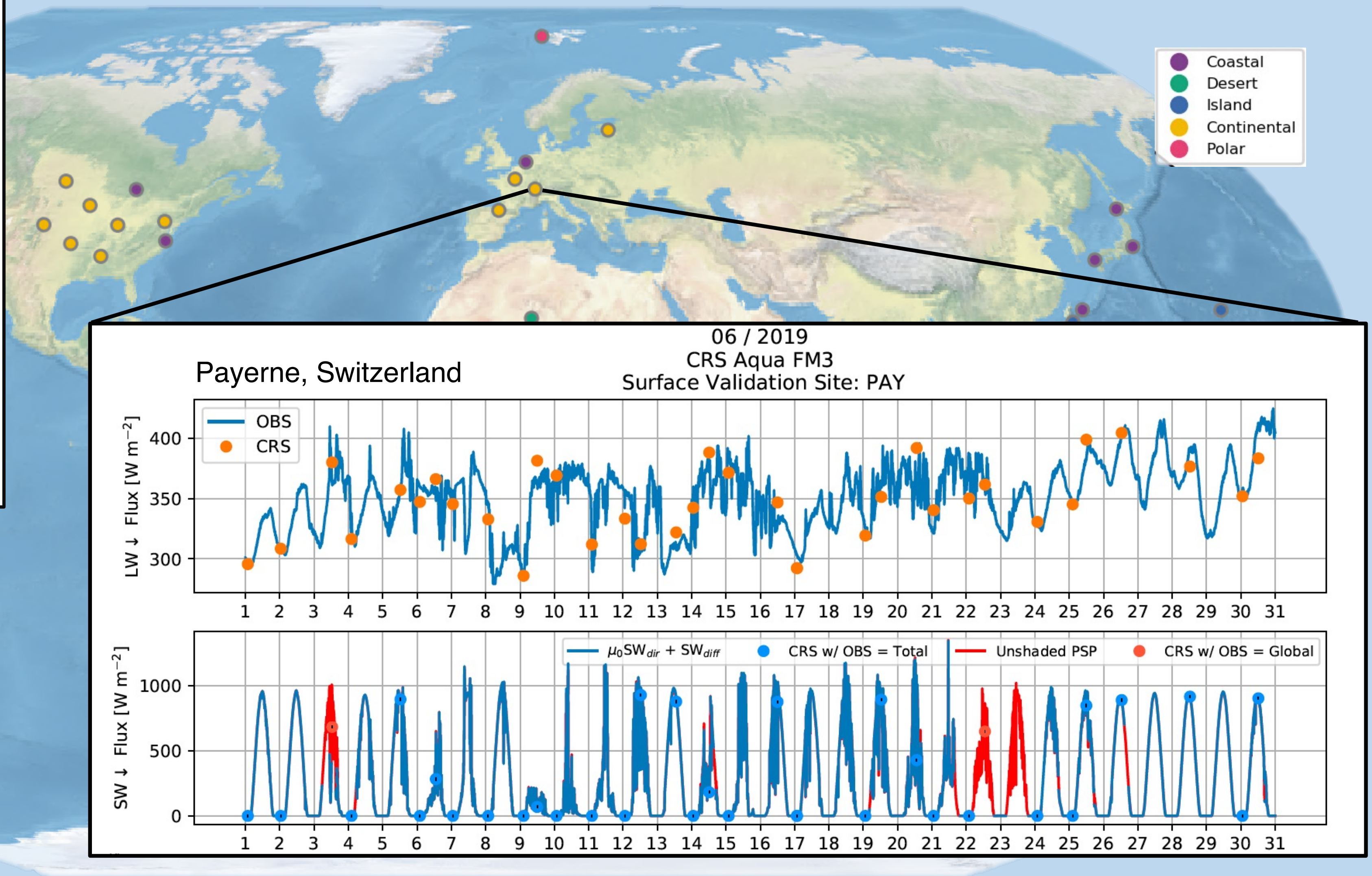
Surface Flux Validation Methodology

- Using 1-min resolution surface data
- Extracting footprints within 10 km
- **LW↓** : instantaneous match to pyrgeometer obs. at footprint time
- **SW↓** : averaging surface obs. for 30 mins centered at footprint time
    - **Total = Direct + Diffuse**, resort to Global from unshaded PSP if total is unavailable
    - **SW↓$_{CRS}$** scaled by avg(μ_{OBS}) / μ_{CRS} to account for changing μ = cos(SZA)
- FOV size varies with instrument view zenith angle (source of noise)



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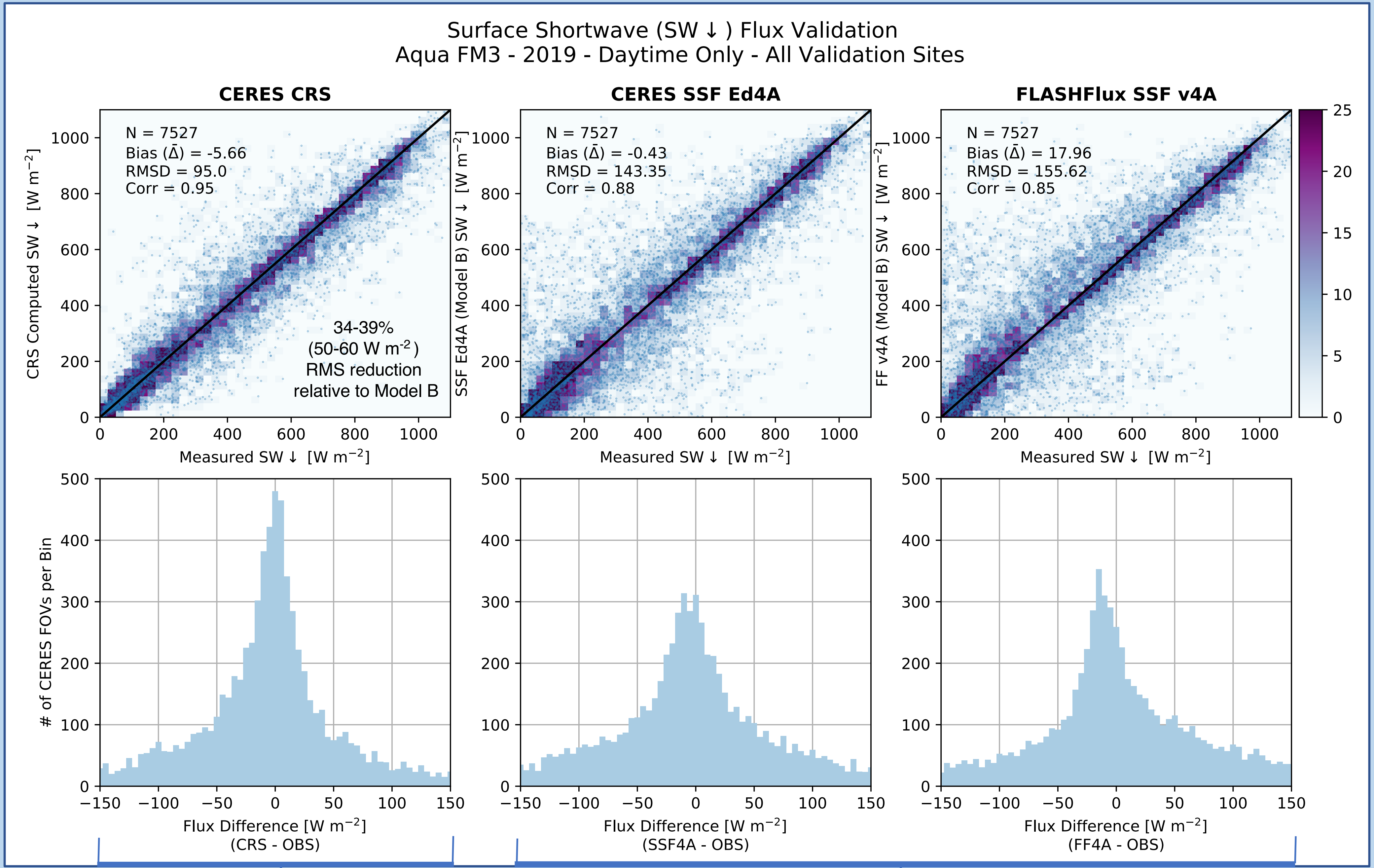


Fu-Liou RT Model Fluxes

Model B Parameterized Fluxes

Aqua FM3 Daytime SW↓
Fu-Liou vs Model B by surface type

CERES CRS

SW↓	N	Bias	RMSE	Corr.
All	7527	-5.66	**95.0**	**0.95**
Coastal	1366	-**4.4**	**100.21**	**0.93**
Desert	378	-11.4	**78.87**	**0.92**
Island	240	**45.62**	**147.13**	**0.86**
Continent	3049	-**1.69**	**108.32**	**0.92**
Polar	2494	-**15.27**	**66.11**	**0.94**

CERES SSF Ed4A

SW↓	N	Bias	RMSE	Corr.
All	7527	-**0.43**	143.35	0.88
Coastal	1366	14.14	130.82	0.88
Desert	378	-**0.54**	89.09	0.89
Island	240	68.57	154.37	*0.86*
Continent	3049	6.12	120.36	0.91
Polar	2494	-23.03	177.32	0.58

FLASHFlux SSF v4A

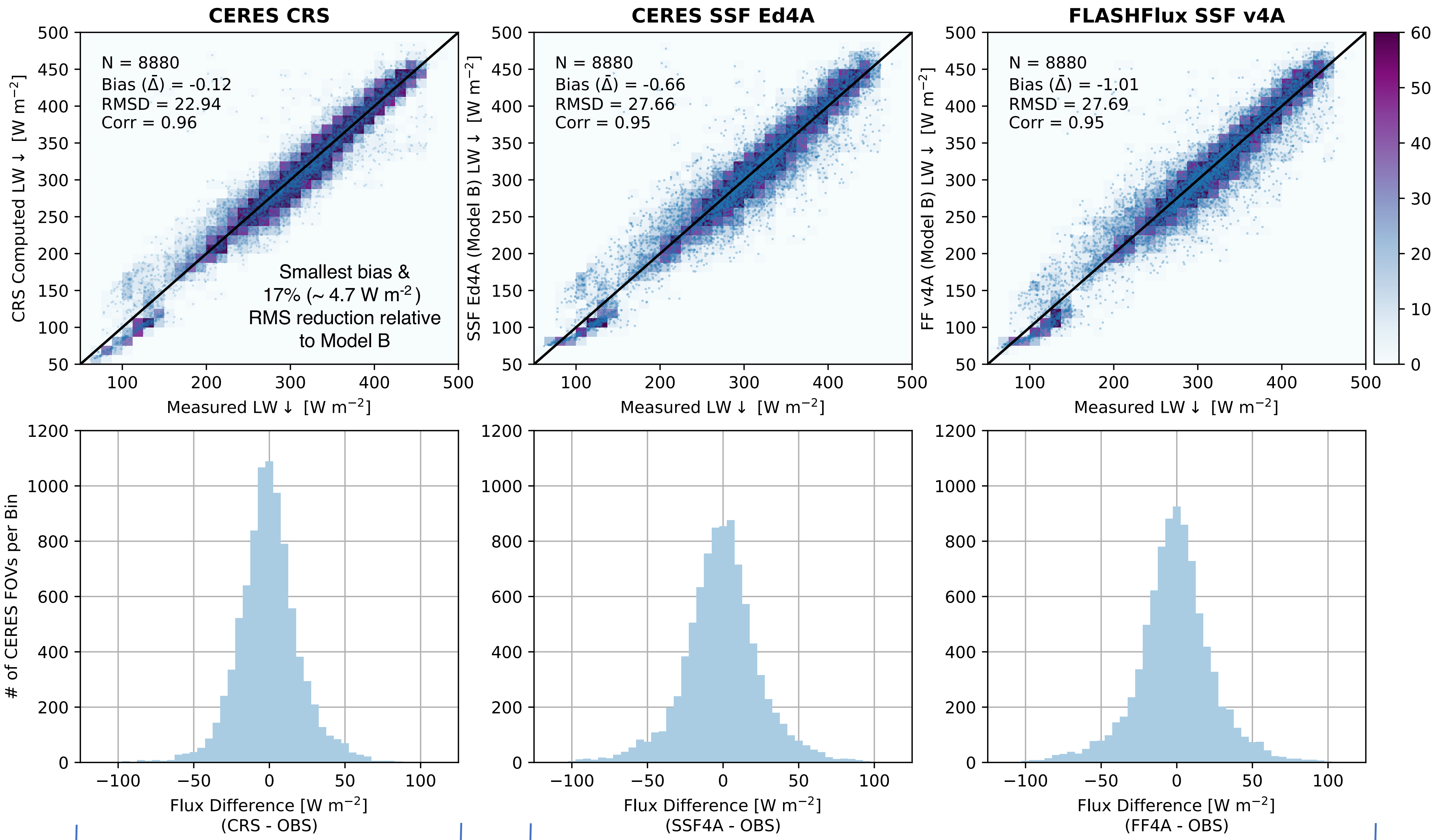
SW↓	N	Bias	RMSE	Corr.
All	7527	17.96	155.62	0.85
Coastal	1366	10.53	136.55	0.87
Desert	378	-13.7	92.74	0.88
Island	240	70.22	156.01	*0.86*
Continent	3049	13.39	132.54	0.88
Polar	2494	27.39	194.32	0.56

Fu-Liou RT Model Fluxes

Model B Parameterized Fluxes

Results for Terra FM1 are similar
* Bias, RMSE units: W m^{-2}

Surface Longwave (LW ↓) Flux Validation
Aqua FM3 - 2019 - Daytime Only - All Validation Sites



Fu-Liou RT Model Fluxes

Model B Parameterized Fluxes

Aqua FM3 Daytime LW↓
Fu-Liou vs Model B by surface type

CERES CRS

LW↓	N	Bias	RMSE	Corr.
All	8880	**-0.12**	**22.94**	**0.96**
Coastal	1608	3.48	**15.56**	**0.97**
Desert	448	-13.04	**23.24**	**0.93**
Island	313	**4.98**	**13.72**	**0.87**
Continent	3293	3.56	**25.75**	**0.91**
Polar	3218	-4.37	**23.65**	**0.95**

CERES SSF Ed4A

LW↓	N	Bias	RMSE	Corr.
All	8880	-0.66	27.66	0.95
Coastal	1608	**-0.38**	26.25	0.91
Desert	448	**-7.51**	29.71	0.85
Island	313	6.38	17.82	0.83
Continent	3293	0.9	28.73	0.89
Polar	3128	-2.13	27.73	0.93

FLASHFlux SSF v4A

LW↓	N	Bias	RMSE	Corr.
All	8880	-1.01	27.69	0.95
Coastal	1608	-1.01	26.55	0.91
Desert	448	-7.83	26.78	0.87
Island	313	5.35	18.34	0.82
Continent	3293	**-0.7**	29.16	0.89
Polar	3128	-**1.0**	27.6	0.93

Fu-Liou RT Model Fluxes

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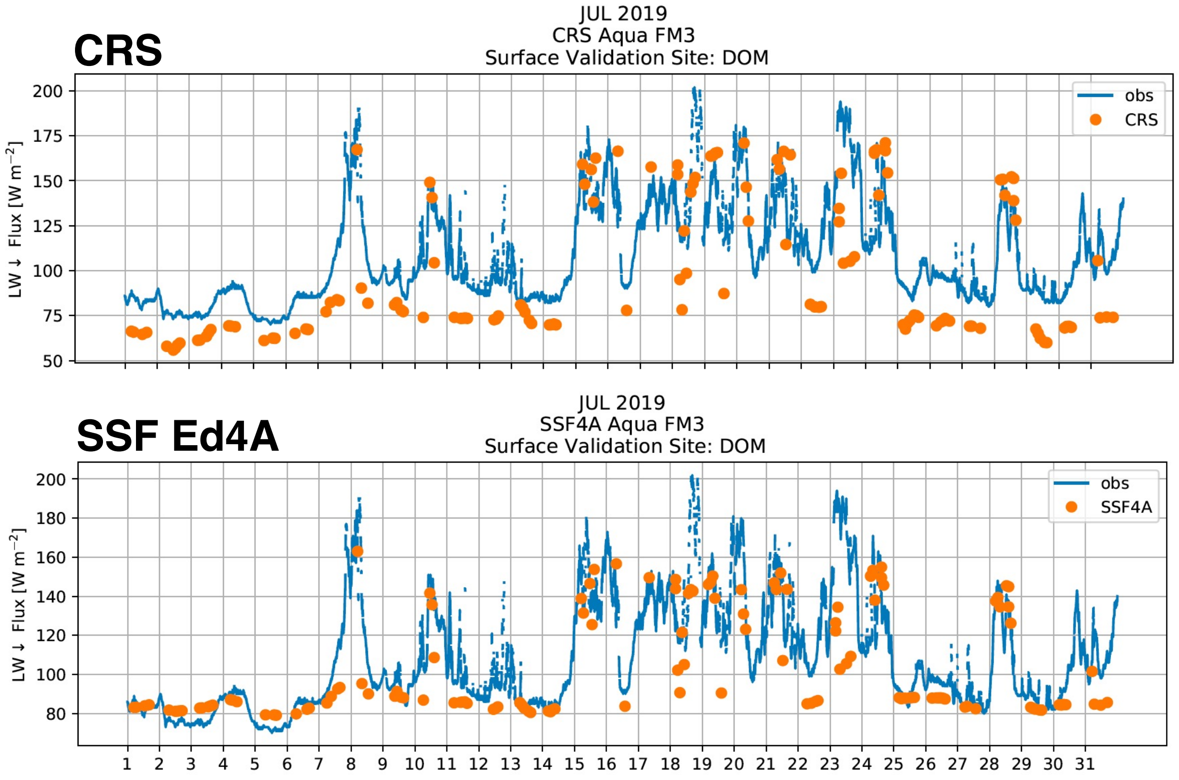
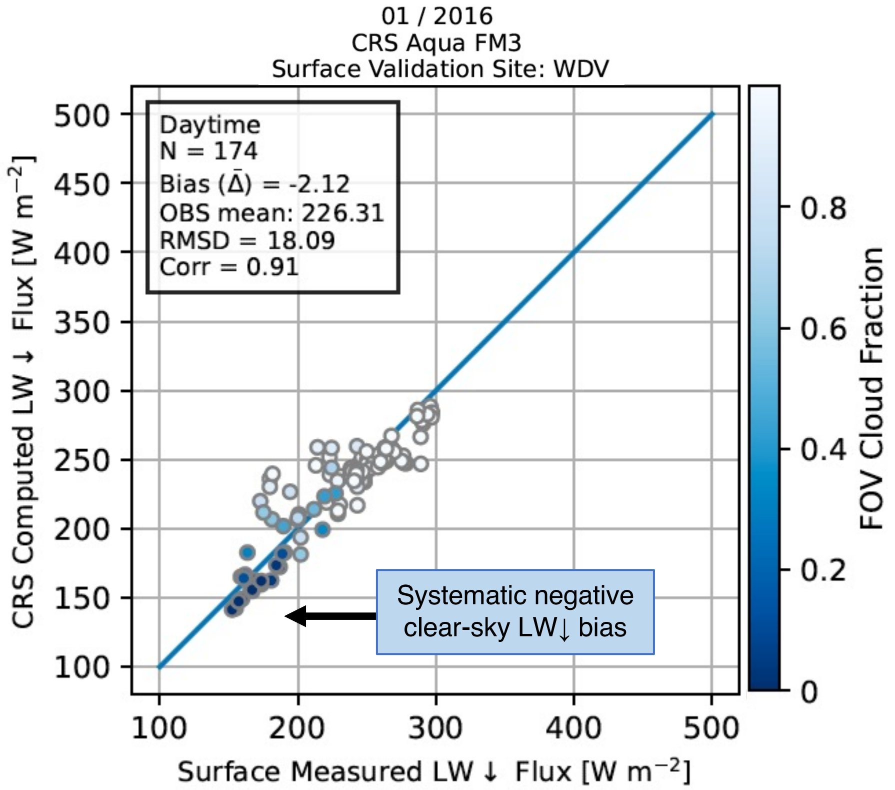
Polar Clear-Sky Surface LW↓ Fluxes





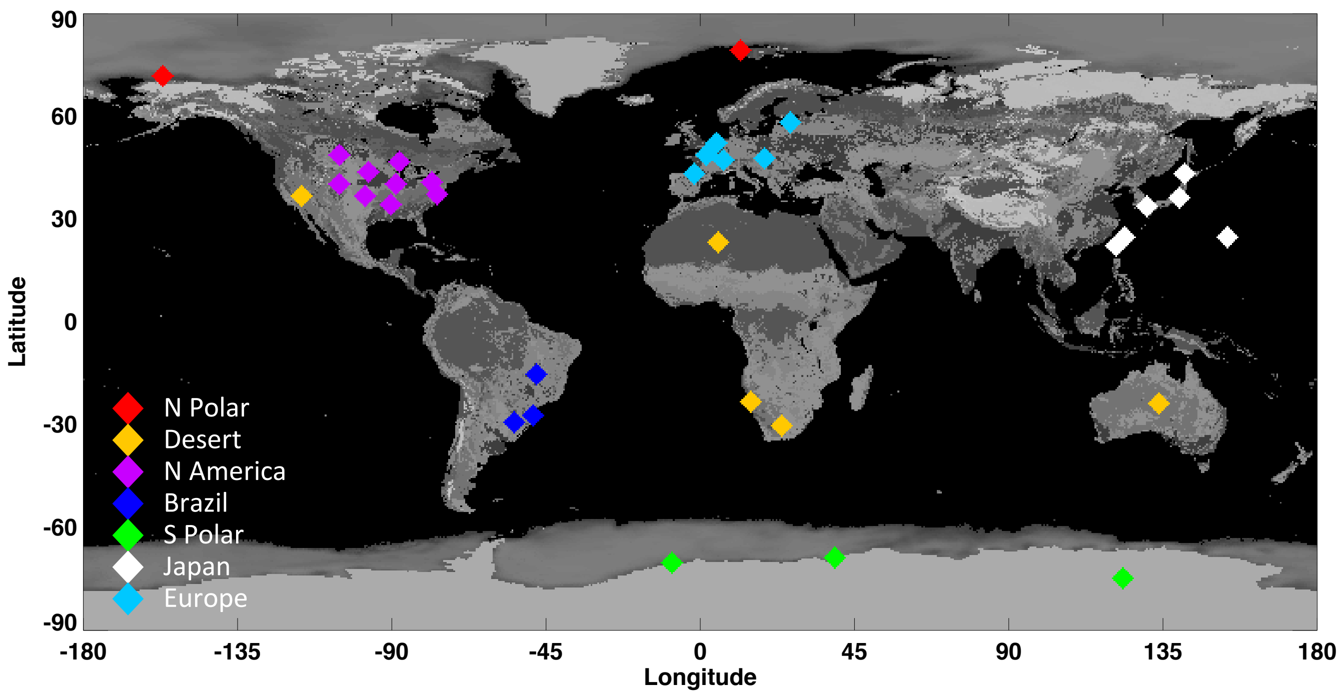
Systematic underestimation of clear-sky LW↓@ (left) **Dome C** & (right) **WAIS Divide, Antarctica**

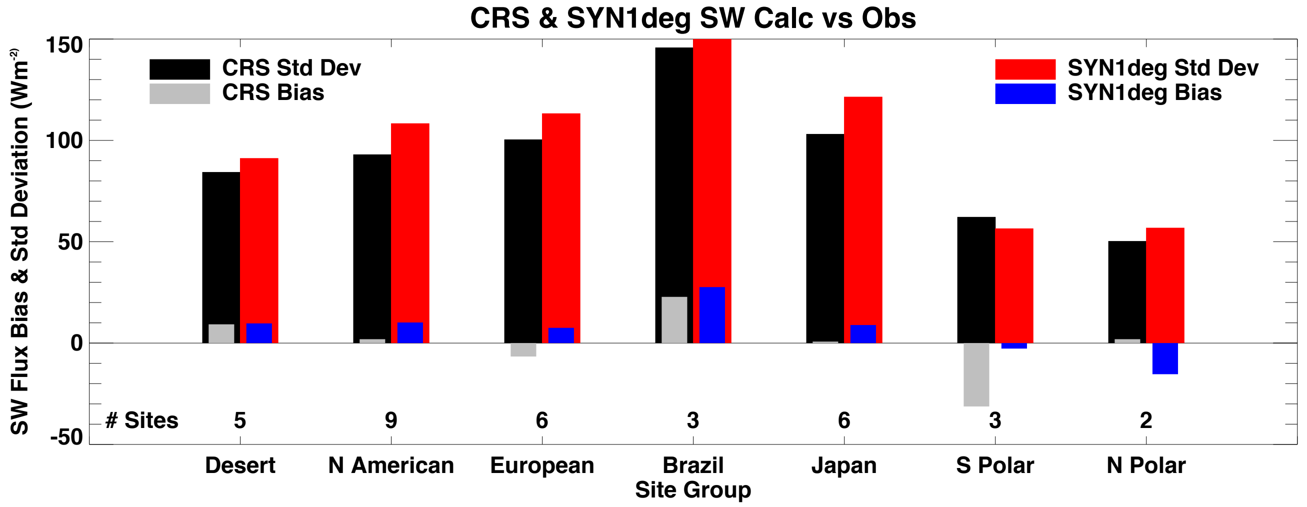
Surface-based thermal inversion not well resolved in GEOS 5.4.1

Starting to develop inversion correction following Gupta et al. 2010

CRS vs SYN1deg Surface (↓) Flux Validation

- SYN1deg provides gridded hourly surface fluxes also calculated using the Fu-Liou RT model
- We also compared CRS to SYN1deg
  - **SYN1deg** fluxes compared to **1-hr average** of the obs. centered on the half hour
- Both products are reasonably consistent & show similar statistics
- CRS has a smaller SW↓ bias & std. dev. (σ) everywhere but Antarctica
  - Footprints more representative of surface observations than 1° grid cells
  - CRS cloud optical depths are unrealistically high over permanent snow and ice surfaces
- CRS and SYN1deg also show similar results in the LW↓





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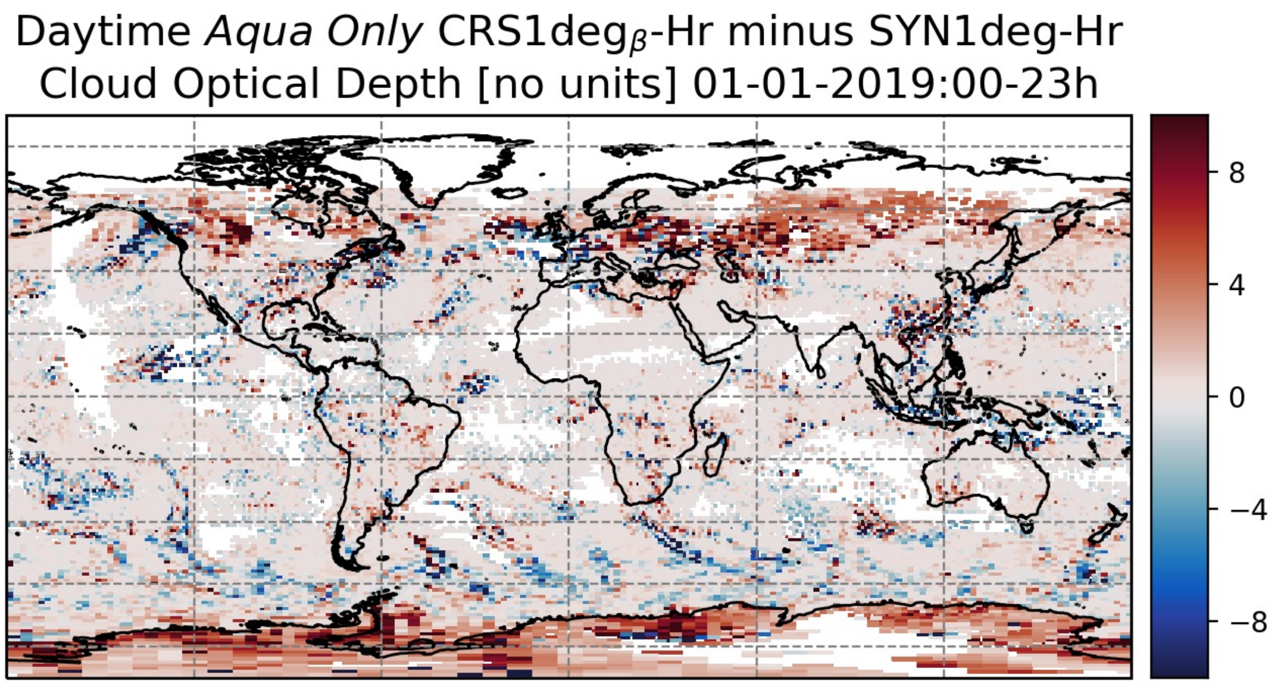

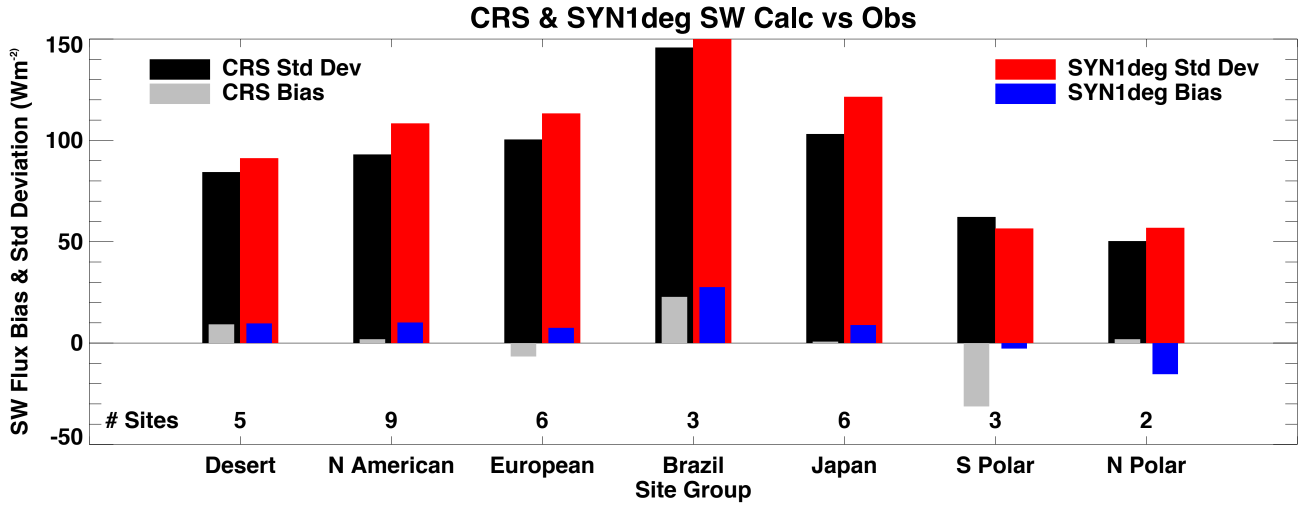

Can We Use CRS & Machine Learning to Improve FLASHFlux SSF Surface Fluxes?

Problem:

- FLASHFlux (P. Stackhouse's talk next) provides near real-time estimates of Earth's surface radiation budget components for agricultural, renewable energy, and other applications
- Currently, footprint-level surface fluxes are estimated using decades-old parameterizations (Model B) that, as we just showed, are generally inferior to CRS fluxes from the Fu-Liou radiative transfer model.
- However, running the Fu-Liou code at the CERES instrument footprint level is computationally expensive (~ 2.3M computations, ~12-16+ hours/day) and increases the difficulty of meeting latency requirements

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Approach / Solution:

- Train supervised machine learning algorithms on CRS data, tune hyperparameters, & evaluate model performance to "learn" functional mappings that can *accurately* & *rapidly* predict CRS surface fluxes – no need to run the Fu-Liou RT code!
    - Linear, Decision Tree, Random Forest, & XGBoost Regressors

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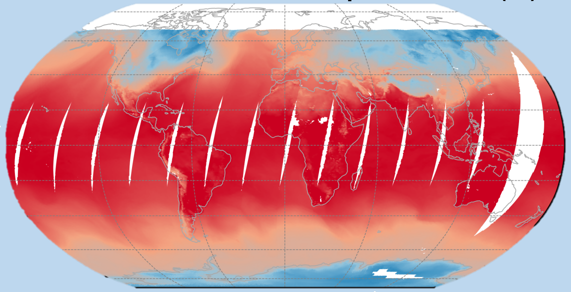
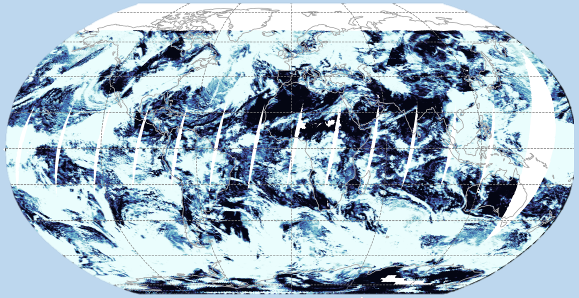
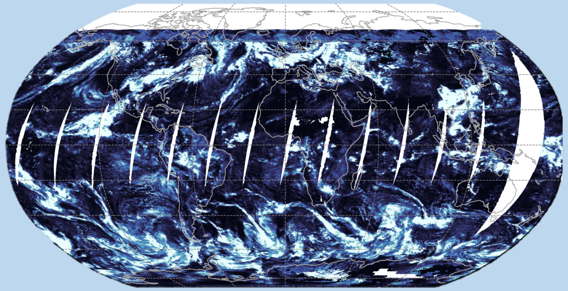
Eff. Emission Temperature (T)



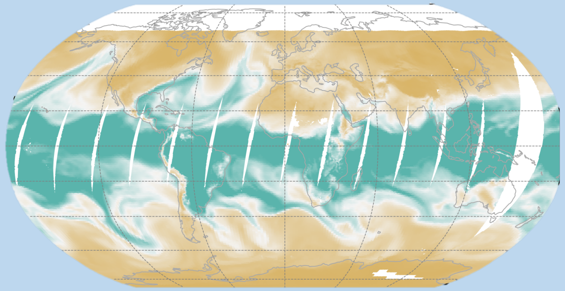
Cloud Fraction (CF)



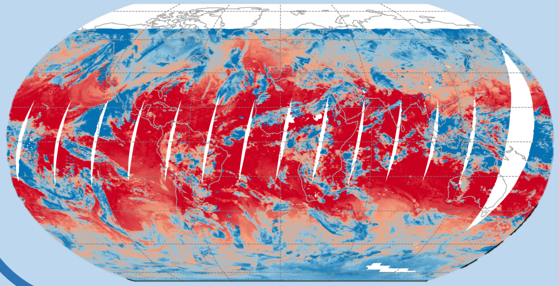
Cloud Optical Depth (COD)



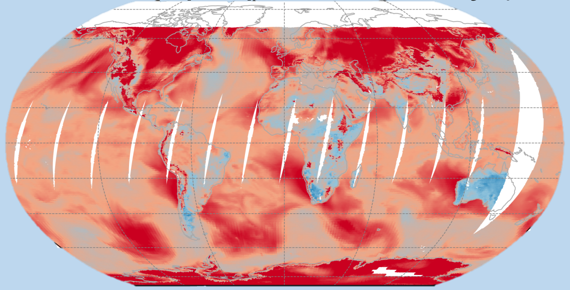
Precipitable Water Vapor (PWV)



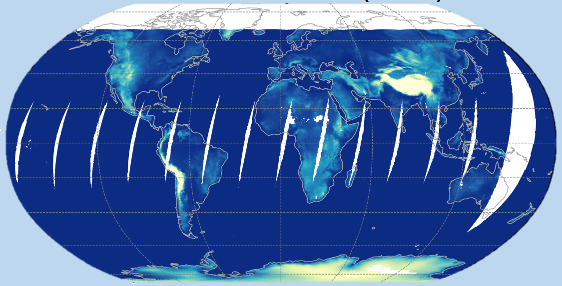
Eff. Cloud Temperature (CT)



Lower Tropospheric Stability (LTS)



Surface Altitude (ALT)



- Provides functional mappings between meteorological parameters

$\mathbf{X} =$

T, CF, COD, CT, PWV, LTS, ALT

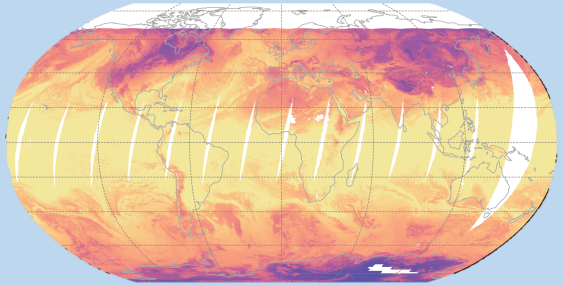
that are physically relevant and readily available in the FLASHFlux data processing stream & the CRS flux

$$\boxed{LW\downarrow = f_i(\mathbf{X})}$$

<u>Supervised ML Algorithms</u>:

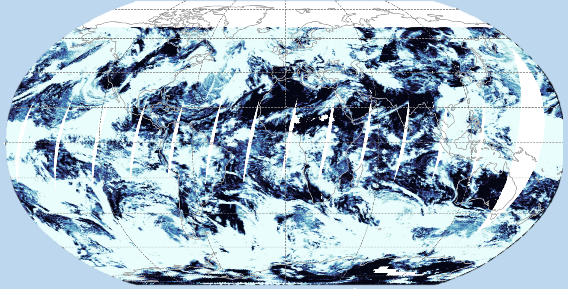
```
Linear
Decision Tree
Random Forest
XGBoost
```

Surface Longwave Flux (LW↓)

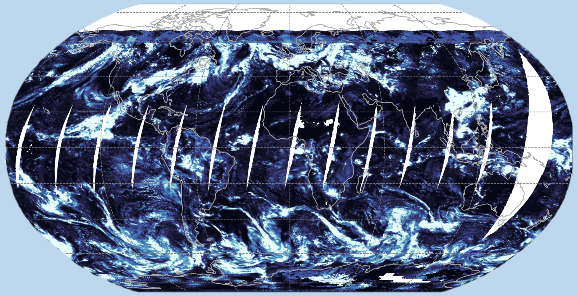


- Standardize **X** prior to training
- Train on day & night footprints
- Assess performance & tune hyperparameters using different evaluation metrics:
  - `80/20 Train-Test Split`
  - `K-Fold Cross Validation`
  - `Randomized Search CV (in progress)`

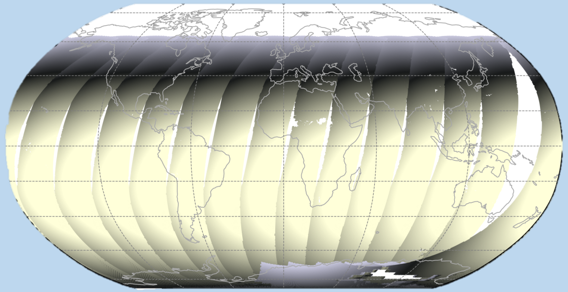
Cloud Fraction (CF)



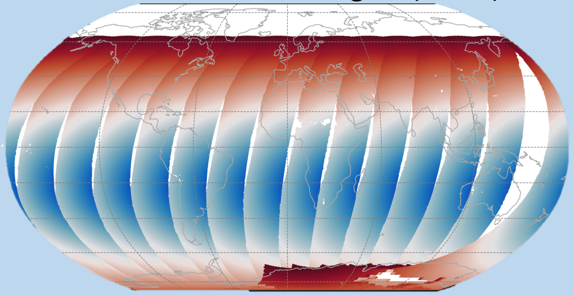
Cloud Optical Depth (COD)



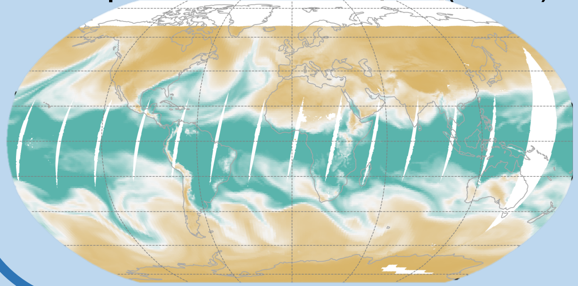
TOA Insolation (INS)



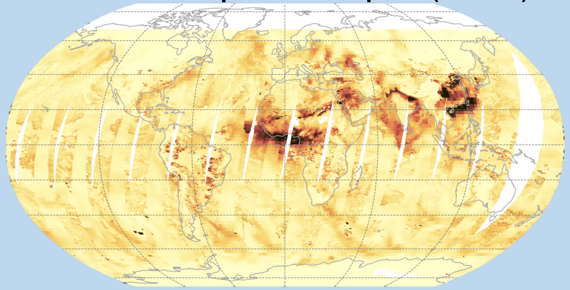
Solar Zenith Angle (SZA)



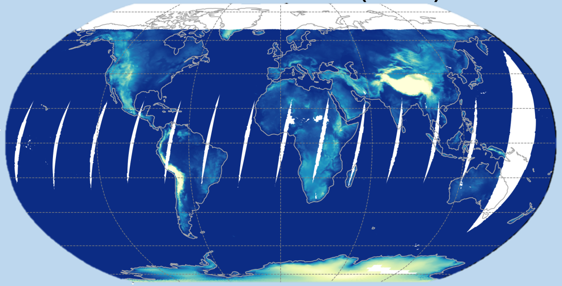
Precipitable Water Vapor (PWV)



Aerosol Optical Depth (AOD)



Surface Altitude (ALT)



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$$\boxed{SW\downarrow = g_i(\mathbf{X})}$$

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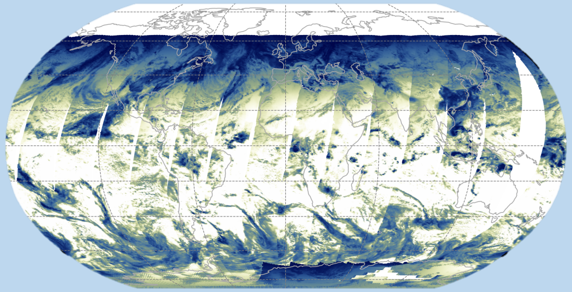
Surface Shortwave Flux (SW↓)

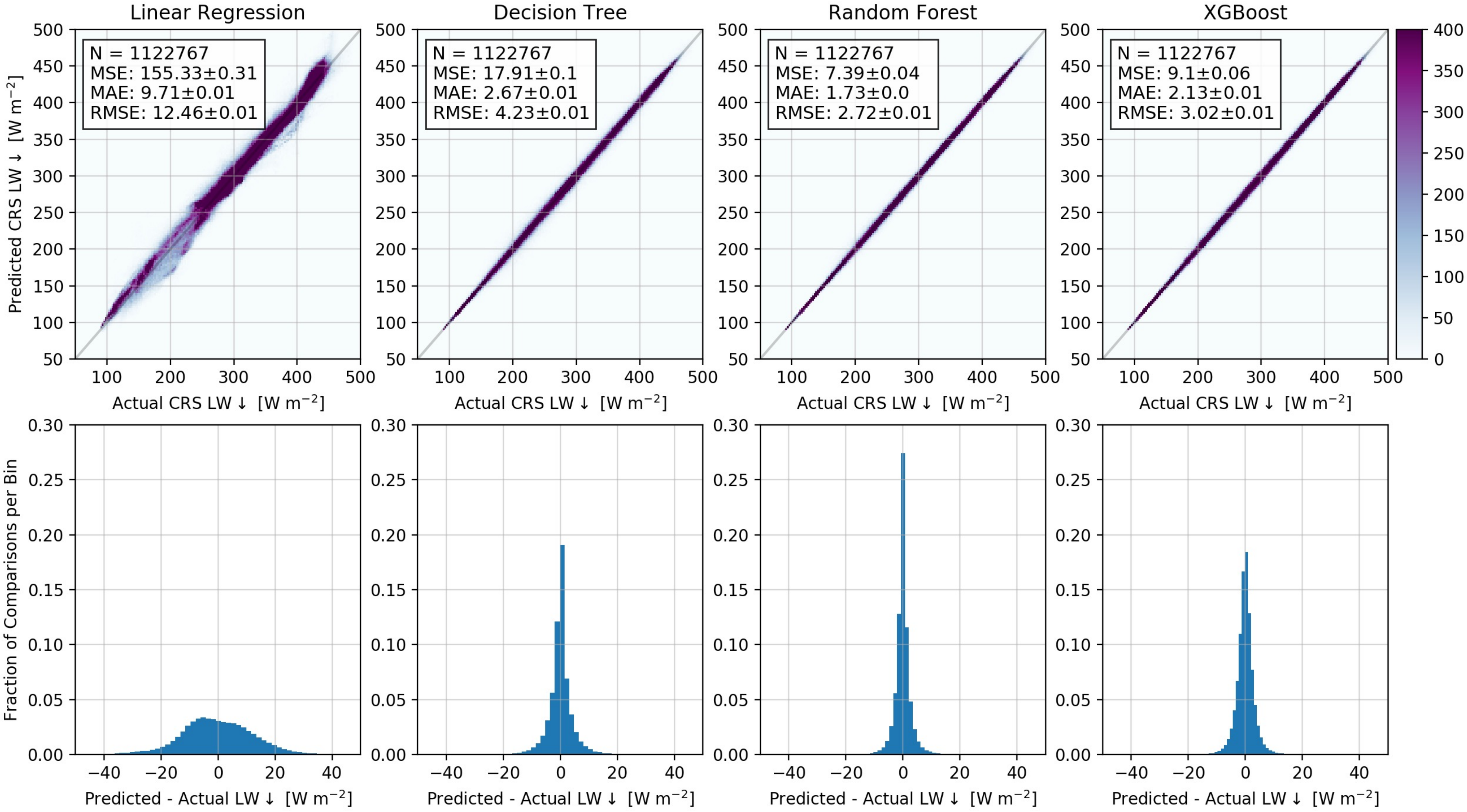


- Standardize $\mathbf{X}$ prior to training
- Train on daytime footprints
- Assess performance & tune hyperparameters using different evaluation metrics:
  - `80/20 Train-Test Split`
  - `K-Fold Cross Validation`
  - `Randomized Search CV (in progress)`

LW↓

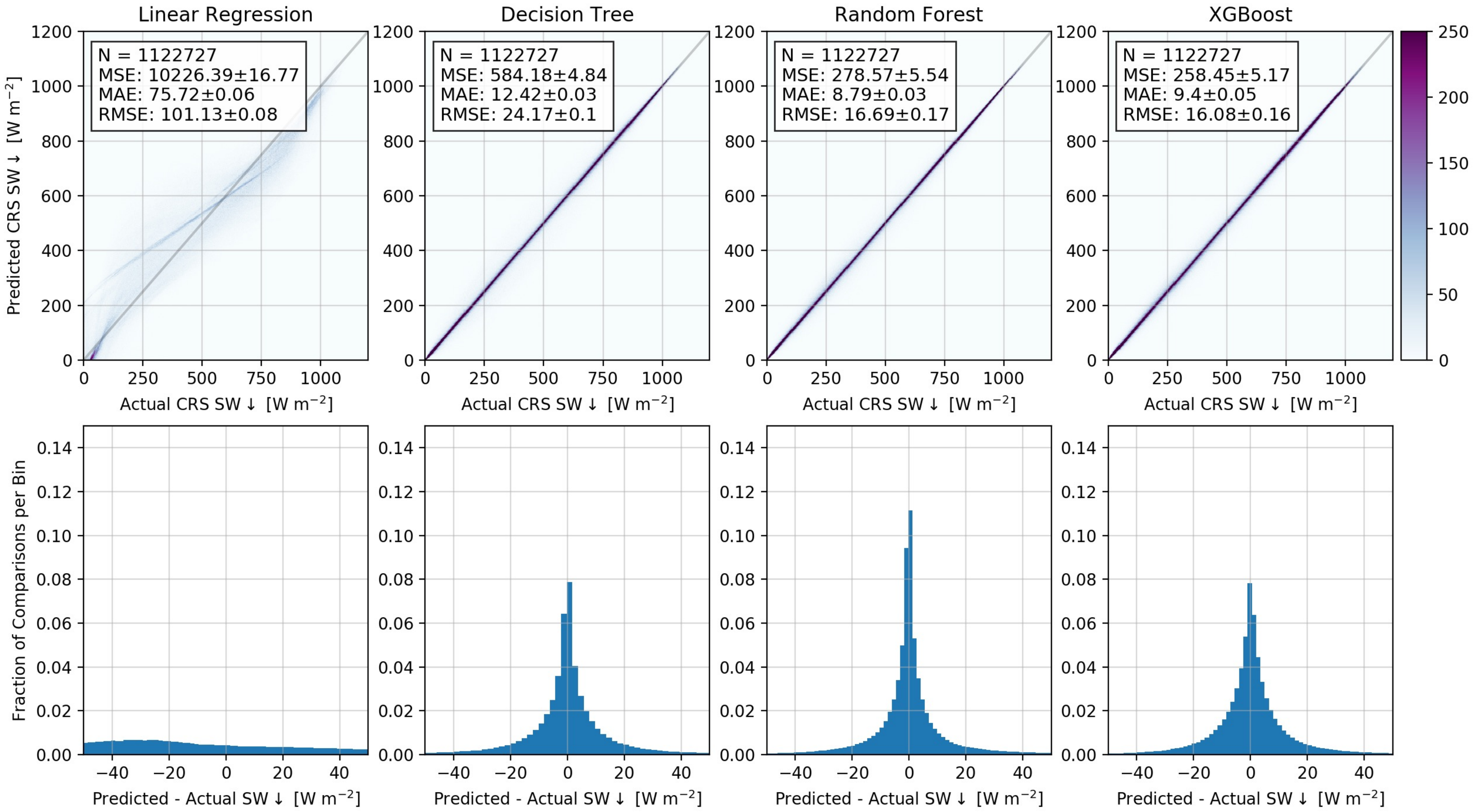
CER_CRS4_Terra-FM1-MODIS_GH4_1111TH.20190101:00-23h

Training features: Cloud properties (fraction, optical depth, temperature), $\bar{T}$, PWV, LTS, ALT



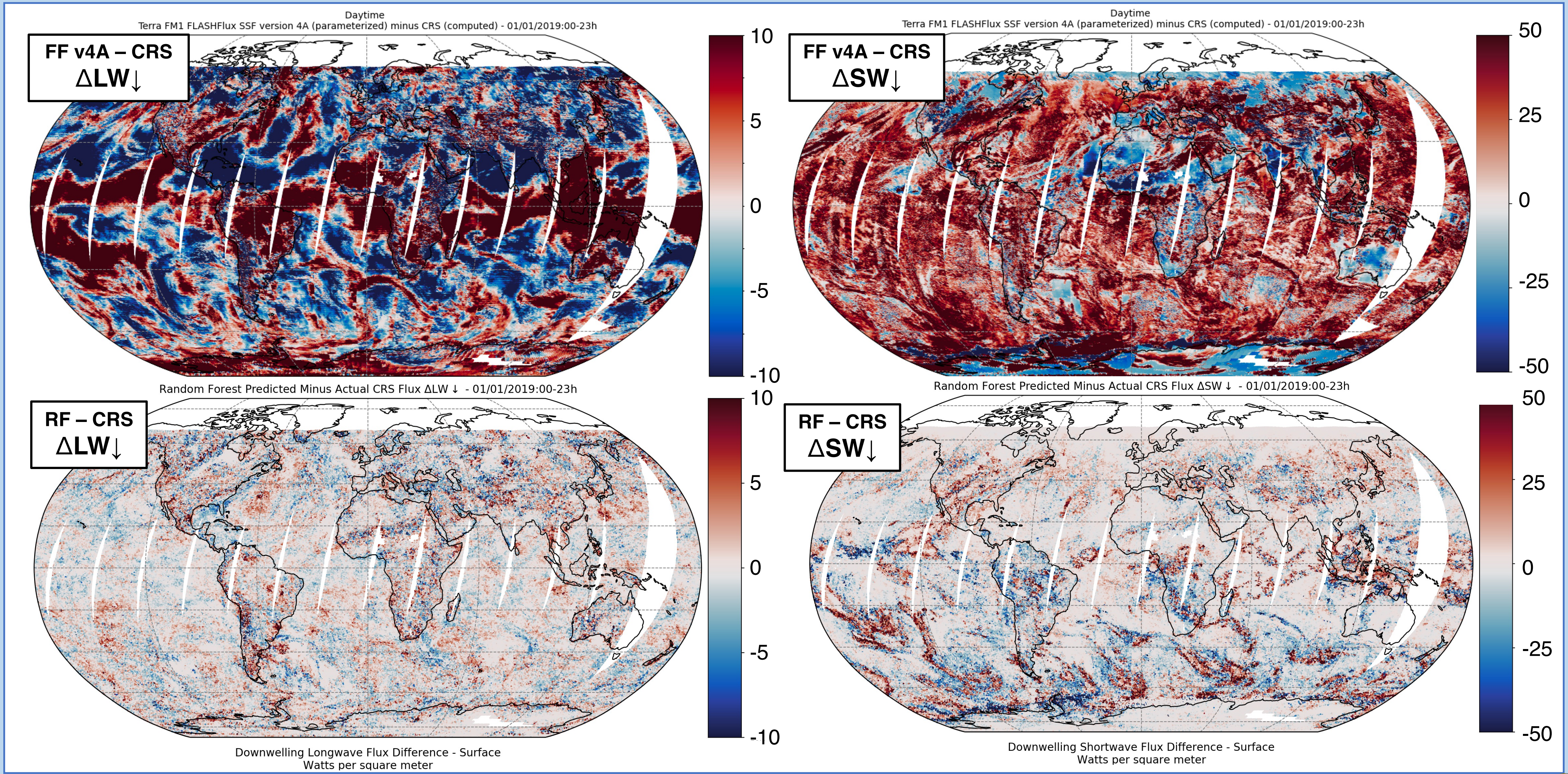
SW↓

CER_CRS4_Terra-FM1-MODIS_GH4_1111TH.20190101:00-23h
Training features: Insolation, SZA, CF, COD, AOD, PWV, Altitude



Random Forest (RF) surface flux predictions much closer to CRS than FLASHFlux Model B

(top) FLASHFlux SSF v4A – CRS (bottom) RF – CRS flux difference (Δ) [W m^{-2}]



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Summary & Future Work

- CRS computes instantaneous footprint-level irradiances using the NASA Langley Fu-Liou RT code
  - Here we summarized our progress resurrecting & validating CRS since we first reintroduced it 6 months ago
- Comparisons to CERES global TOA measurements show reasonable & stable performance
  - Global mean all-sky LW↑ within 1% of CERES, SW↑ within 3 - 4% of CERES throughout 2019
- CRS surface fluxes are superior to SOFA Model B parameterized fluxes (SSF Ed4A, FF SSF v4A)
  - Based on 2019 validation by surface site type using measurements from the CAVE database
  - SW↓ – RMS reduction of 34 - 39% (50 - 60 W m^{-2}), higher correlation, lower bias for most site types
  - LW↓ – RMS reduction of 17% (~ 4.7 W m^{-2}), marginally increased correlation, lowest overall bias
  - Corrections needed for excessive Antarctic cloud optical depth & unresolved temperature inversions
- Machine learning with CRS offers a viable solution to improve FLASHFlux SSF surface fluxes
  - We have developed, trained, & evaluated Linear, Decision Tree, Random Forest, & XGBoost regressors
  - Random Forest & XGBoost successfully reproduce CRS fluxes w/ model RMS values less than the validation RMS Δ between CRS & Model B; individual footprint errors are typically << Δ(FF – CRS)
  - *Next Steps*: continue tuning models (RF & XGBoost) & devise scalable training methodology
    deploy models in production & use as the operational source of FLASHFlux SSF surface fluxes
- We plan to release CRS publicly with CERES Edition 5 data products
- Thank You!

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Extra Slides

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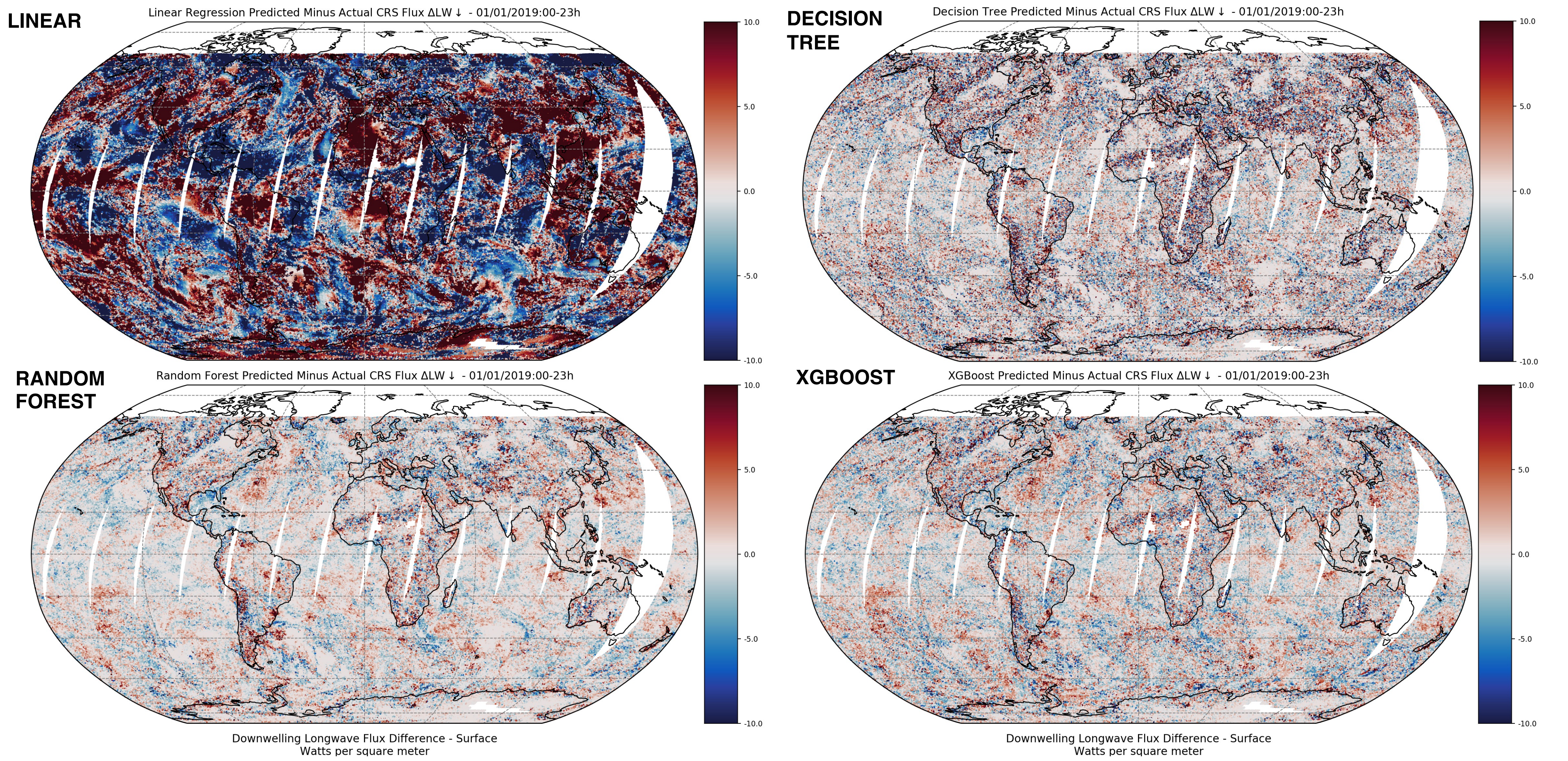
Surface LW↓ Model Performance

Predicted - Actual Flux [W m^{-2}]



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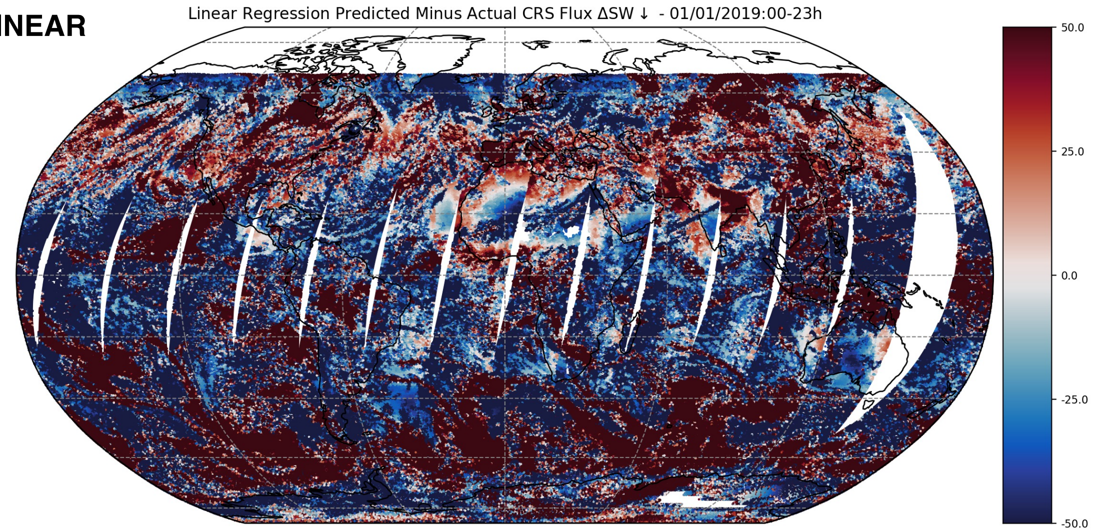
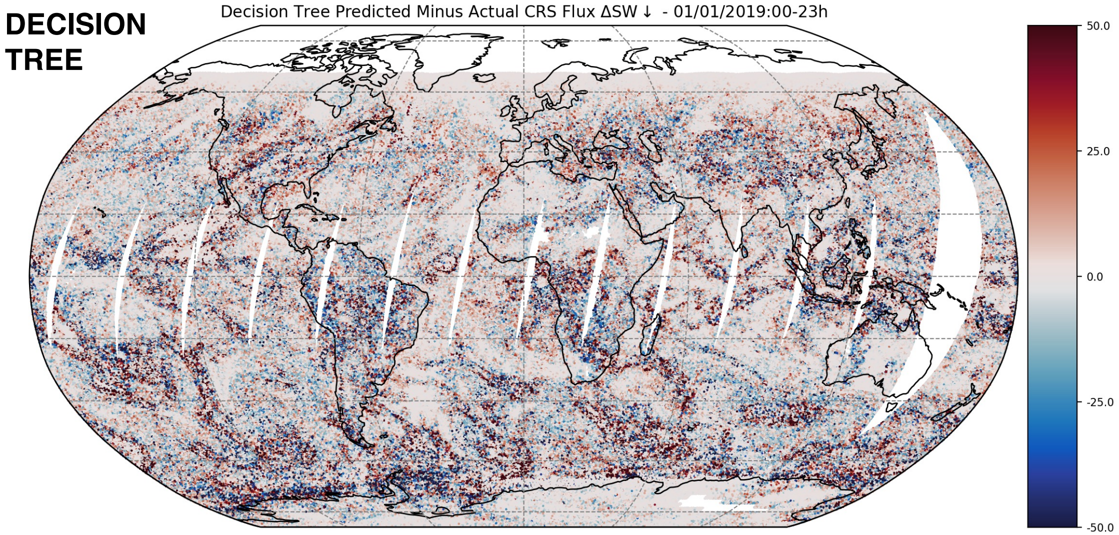
Surface SW↓ Model Performance

Predicted - Actual Flux [W m^{-2}]

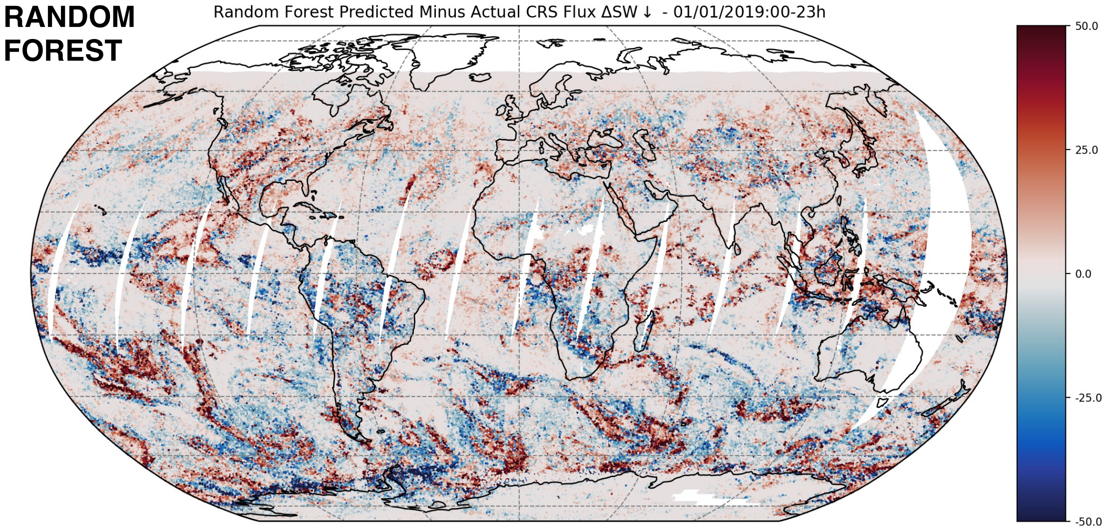
LINEAR



DECISION TREE

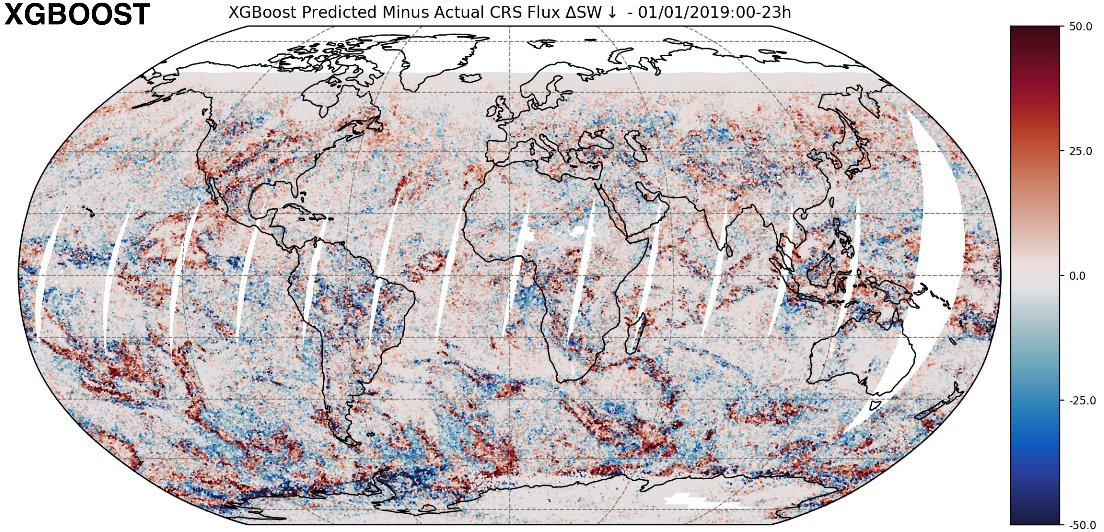


RANDOM FOREST



Downwelling Shortwave Flux Difference - Surface
Watts per square meter

XGBOOST



Downwelling Shortwave Flux Difference - Surface
Watts per square meter

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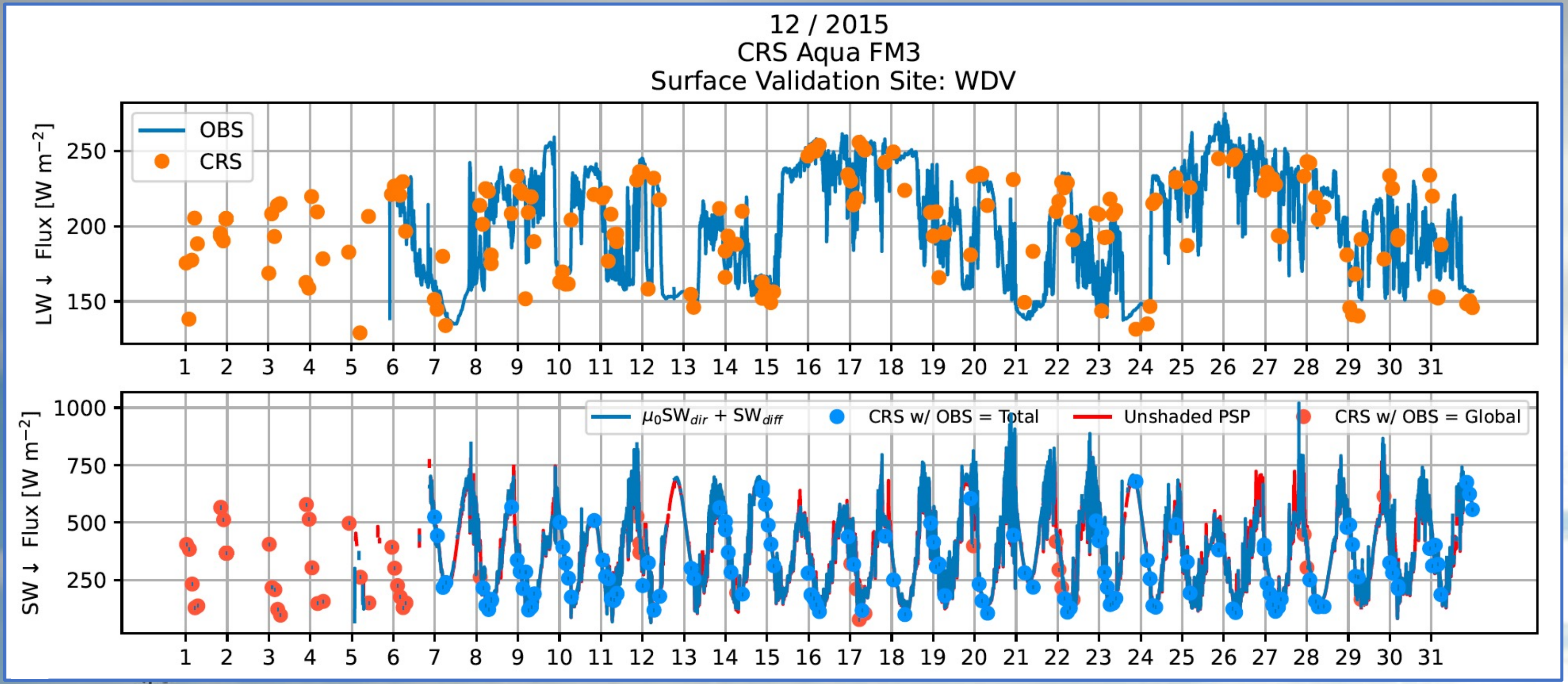

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