Cloud Radiative Swath Update: Enhancing Level 2 Surface Fluxes w/ the Fu-Liou RTM & Machine Learning

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CERES L2 Surface Fluxes

- Climate studies require info on energy flows internal to the climate system, esp. @ surface, on various scales
  - Current L2 Single Scanner Footprint (SSF) products estimate broadband surface fluxes with simple parameterizations: Surface-Only Flux Algorithms (SOFA) Models A, B, C – all are limited in scope & accuracy, were meant as a temporary solution

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- The Cloud Radiative Swath (CRS) data product builds upon the standard L2 SSF by calculating a suite of instantaneous irradiances at the footprint scale using the NASA LaRC Fu-Liou radiative transfer model (RTM)
  - Developed in 2000s & last released w/ Ed 2. SARB has resurrected CRS to provide more sophisticated L2 flux products
  - SW↓↑ & LW↓↑ broadband flux profiles; spectral surface (↓) & TOA (↑) fluxes; surface direct + diffuse SW↓, PAR, UV

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- Here we report our latest progress toward enhancing the CERES & FLASHFlux Level 2 surface flux products

1. **How accurate are CRS Ed4 surface fluxes? How does CRS perform compared to current-generation SOFA models?**
   i. Validation of surface ↓ fluxes stratified by cloud conditions & surface type against a global network of observations
      - CRS *vs* the SOFA (Models A, B, C) fluxes available in current CERES & FLASHFlux SSF products

   ii. Plus: unique validation opportunities in remote polar environments - MOSAiC, Arctic Ocean & Siple Dome, Antarctica

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    ii. Plus: unique validation opportunities in remote polar environments - MOSAiC, Arctic Ocean & Siple Dome, Antarctica
2. **Using Machine Learning to provide CRS-quality surface ↓ fluxes in near real-time on the FLASHFlux SSF**
    iii. Tuning hyperparameters of **XGBoost** regressor trained on CRS simulations for enhanced generalization performance

    iv. How the models will be applied to FLASHFlux SSF near real-time data production

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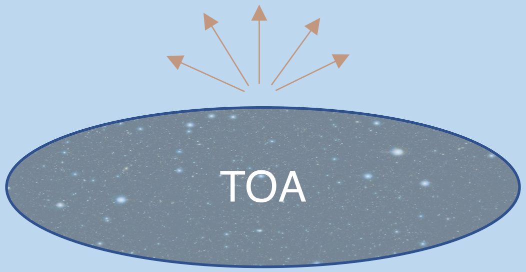
CERES SSF



Surface-Only Flux Algorithms (SOFA)

Model B (All-Sky)

Langley Parameterized LW Algorithm
Langley Parameterized SW Algorithm

Model A (Clear-Sky Only)

Model C (All-Sky, LW Only)

SW↓↑ Surface **LW↓↑**

~20-50 km

CERES Footprint / FOV
Terra, Aqua, NPP, NOAA-20

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

Surface 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** & **spectrally-resolved** fluxes @ the surface (↓) and TOA (↑)

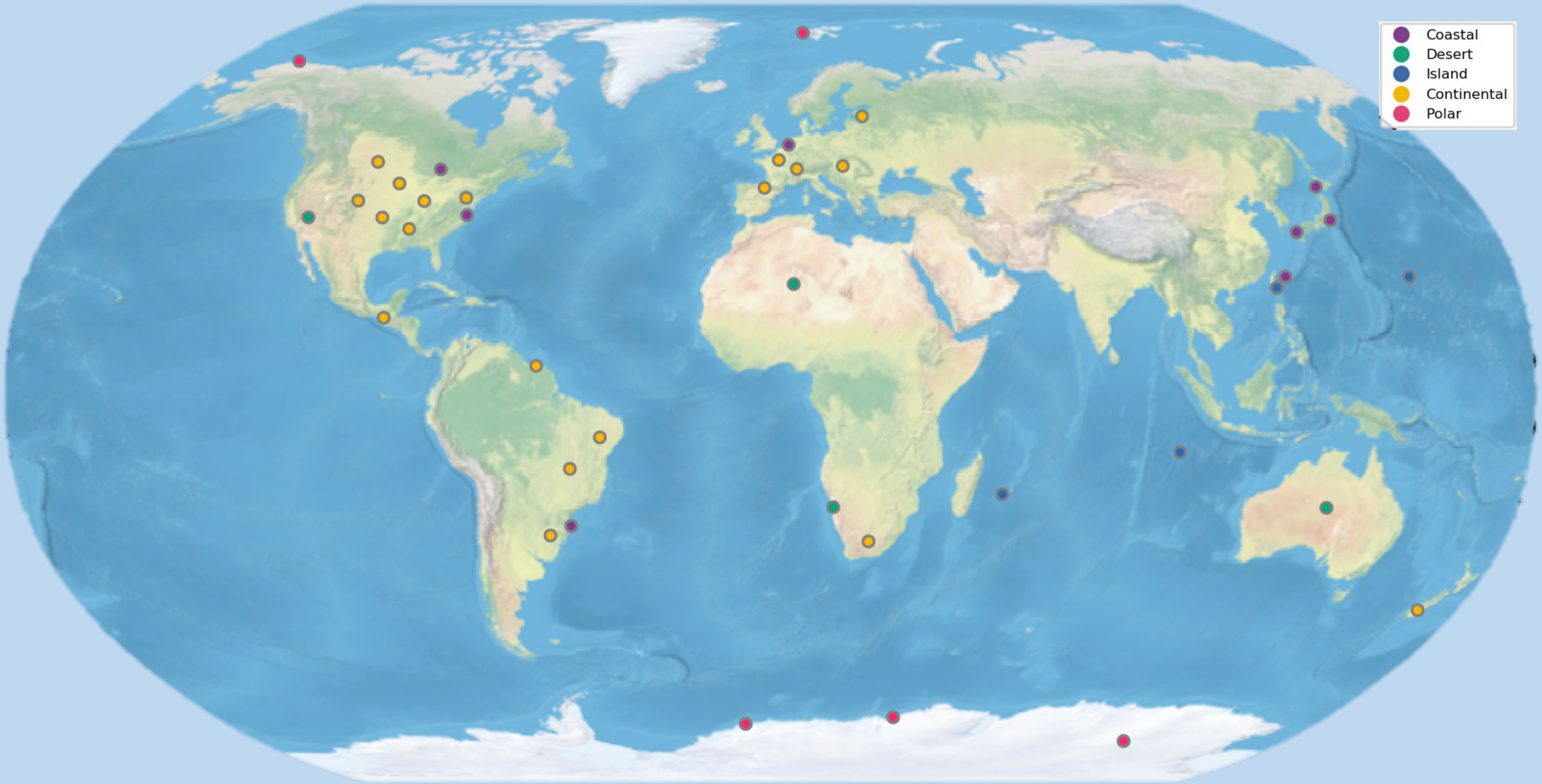
2-stream LW
4-stream SW

LW : 12 bands
SW : 14 bands

SW↓ direct + diffuse
PAR, UV fluxes

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

CERES L2 Surface Validation Sites



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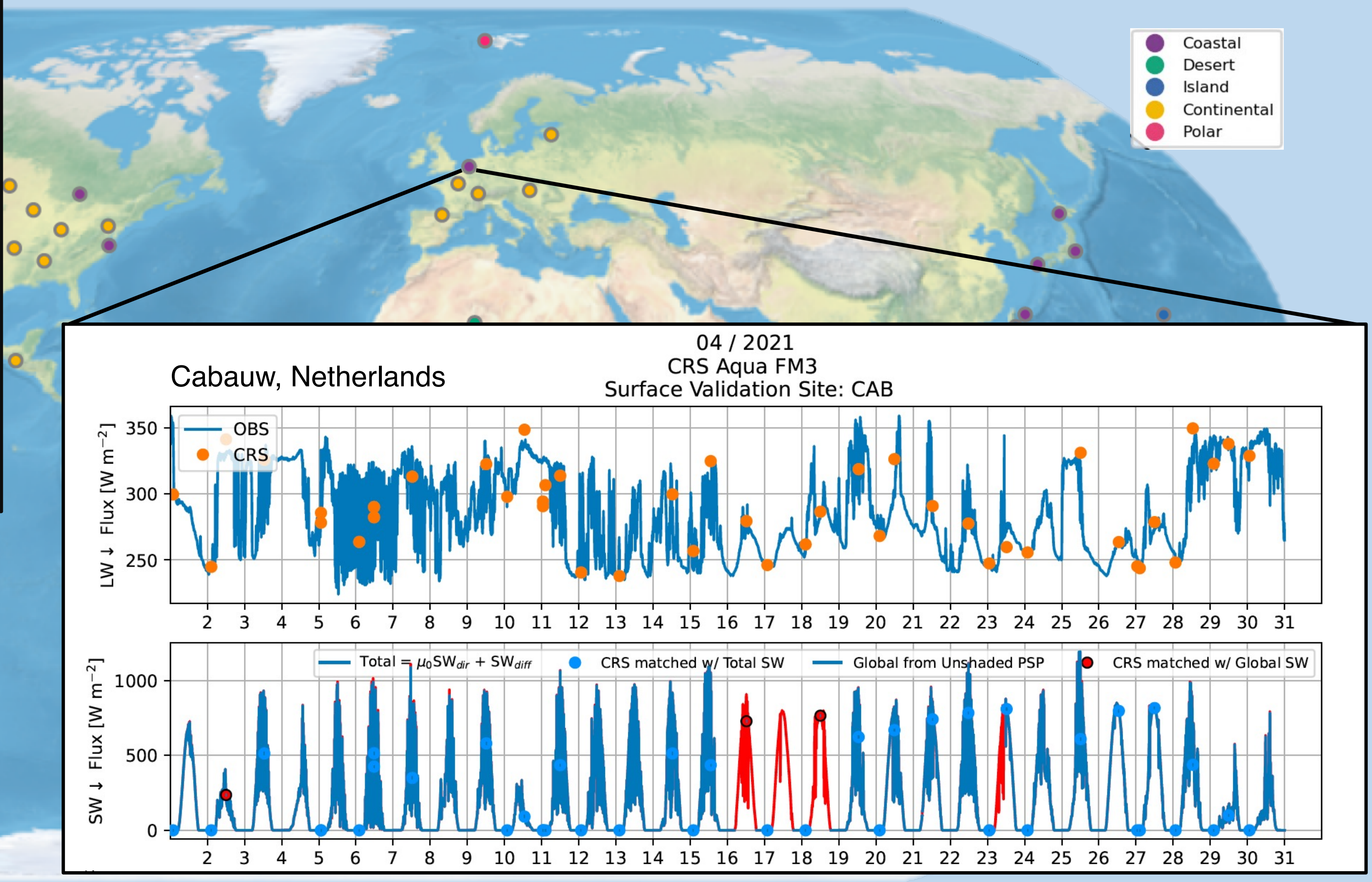
Surface Flux Validation Methodology

- 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
    - **$SW\downarrow_{CRS}$** scaled by avg(μ_{OBS}) / μ_{CRS} to account for changing μ = cos(SZA)
- Sort by surface type & cloud conditions



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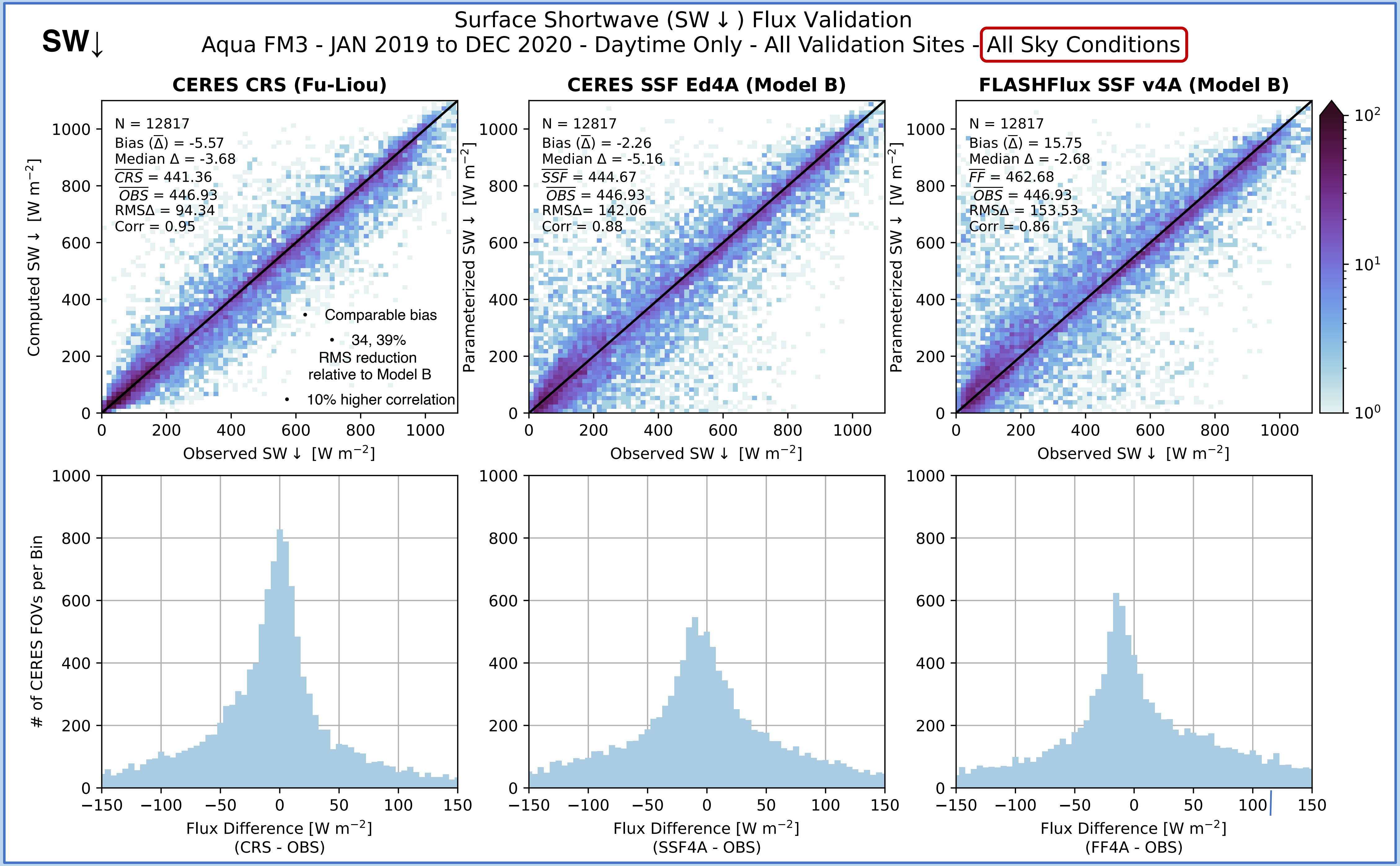
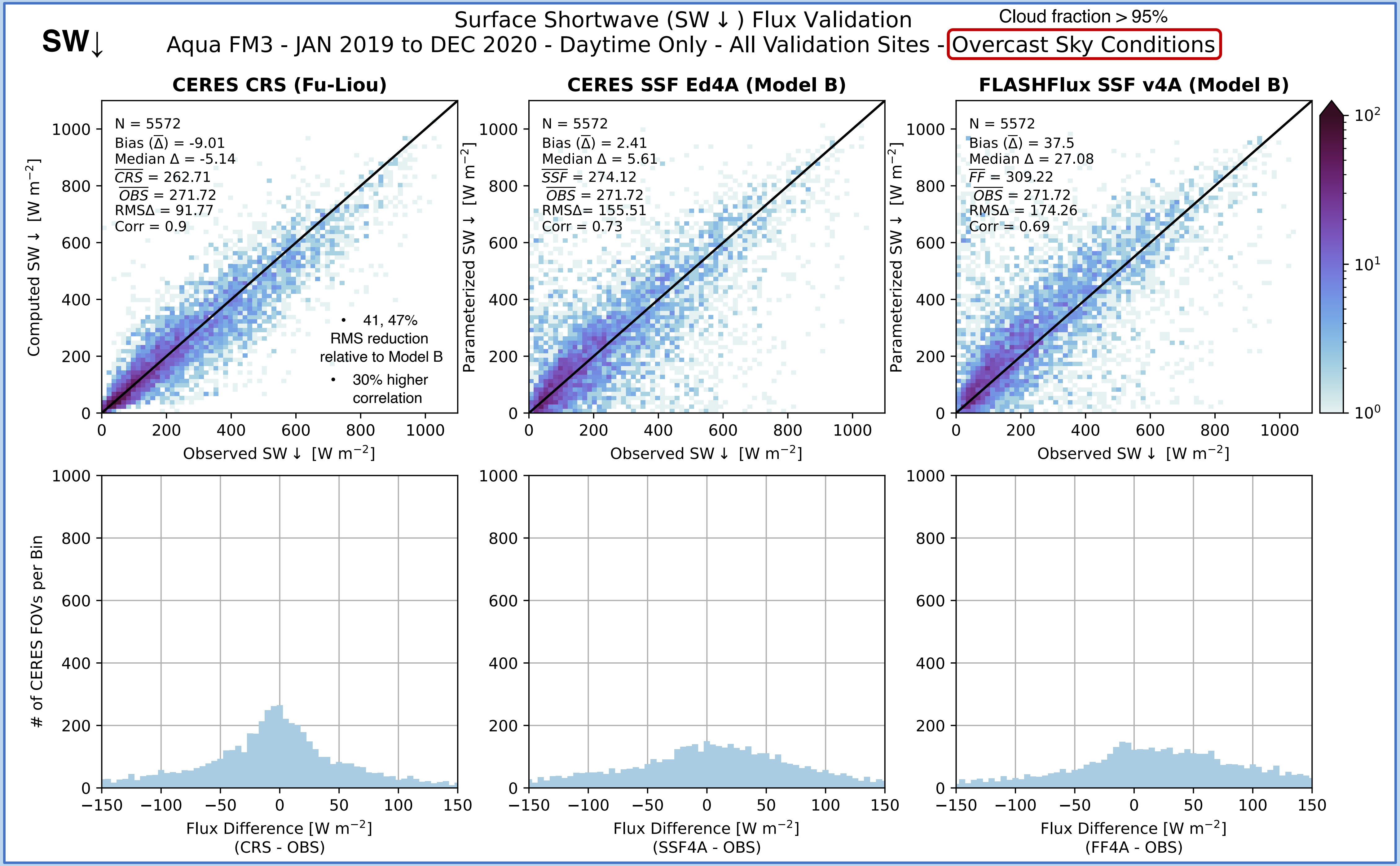


SW↓
Surface Shortwave (SW ↓) Flux Validation
Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - All Sky Conditions
CERES CRS (Fu-Liou)
N = 12817
Bias (Δ) = -5.57
Median Δ = -3.68
CRS = 441.36
OBS = 446.93
RMSΔ = 94.34
Corr = 0.95
• Comparable bias
• 34, 39% RMS reduction relative to Model B
• 10% higher correlation
Computed SW ↓ [W m−2]
Observed SW ↓ [W m−2]
CERES SSF Ed4A (Model B)
N = 12817
Bias (Δ) = -2.26
Median Δ = -5.16
SSF = 444.67
OBS = 446.93
RMSΔ= 142.06
Corr = 0.88
Parameterized SW ↓ [W m−2]
FLASHFlux SSF v4A (Model B)
N = 12817
Bias (Δ) = 15.75
Median Δ = -2.68
FF = 462.68
OBS = 446.93
RMSΔ = 153.53
Corr = 0.86
# of CERES FOVs per Bin
Flux Difference [W m−2]
(CRS - OBS)
(SSF4A - OBS)
(FF4A - OBS)
NASA
CERES



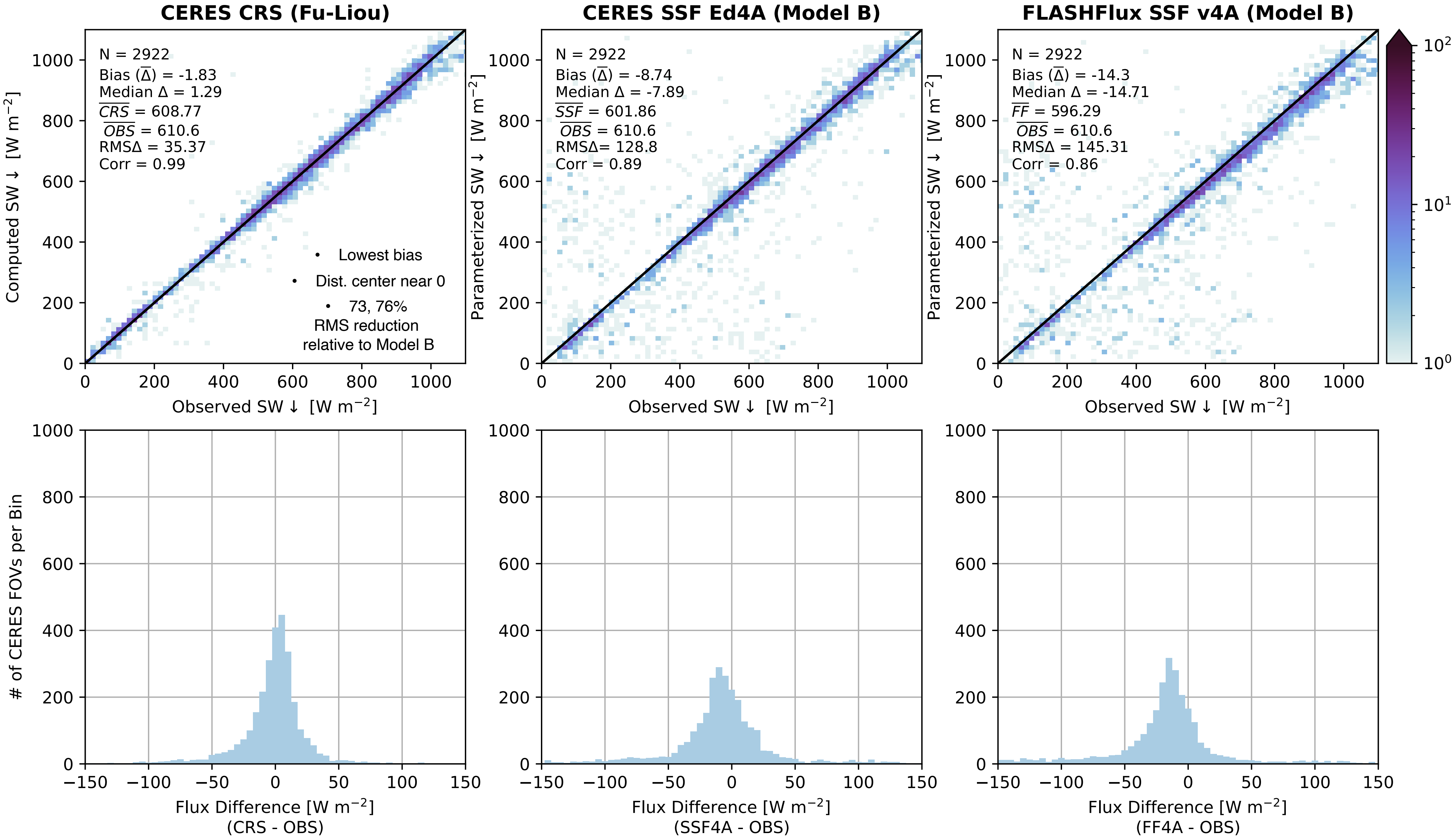
SW↓
Surface Shortwave (SW ↓) Flux Validation
Cloud fraction > 95%
Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - Overcast Sky Conditions
CERES CRS (Fu-Liou)
N = 5572
Bias ($\overline{\Delta}$) = -9.01
Median Δ = -5.14
$\overline{CRS}$ = 262.71
$\overline{OBS}$ = 271.72
RMSΔ = 91.77
Corr = 0.9
• 41, 47% RMS reduction relative to Model B
• 30% higher correlation
Computed SW ↓ [W m^{-2}]
Observed SW ↓ [W m^{-2}]
CERES SSF Ed4A (Model B)
N = 5572
Bias ($\overline{\Delta}$) = 2.41
Median Δ = 5.61
$\overline{SSF}$ = 274.12
$\overline{OBS}$ = 271.72
RMSΔ= 155.51
Corr = 0.73
Parameterized SW ↓ [W m^{-2}]
Observed SW ↓ [W m^{-2}]
FLASHFlux SSF v4A (Model B)
N = 5572
Bias ($\overline{\Delta}$) = 37.5
Median Δ = 27.08
$\overline{FF}$ = 309.22
$\overline{OBS}$ = 271.72
RMSΔ = 174.26
Corr = 0.69
Parameterized SW ↓ [W m^{-2}]
Observed SW ↓ [W m^{-2}]
10^2
10^1
10^0
# of CERES FOVs per Bin
Flux Difference [W m^{-2}]
(CRS - OBS)
Flux Difference [W m^{-2}]
(SSF4A - OBS)
Flux Difference [W m^{-2}]
(FF4A - OBS)
NASA
CERES

SW↓

Surface Shortwave (SW ↓) Flux Validation

Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - Clear Sky Conditions

Cloud fraction < 5%

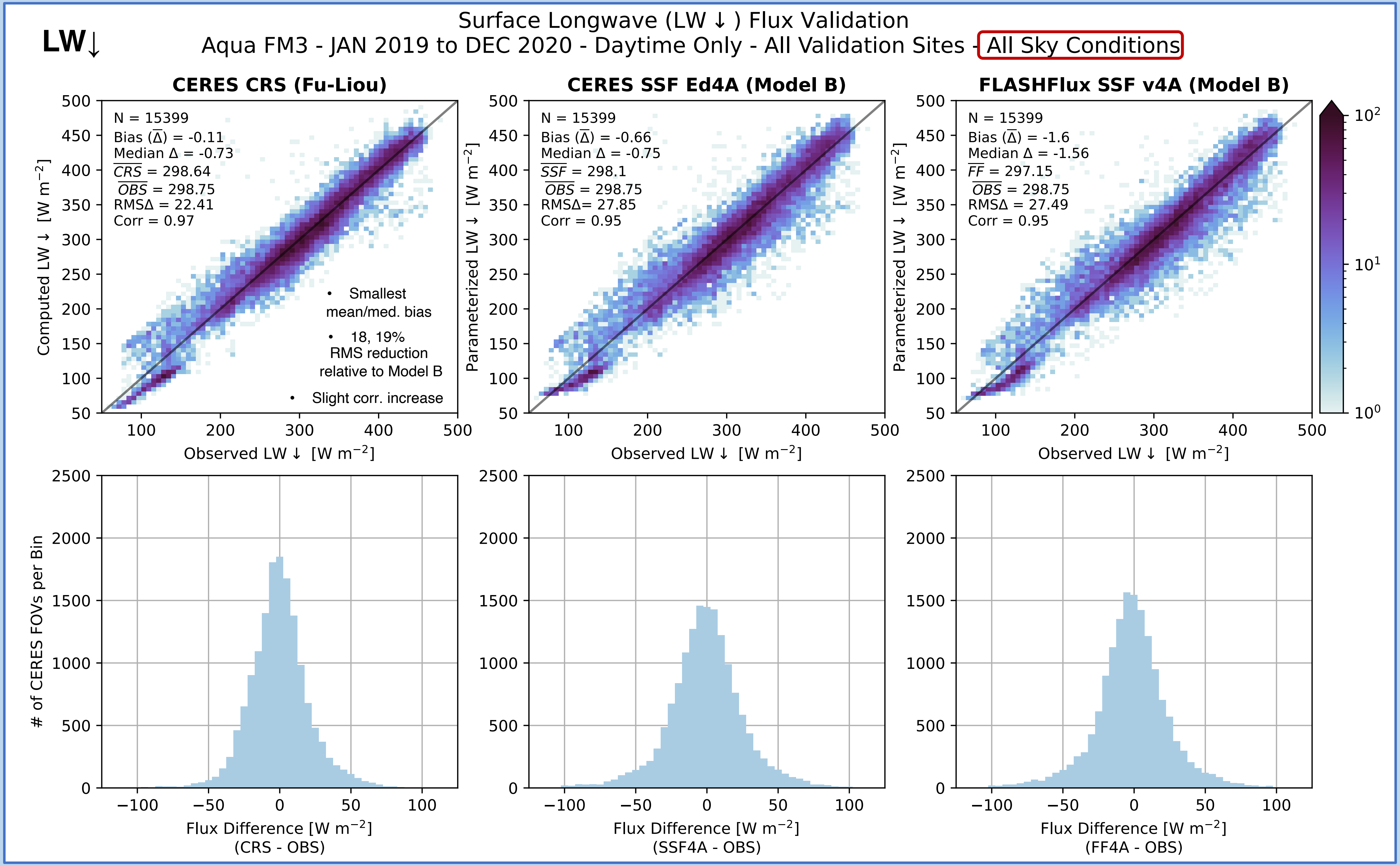


CERES Aqua FM3 Surface SW↓ [W m^{-2}]
CRS vs SOFA Model B (Daytime)

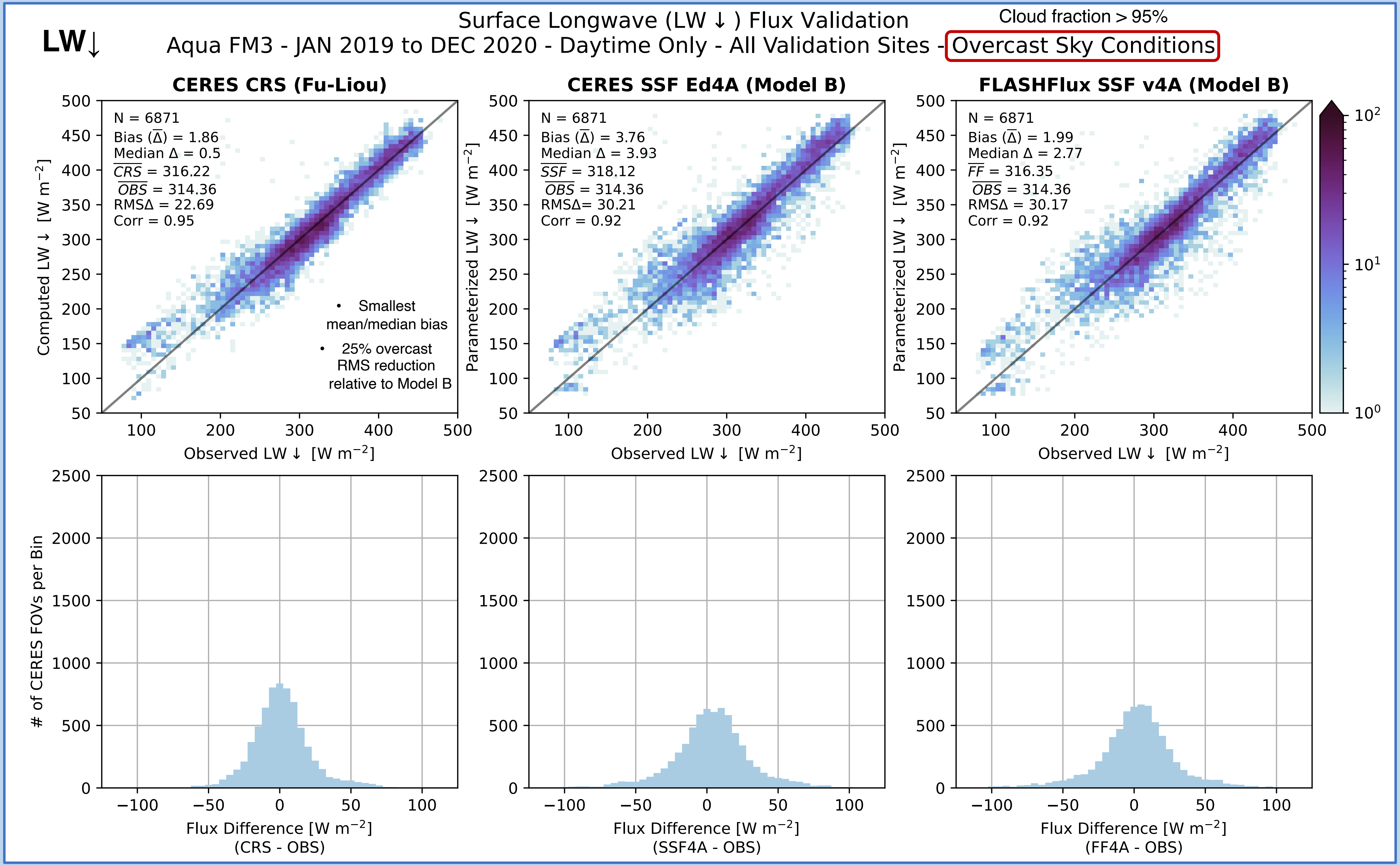
All-sky SW↓	N	Mean Flux	Bias ($\bar{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	12817	441.4, 444.7, 462.7	-5.57, **-2.26**, 15.75	-3.68, -5.16, **-2.68**	**94.34**, 142.06, 153.53	**0.95**, 0.88, 0.86
Coastal	2443	464.8, 482.5, 478.5	**-5.88**, 11.86, 7.83	-8.46, **0.83**, -5.55	**98.99**, 124.70, 135.30	**0.93**, 0.90, 0.87
Desert	822	795.7, 803.4, 791.4	-11.53, **-3.84**, -15.78	-7.33, **-5.13**, -13.96	**75.87**, 86.06, 89.39	**0.93**, 0.91, 0.90
Island	604	644.3, 663.1, 669.9	**53.78**, 72.55, 79.39	**13.95**, 37.24, 43.89	**159.48**, 173.19, 185.85	**0.84**, 0.82, 0.79
Continental	4754	514.5, 524.5, 530.7	**-0.97**, 9.02, 15.15	**-1.10**, 5.28, 2.20	**103.80**, 115.73, 126.82	**0.93**, 0.91, 0.89
Polar	4194	246.1, 230.4, 282.2	**-18.00**, -33.74, 18.05	**-5.14**, -27.20, -8.40	**67.00**, 177.93, 191.32	**0.95**, 0.60, 0.57
Overcast-sky SW↓	N	Mean Flux	Bias ($\bar{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	5572	262.7, 274.1, 309.2	-9.01, **2.41**, 37.50	**-5.14**, 5.61, 27.08	**91.77**, 155.51, 174.26	**0.90**, 0.73, 0.69
Coastal	1197	294.8, 319.0, 321.6	**-3.94**, 20.28, 22.86	**-2.64**, 20.08, 19.58	**86.35**, 136.98, 154.41	**0.92**, 0.80, 0.74
Desert	74	510.3, 548.4, 532.0	-14.59, 23.48, **7.11**	**-4.21**, 27.62, 27.91	**128.00**, 159.50, 166.20	**0.87**, 0.81, 0.78
Island	216	454.7, 480.4, 496.7	**64.94**, 90.64, 106.91	**43.42**, 73.86, 82.93	**163.32**, 186.39, 214.21	**0.81**, 0.78, 0.71
Continental	1862	302.0, 322.3, 336.7	**-0.70**, 19.69, 34.07	**0.96**, 25.61, 35.82	**94.88**, 111.34, 138.11	**0.90**, 0.87, 0.81
Polar	2223	185.7, 180.4, 253.9	**-25.71**, -30.98, 42.53	**-12.47**, -29.07, 14.67	**80.12**, 189.50, 204.75	**0.90**, 0.35, 0.44
Clear-sky SW↓	N	Mean Flux	Bias ($\bar{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	2922	608.7, 601.8, 596.3	**-1.83**, -8.74, -14.30	**1.29**, -7.89, -14.71	**35.37**, 128.80, 145.31	**0.99**, 0.89, 0.86
Coastal	318	663.3, 670.2, 656.5	-4.36, **2.61**, -11.16	**-4.92**, -7.96, -23.97	**31.89**, 132.47, 143.57	**0.99**, 0.78, 0.74
Desert	570	839.8, 837.9, 822.8	**-9.79**, -11.71, -26.78	**-3.49**, -5.67, -15.75	**35.40**, 57.98, 65.70	**0.98**, 0.94, 0.93
Island	41	870.0, 872.2, 860.6	**1.56**, 3.77, -7.85	**-0.20**, 1.66, -4.60	**29.11**, 41.57, 45.45	**0.97**, 0.94, 0.94
Continental	1000	704.8, 699.0, 690.7	4.65, **-1.14**, -9.39	3.00, **-1.19**, -11.11	**39.93**, 61.79, 73.47	**0.98**, 0.95, 0.93
Polar	993	351.3, 335.5, 341.0	**-3.10**, -18.83, -13.36	**2.34**, -16.29, -17.72	**31.56**, 193.26, 218.03	**0.99**, 0.60, 0.49

Cells with multiple entries correspond to

CRS (Fu-Liou), SSF Ed4A (Model B), SSF V4A (Model B)



LW↓
Surface Longwave (LW ↓) Flux Validation
Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - All Sky Conditions
CERES CRS (Fu-Liou)
N = 15399
Bias ($\overline{\Delta}$) = -0.11
Median Δ = -0.73
$\overline{CRS}$ = 298.64
$\overline{OBS}$ = 298.75
RMSΔ = 22.41
Corr = 0.97
• Smallest mean/med. bias
• 18, 19% RMS reduction relative to Model B
• Slight corr. increase
Computed LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
CERES SSF Ed4A (Model B)
N = 15399
Bias ($\overline{\Delta}$) = -0.66
Median Δ = -0.75
$\overline{SSF}$ = 298.1
$\overline{OBS}$ = 298.75
RMSΔ= 27.85
Corr = 0.95
Parameterized LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
FLASHFlux SSF v4A (Model B)
N = 15399
Bias ($\overline{\Delta}$) = -1.6
Median Δ = -1.56
$\overline{FF}$ = 297.15
$\overline{OBS}$ = 298.75
RMSΔ = 27.49
Corr = 0.95
Parameterized LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
10^2
10^1
10^0
# of CERES FOVs per Bin
Flux Difference [W m^{-2}]
(CRS - OBS)
Flux Difference [W m^{-2}]
(SSF4A - OBS)
Flux Difference [W m^{-2}]
(FF4A - OBS)
NASA
CERES



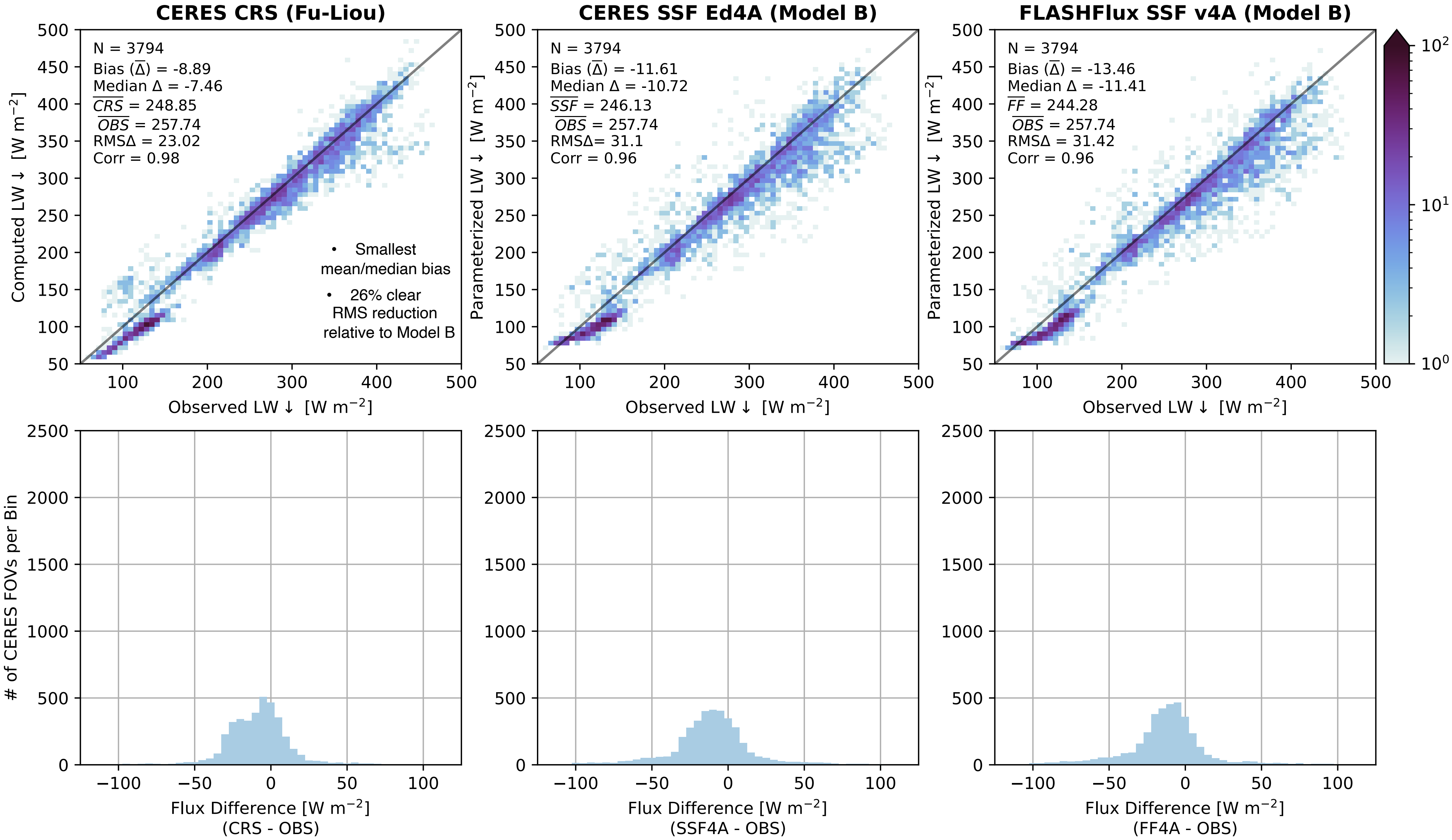
LW↓
Surface Longwave (LW ↓) Flux Validation
Cloud fraction > 95%
Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - Overcast Sky Conditions
CERES CRS (Fu-Liou)
N = 6871
Bias ($\overline{\Delta}$) = 1.86
Median Δ = 0.5
$\overline{CRS}$ = 316.22
$\overline{OBS}$ = 314.36
RMSΔ = 22.69
Corr = 0.95
• Smallest mean/median bias
• 25% overcast RMS reduction relative to Model B
Computed LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
CERES SSF Ed4A (Model B)
N = 6871
Bias ($\overline{\Delta}$) = 3.76
Median Δ = 3.93
$\overline{SSF}$ = 318.12
$\overline{OBS}$ = 314.36
RMSΔ= 30.21
Corr = 0.92
Parameterized LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
FLASHFlux SSF v4A (Model B)
N = 6871
Bias ($\overline{\Delta}$) = 1.99
Median Δ = 2.77
$\overline{FF}$ = 316.35
$\overline{OBS}$ = 314.36
RMSΔ = 30.17
Corr = 0.92
Parameterized LW ↓ [W m^{-2}]
Observed LW ↓ [W m^{-2}]
10^2
10^1
10^0
# of CERES FOVs per Bin
Flux Difference [W m^{-2}] (CRS - OBS)
Flux Difference [W m^{-2}] (SSF4A - OBS)
Flux Difference [W m^{-2}] (FF4A - OBS)

LW↓

Surface Longwave (LW ↓) Flux Validation

Cloud fraction < 5%

Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - Clear Sky Conditions



CERES Aqua FM3 Surface LW↓ [W m^{-2}]
CRS vs SOFA Model B (Daytime)

All-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	15399	298.6, 298.1, 297.2	**-0.11**, -0.66, -1.60	**-0.73**, -0.75, -1.56	**22.41**, 27.85, 27.49	**0.97**, 0.95, 0.95
Coastal	2904	350.5, 346.9, 345.8	4.17, 0.61, **-0.47**	3.26, 1.83, **1.05**	**15.71**, 26.47, 26.09	**0.97**, 0.91, 0.91
Desert	932	335.3, 342.1, 341.0	-16.79, **-9.98**, -11.02	-14.7, -7.24, **-5.12**	**28.63**, 33.68, 31.08	**0.89**, 0.78, 0.82
Island	735	411.3, 414.1, 413.6	**2.17**, 5.01, 4.45	**2.32**, 4.63, 4.51	**14.92**, 18.56, 19.39	**0.84**, 0.82, 0.8
Continental	5251	330.5, 327.6, 325.3	3.30, **0.34**, -1.94	2.12, 1.43, **-0.55**	**22.82**, 27.52, 28.16	**0.93**, 0.9, 0.9
Polar	5577	220.6, 222.3, 223.7	-3.08, -1.46, **-1.09**	-6.65, -4.83, **-4.49**	**24.52**, 28.80, 27.83	**0.95**, 0.93, 0.93
Overcast-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	6871	316.2, 318.1, 316.4	**1.86**, 3.76, 1.99	**0.50**, 3.93, 2.77	**22.69**, 30.21, 30.17	**0.95**, 0.92, 0.92
Coastal	1502	362.0, 362.3, 360.5	3.17, 3.40, **1.66**	**2.72**, 5.63, 4.96	**14.67**, 29.56, 29.36	**0.97**, 0.88, 0.88
Desert	80	372.8, 387.2, 384.2	**0.10**, 14.42, 11.45	**0.88**, 16.83, 17.71	**18.61**, 40.31, 29.96	**0.94**, 0.74, 0.85
Island	275	425.4, 433.1, 433.2	**4.04**, 11.77, 11.80	**4.93**, 12.15, 11.87	**13.86**, 21.49, 22.45	**0.77**, 0.68, 0.64
Continental	2114	342.0, 344.4, 339.8	5.46, 7.89, **3.28**	**3.44**, 8.86, 5.70	**24.46**, 29.98, 32.00	**0.89**, 0.84, 0.81
Polar	2900	261.8, 263.3, 263.4	-1.61, -0.12, **0.03**	-5.06, -3.25, **-2.72**	**25.38**, 31.08, 29.85	**0.92**, 0.87, 0.88
Clear-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	3794	248.9, 246.1, 244.3	**-8.89**, -11.61, -13.46	**-7.46**, -10.72, -11.41	**23.02**, 31.10, 31.42	**0.98**, 0.96, 0.96
Coastal	454	315.5, 302.7, 299.2	**1.38**, -11.36, -14.88	**1.04**, -8.93, -10.37	**11.85**, 40.60, 41.00	**0.98**, 0.77, 0.77
Desert	669	322.2, 326.9, 325.8	-21.56, **-16.83**, -17.95	-18.32, -12.37, **-9.77**	**31.08**, 35.13, 32.77	**0.86**, 0.74, 0.79
Island	48	385.8, 380.5, 380.5	**0.60**, -4.73, -4.67	**-1.46**, -6.87, -7.03	**9.21**, 12.81, 14.47	**0.92**, 0.90, 0.88
Continental	1233	303.9, 295.9, 293.0	**-4.28**, -12.32, -15.23	**-2.40**, -7.25, -9.47	**20.61**, 28.67, 31.70	**0.94**, 0.91, 0.89
Polar	1390	138.2, 140.0, 139.2	-10.55, **-8.78**, -9.57	-16.39, **-14.03**, -14.23	**23.57**, 27.79, 27.02	**0.93**, 0.88, 0.90

Cells with multiple entries correspond to

CRS (Fu-Liou), SSF Ed4A (Model B), SSF V4A (Model B)

CERES Aqua FM3 Surface LW↓ & SW↓ [W m^{-2}]
CRS vs SOFA Clear-Sky Model A

Day Clear-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	1718	236.0, 232.4, 232.2	**-11.58**, 15.15, 15.43	**-11.80**, -13.09, -14.04	**22.17**, 26.29, 25.94	**0.99**, 0.98, 0.98
Coastal	110	305.8, 284.5, 285.0	**1.45**, -19.83, -19.32	**2.00**, -4.87, -5.18	**10.63**, 38.34, 37.21	**0.98**, 0.77, 0.78
Desert	473	323.5, 331.7, 330.0	-18.12, **-9.94**, -11.62	-17.27, -5.75, **-5.50**	**25.19**, 26.07, 26.86	**0.91**, 0.80, 0.79
Island	11	385.3, 374.5, 371.9	**1.31**, -9.47, -12.13	**-2.80**, -13.36, -13.75	**11.90**, 15.90, 17.05	**0.86**, 0.84, **0.86**
Continental	492	298.2, 293.9, 300.9	**-2.71**, -7.02, -8.11	**-1.83**, -2.67, -3.05	**16.20**, 22.40, 22.24	**0.96**, 0.93, 0.94
Polar	632	107.4, 98.8, 100.1	**-16.09**, -24.66, -23.36	**-21.1**, -24.69, -23.35	**25.21**, 26.82, 25.65	0.86, **0.95**, **0.95**
Night Clear-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	2287	186.7, 187.1, 187.3	13.57, -13.17, **-12.96**	-13.85, **-12.82**, -13.33	**18.84**, 21.81, 21.17	**0.99**, **0.99**, **0.99**
Coastal	180	281.4, 278.0, 287.1	**-5.76**, -9.12, -7.10	-6.28, -6.67, **-5.44**	**12.79**, 21.82, 21.11	**0.98**, 0.92, 0.92
Desert	289	297.5, 305.2, 305.7	-16.81, -9.10, **-8.56**	-13.88, -14.59, **-10.99**	**25.35**, 30.67, 26.98	**0.84**, 0.71, 0.77
Island	24	387.4, 378.1, 377.7	**3.20**, -6.06, -6.47	**4.12**, -4.34, -5.26	**7.86**, 9.83, 11.37	**0.92**, 0.90, 0.87
Continental	768	268.2, 267.6, 269.5	-9.96, -10.55, **-8.57**	-8.57, -8.34, **-7.84**	**15.54**, 20.15, 18.40	**0.97**, 0.94, 0.95
Polar	1026	73.2, 73.2, 71.7	**-17.11**, -17.14, -18.66	-17.25, **-15.56**, -16.75	**20.00**, 20.14, 21.44	**0.87**, 0.82, 0.82
Day Clear-sky SW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	1426	645.0, 625.8	**0.01**, -19.25	**3.21**, -10.40	**36.70**, 113.85	**0.99**, 0.91
Coastal	83	631.9, 672.0	**-2.74**, 37.35	-1.65, **-0.63**	**20.03**, 154.83	**0.99**, 0.68
Desert	430	843.5, 826.7	**-11.15**, -27.99	**-5.78**, -10.87	**37.20**, 73.88	**0.98**, 0.91
Island	10	907.9, 924.0	**9.10**, 25.12	**7.90**, 25.76	**15.93**, 28.99	**0.99**, **0.99**
Continental	475	693.6, 687.8	8.48, **2.69**	5.63, **-1.97**	**49.19**, 59.53	**0.97**, 0.95
Polar	428	388.2, 339.2	**2.15**, -46.84	**4.44**, -61.26	**18.14**, 170.59	**1.0**, 0.7

Cells with multiple entries correspond to

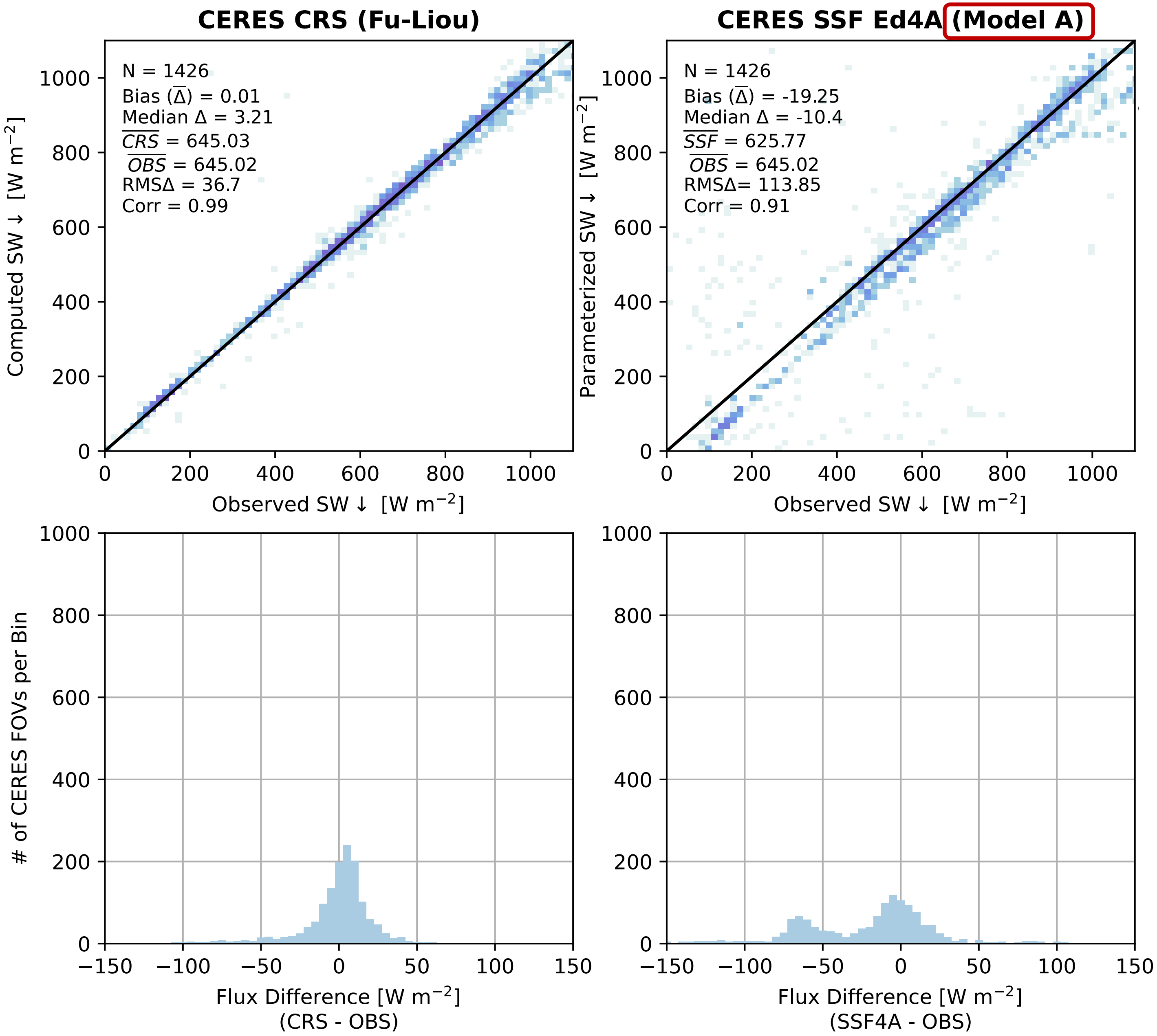
CRS (Fu-Liou), SSF Ed4A (Model A), SSF V4A (Model A)

SW↓

Surface Shortwave (SW ↓) Flux Validation

Cloud fraction = 0%

Aqua FM3 - JAN 2019 to DEC 2020 - Daytime Only - All Validation Sites - Clear Sky Conditions



- SW Model A is only for clear footprints
- FLASHFlux does not run SW Model A
- CRS eliminates a large systematic bias present in SW Model A
- Model A flux Δ histogram is bimodal while CRS's is approx. normal
- CRS exhibits a 67% drop in RMSΔ
  - from ~114 to 37 W m^{-2}
  - 8% higher correlation

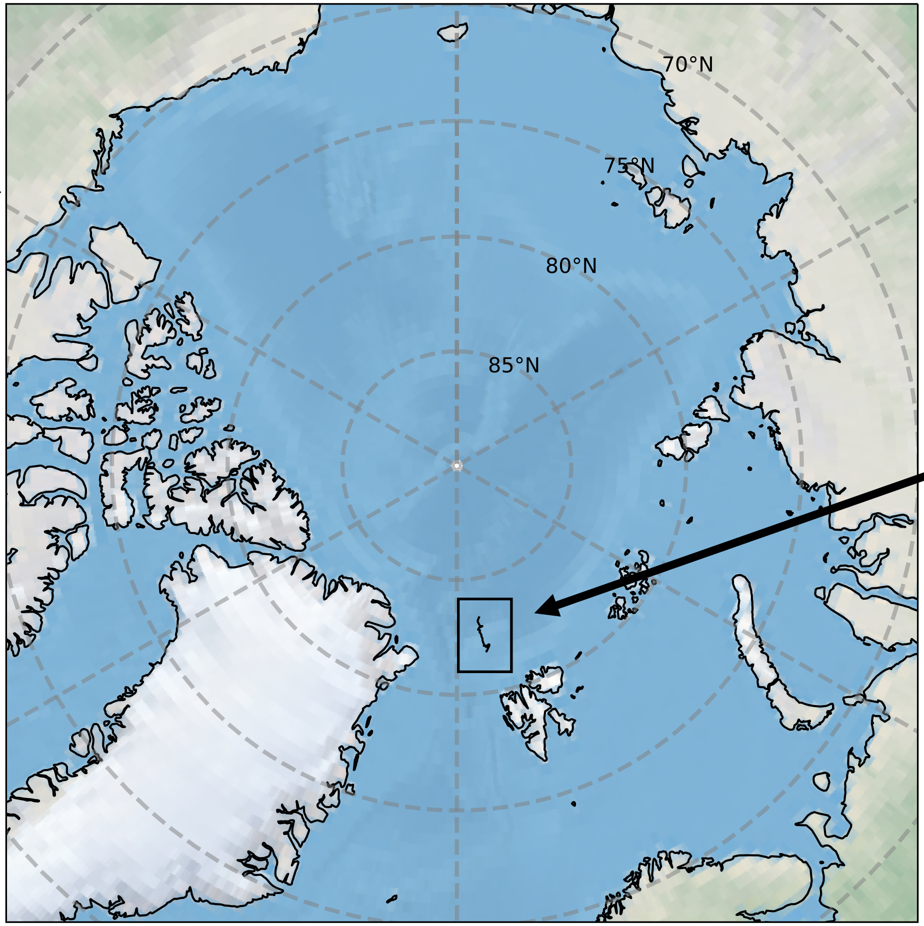
CERES Aqua FM3 Surface LW↓ [W m^{-2}]
CRS vs SOFA All-Sky LW Model C

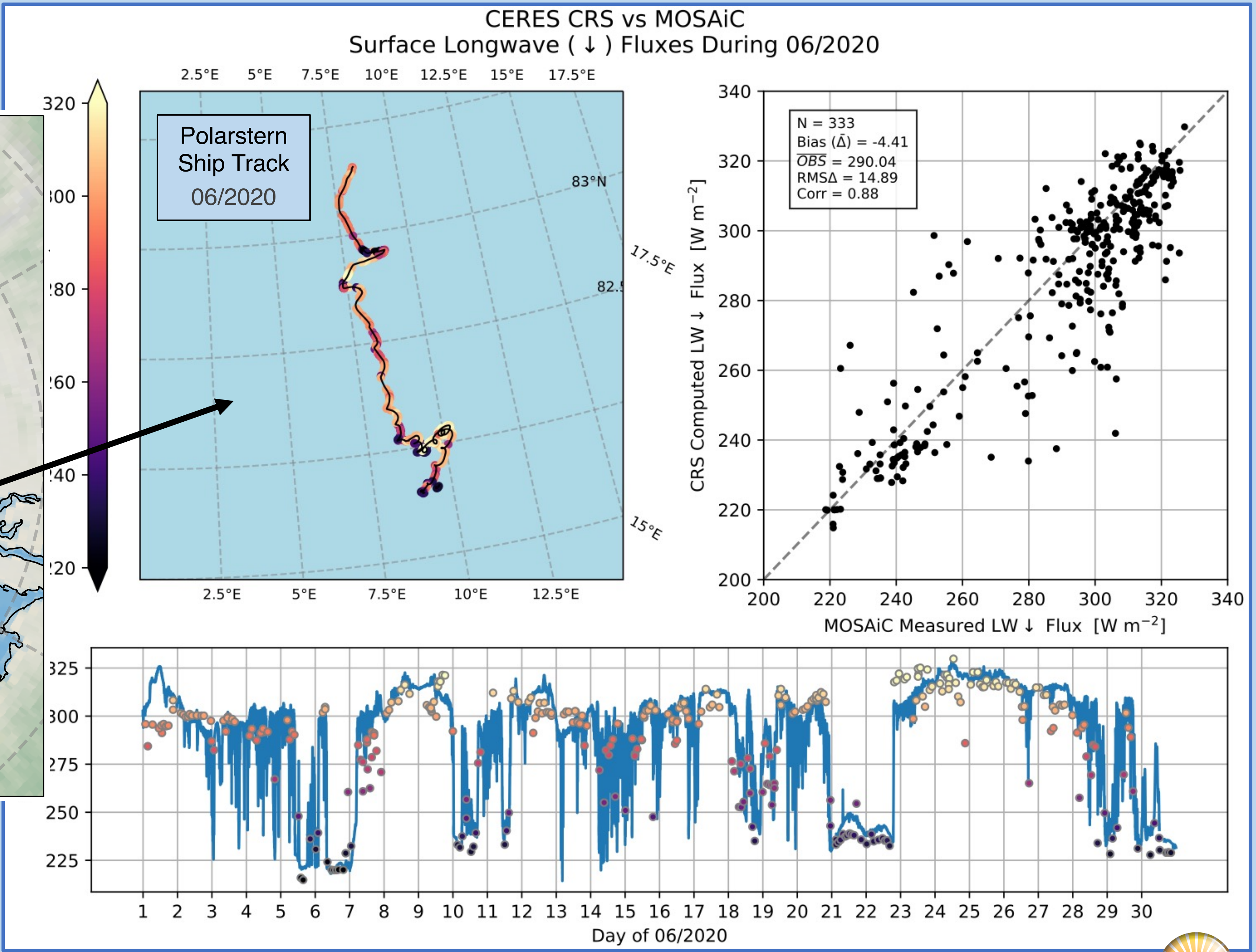
All-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	15298	298.9, 297.1	**-0.07**, -1.87	**-0.70**, -1.27	**22.45**, 26.63	**0.97**, 0.95
Coastal	2874	351.2, 344.0	4.27, **-2.85**	3.34, **-2.25**	**15.73**, 25.67	**0.97**, 0.91
Desert	916	335.6, 334.6	**-16.65**, -17.7	-14.65, **-12.14**	**28.61**, 35.87	**0.88**, 0.77
Island	734	411.3, 405.0	**2.18**, -4.13	**2.32**, -4.21	**14.93**, 15.77	**0.84**, 0.82
Continental	5520	330.9, 326.7	3.36, **-0.87**	2.19, **0.38**	**22.89**, 27.46	**0.93**, 0.89
Polar	5554	220.8, 224.5	-3.10, **0.61**	-6.69, **0.04**	**24.55**, 25.66	**0.95**, 0.94
Overcast LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	6877	316.3, 311.7	**1.86**, -2.66	**0.50**, -4.45	**22.68**, 28.03	**0.95**, 0.93
Coastal	1503	362.0, 354.4	**3.16**, -4.45	**2.70**, -4.24	**14.67**, 28.14	**0.97**, 0.89
Desert	80	372.8, 372.1	**0.10**, -0.58	**0.88**, 3.67	**18.61**, 30.95	**0.94**, 0.74
Island	275	425.4, 417.5	4.04, **-3.87**	4.93, **-4.79**	**13.86**, 14.90	**0.77**, 0.71
Continental	2118	342.1, 338.9	5.50, **2.25**	3.47, **1.53**	**24.47**, 28.61	**0.89**, 0.84
Polar	2901	261.8, 258.1	**-1.64**, -5.26	**-5.10**, -9.20	**25.36**, 28.42	**0.92**, 0.89
Clear-sky LW↓	N	Mean Flux	Bias ($\overline{\Delta}$)	Median Δ	RMSΔ	Correlation (r)
Global	3679	248.2, 252.3	-9.00, **-4.62**	-7.62, **-0.17**	**23.18**, 29.96	**0.98**, 0.96
Coastal	423	317.8, 309.5	**1.91**, -6.35	**1.18**, -1.99	**11.65**, 39.21	**0.98**, 0.75
Desert	653	322.3, 321.2	**-21.52**, -22.63	-18.27, **-16.14**	**31.12**, 38.58	**0.86**, 0.71
Island	47	385.9, 383.0	**0.73**, -2.19	**-1.43**, -3.45	**9.27**, 9.86	**0.92**, 0.91
Continental	1194	304.6, 300.5	**-4.35**, -8.44	**-2.33**, -2.40	**20.86**, 29.16	**0.94**, 0.89
Polar	1362	136.9, 155.5	-10.80, **7.81**	-16.60, **7.03**	23.68, **22.02**	**0.93**, 0.91

Cells with multiple entries correspond to

CRS (Fu-Liou), SSF Ed4A (Model C)

Arctic Summer CRS Surface LW↓ Flux Validation @ MOSAiC





- MOSAiC measured surface fluxes in the high Arctic from the Polarstern icebreaker from 09/2019-10/2020 (Shupe et al. 2022)

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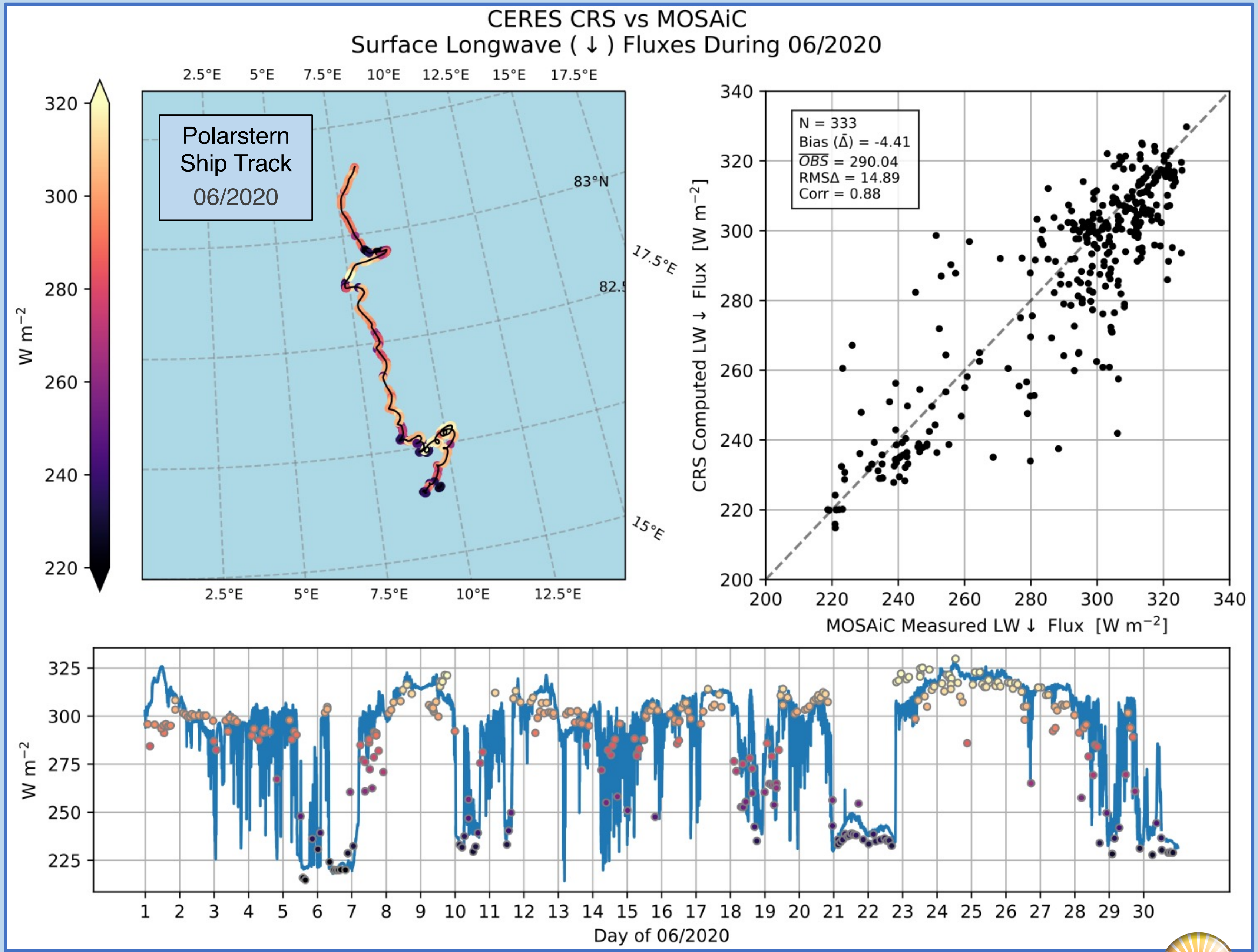
Arctic Summer CRS Surface LW↓ Flux Validation @ MOSAiC

- CRS surface LW↓ from *Terra* FM1 & *Aqua* FM3 vs pyrgeometer measurements
- CRS captures the variations in LW↓
- Small mean LW↓ bias of -4.4 W m^{-2}
- Lower RMS**Δ** (14 W m^{-2}!) than typically seen at routine surface measurement sites



Spring 2022 CERES Science Team Meeting
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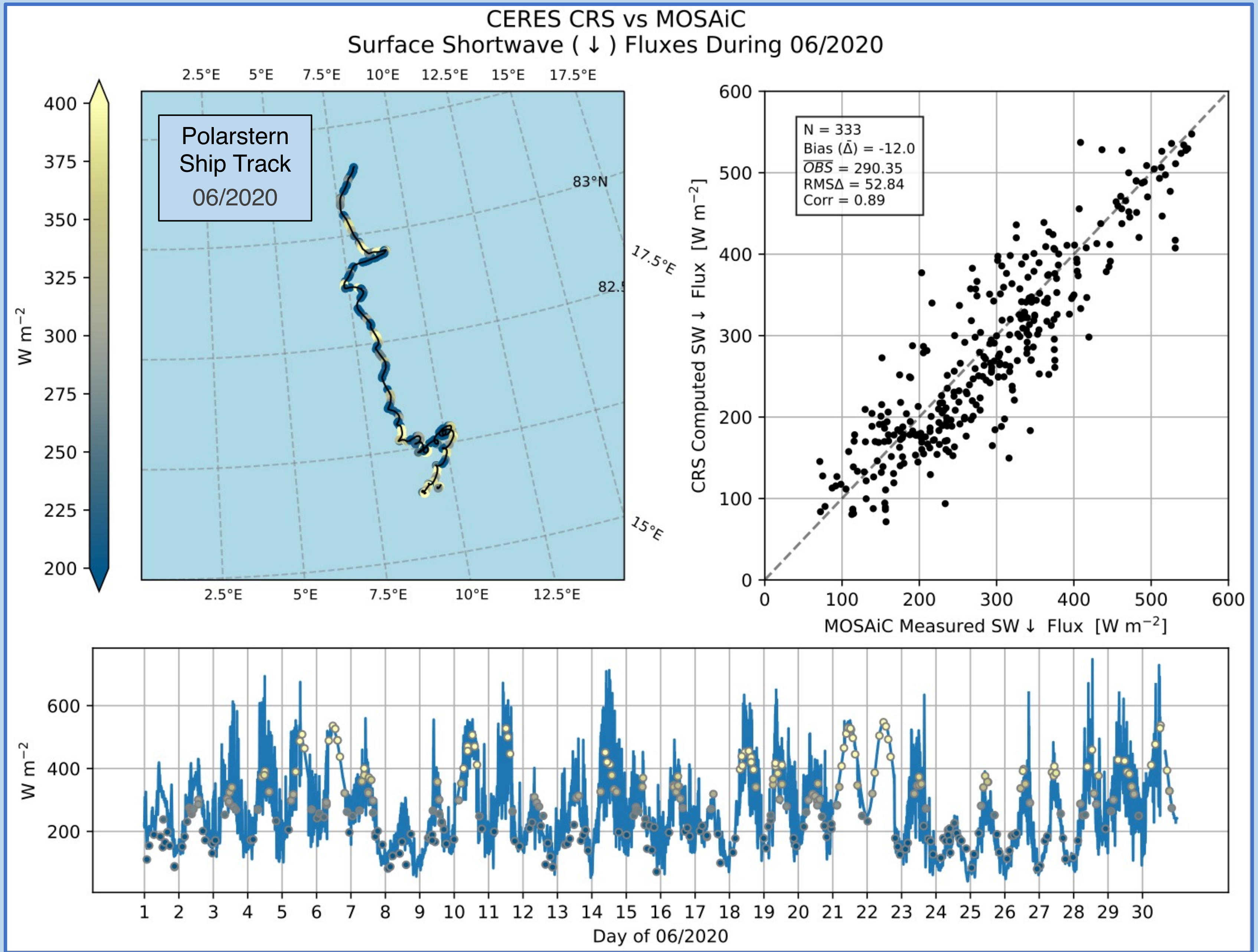
Arctic Summer CRS Surface SW↓ Flux Validation @ MOSAiC

- CRS surface SW↓ from *Terra* FM1 & *Aqua* FM3 *vs* unshaded PSP measurements (Shupe et al. 2022)
- Small mean bias of -12 W m^{-2} consistent w/ well documented Ed4A polar cloud optical depth bias
- Lower RMS**Δ** than typical at routine surface measurement sites



Spring 2022 CERES Science Team Meeting
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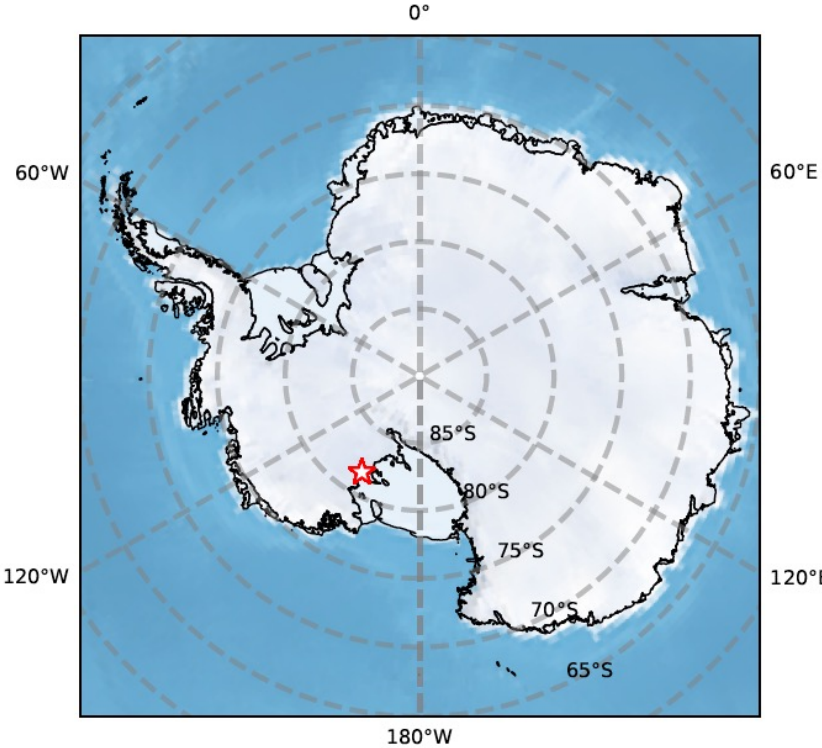
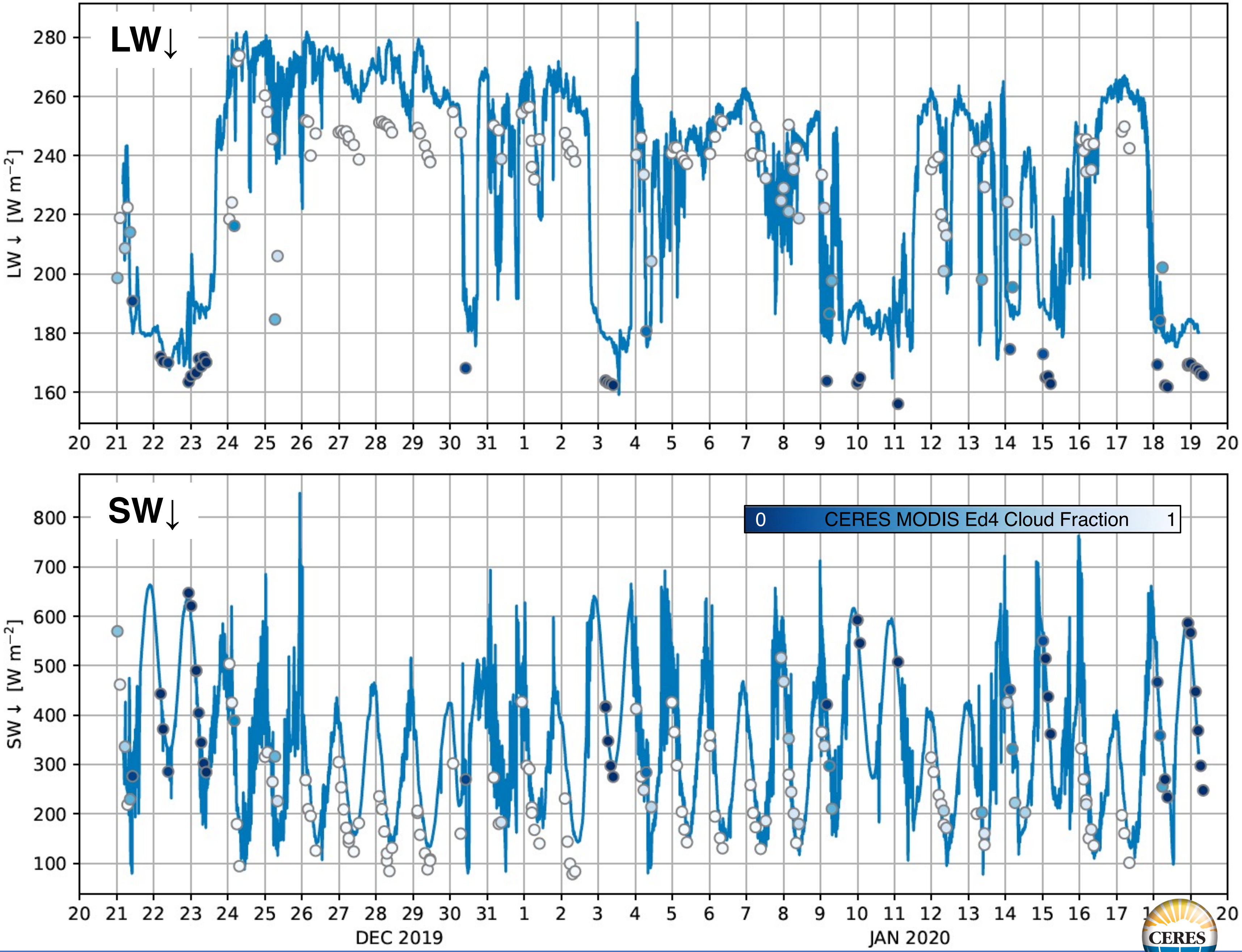
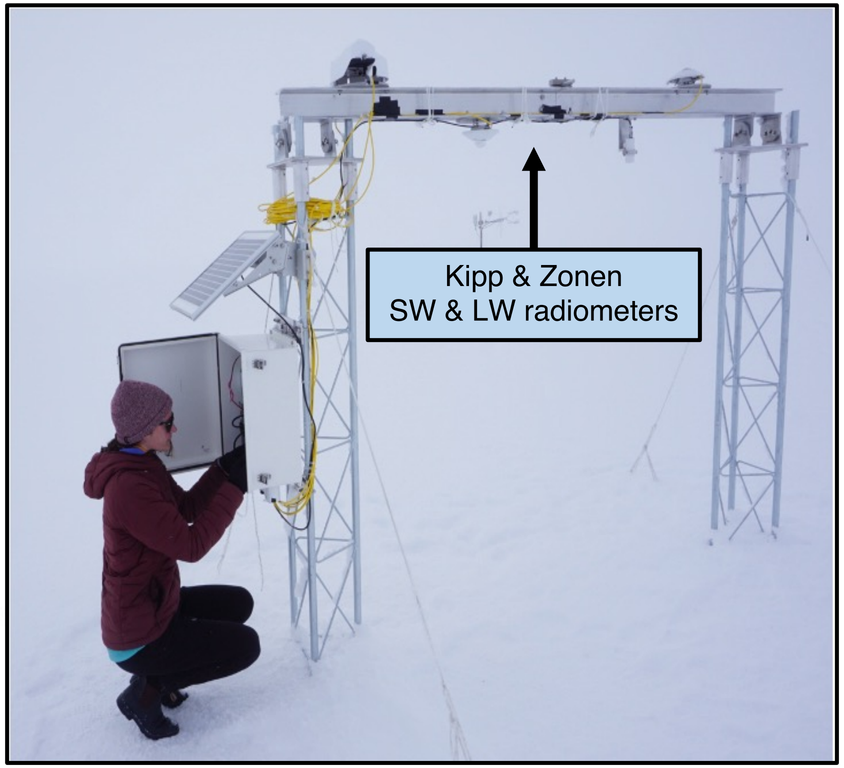
Antarctic Summer CRS Surface Flux Validation @ Siple Dome

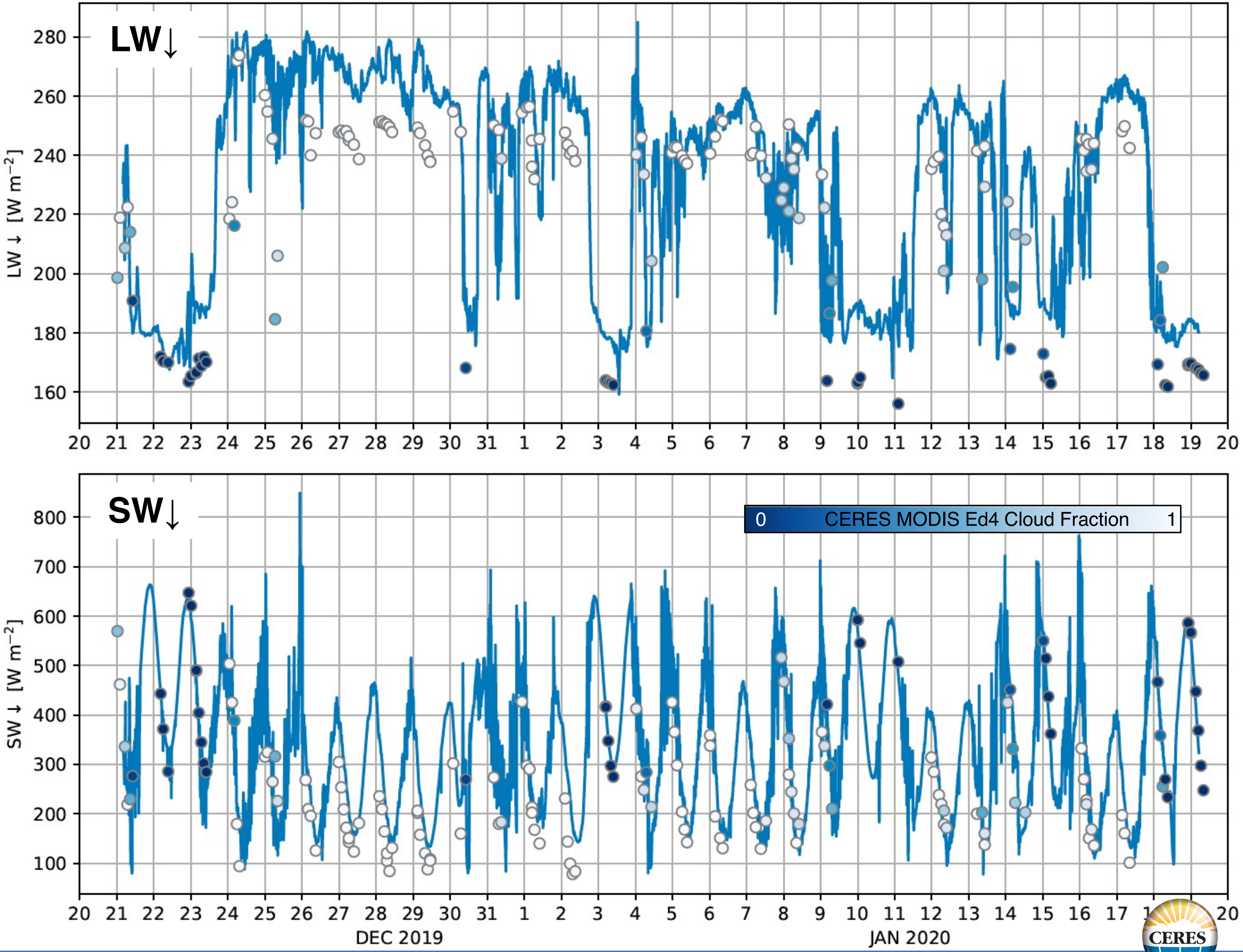




- Lubin et al. measurements (Scripps/UCSD)
- Good clear-sky SW↓, cloudy LW↓, but…
  - Occasional cloud base height errors?
  - Clear-sky LW↓ : unresolved surface $dT/dz > 0$
  - Excessive cloud optical depth (expect to be resolved in Ed5)

Antarctic Summer CRS Surface Flux Validation @ Siple Dome





- Lubin et al. measurements (Scripps/UCSD)
- Good clear-sky SW↓, cloudy LW↓, but…
  - Occasional cloud base height errors?
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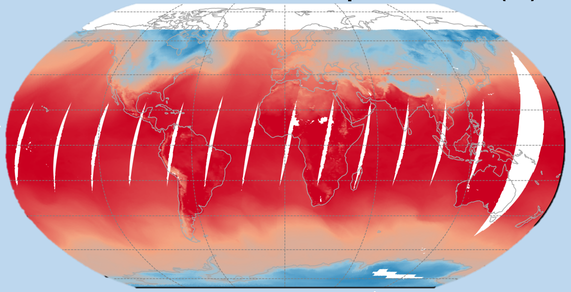
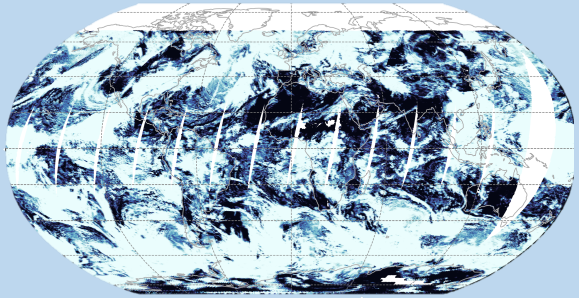
  - Excessive cloud optical depth (expect to be resolved in Ed5)

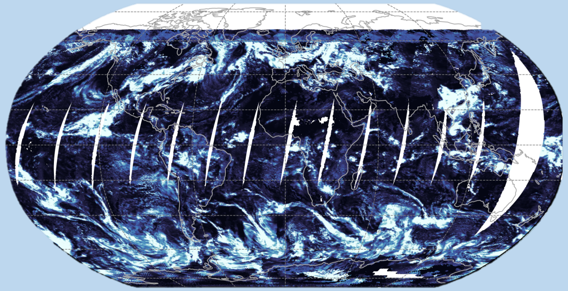
Eff. Emission Temperature (T)



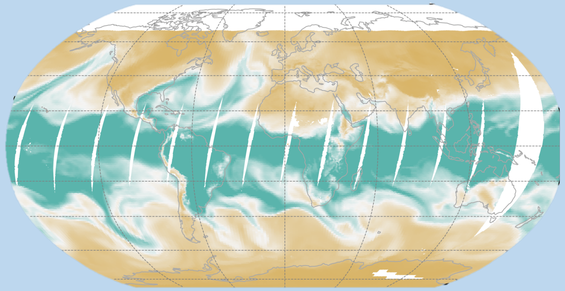
Cloud Fraction (CF)



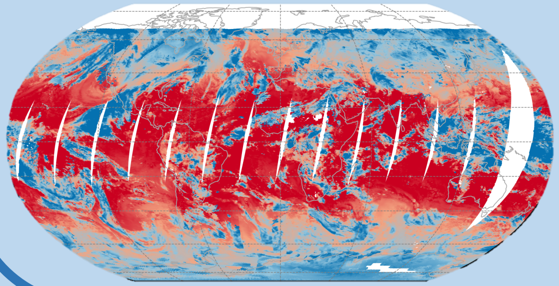
Cloud Optical Depth (COD)



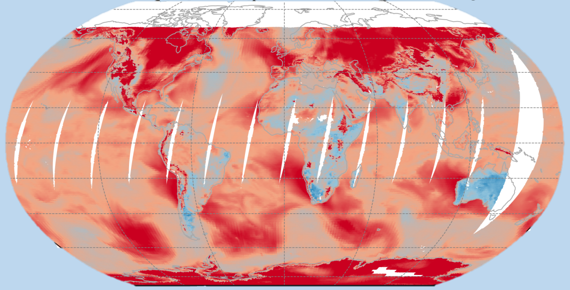
Precipitable Water Vapor (PWV)



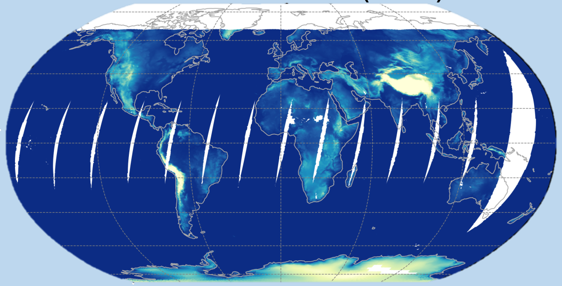
Eff. Cloud Temperature (CT)



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

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

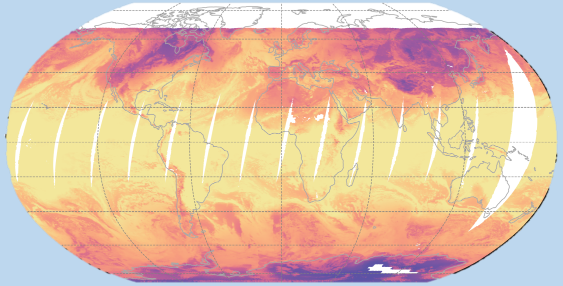
<u>Supervised ML Algorithms</u>:

Random Forest

Deep Neural Network

XGBoost

Surface Longwave Flux (LW↓)

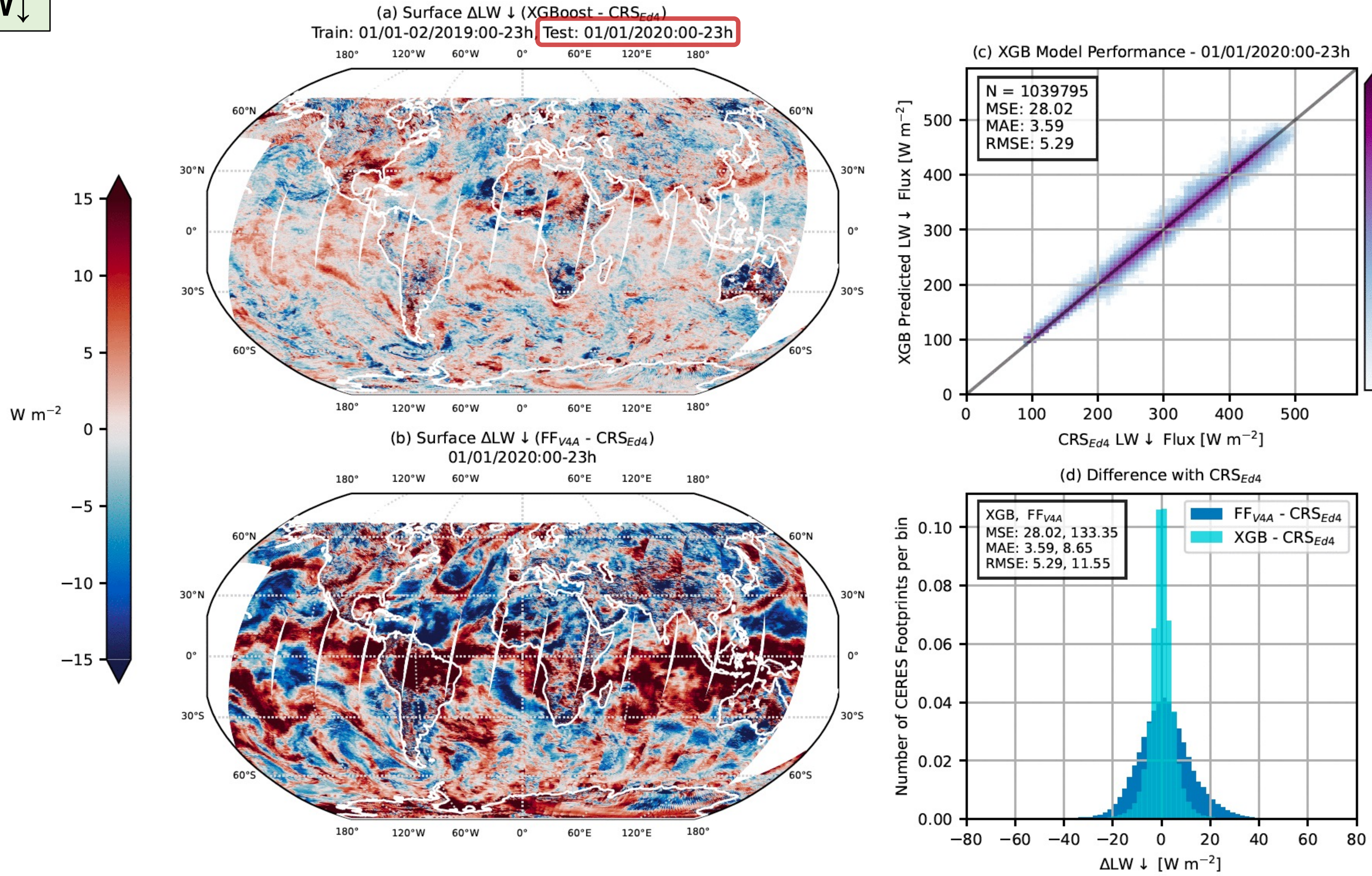


- Standardize $\mathbf{X}$ prior to training
- Train on day & night footprints for multiple days from same month of the previous year
- Evaluate generalization performance & tune hyperparameters using:

K-Fold Cross Validation (CV)

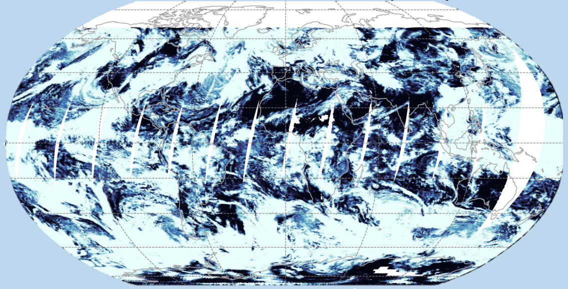
Randomized Grid Search CV

LW↓

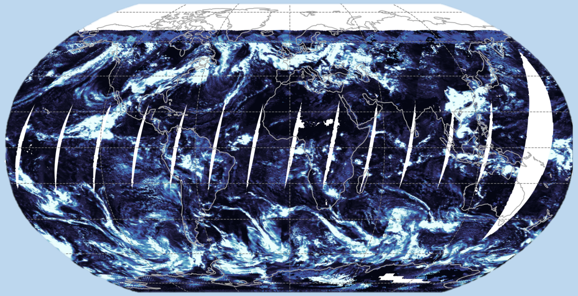


(a) Surface ΔLW ↓ (XGBoost - CRS$_{Ed4}$)
Train: 01/01-02/2019:00-23h Test: 01/01/2020:00-23h
(b) Surface ΔLW ↓ (FF$_{V4A}$ - CRS$_{Ed4}$)
01/01/2020:00-23h
W m^{-2}
(c) XGB Model Performance - 01/01/2020:00-23h
N = 1039795
MSE: 28.02
MAE: 3.59
RMSE: 5.29
XGB Predicted LW ↓ Flux [W m^{-2}]
CRS$_{Ed4}$ LW ↓ Flux [W m^{-2}]
(d) Difference with CRS$_{Ed4}$
XGB, FF$_{V4A}$
MSE: 28.02, 133.35
MAE: 3.59, 8.65
RMSE: 5.29, 11.55
FF$_{V4A}$ - CRS$_{Ed4}$
XGB - CRS$_{Ed4}$
Number of CERES Footprints per bin
ΔLW ↓ [W m^{-2}]

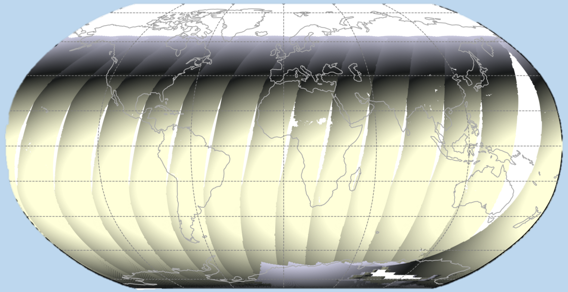
Cloud Fraction (CF)



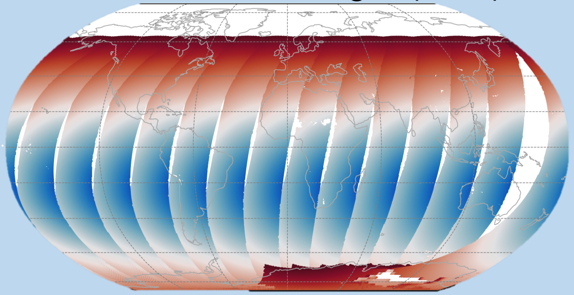
Cloud Optical Depth (COD)



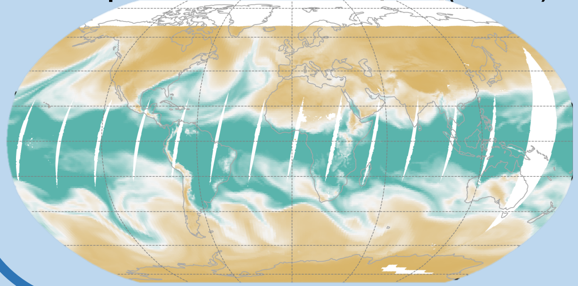
TOA Insolation (INS)



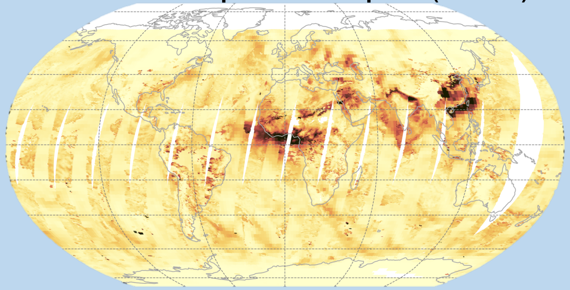
Solar Zenith Angle (SZA)



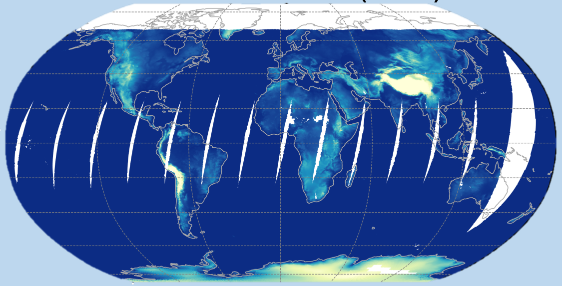
Precipitable Water Vapor (PWV)



Aerosol Optical Depth (AOD)



Surface Altitude (ALT)



- Provides functional mappings between meteorological parameters

$\mathbf{X} =$

INS, SZA, CF, COD, AOD, PWV, ALT

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

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

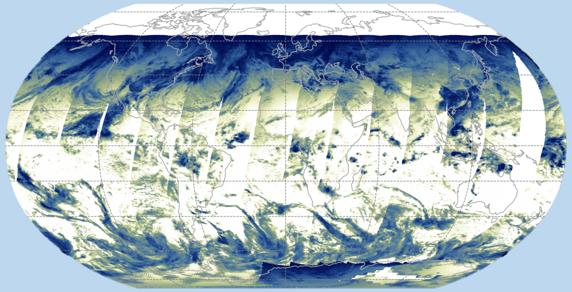
Supervised ML Algorithms:

Random Forest

Deep Neural Network

XGBoost

Surface Shortwave Flux (SW↓)

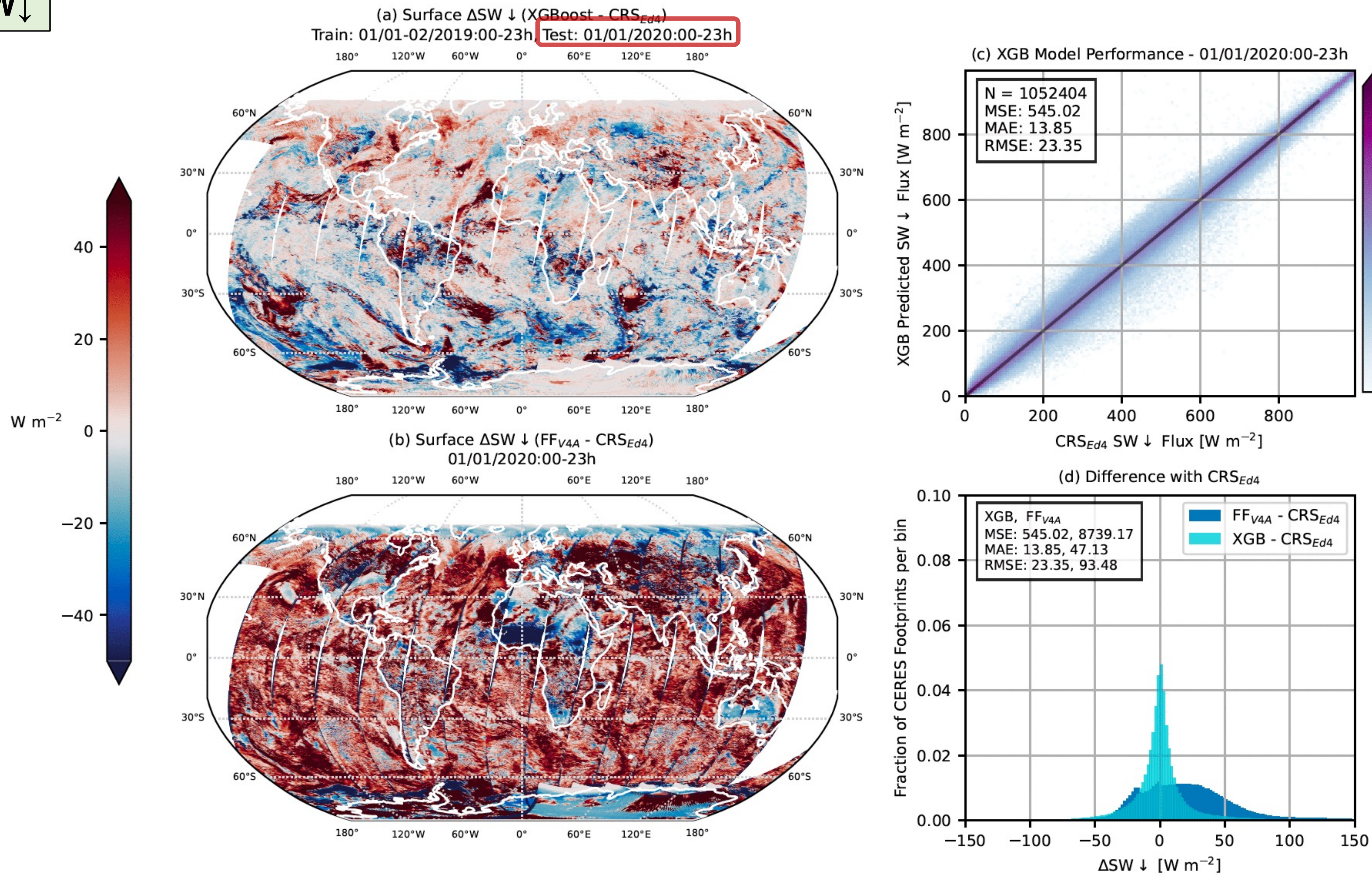


- Standardize **X** prior to training
- Train using multiple days of daytime footprints only from same month of the previous year
- Evaluate generalization performance & tune hyperparameters using:

K-Fold Cross Validation (CV)

Randomized Grid Search CV

SW↓


(a) Surface ΔSW ↓ (XGBoost - CRS$_{Ed4}$)
Train: 01/01-02/2019:00-23h, Test: 01/01/2020:00-23h
(b) Surface ΔSW ↓ (FF$_{V4A}$ - CRS$_{Ed4}$)
01/01/2020:00-23h
W m^{-2}
(c) XGB Model Performance - 01/01/2020:00-23h
N = 1052404
MSE: 545.02
MAE: 13.85
RMSE: 23.35
XGB Predicted SW ↓ Flux [W m^{-2}]
CRS$_{Ed4}$ SW ↓ Flux [W m^{-2}]
(d) Difference with CRS$_{Ed4}$
XGB, FF$_{V4A}$
MSE: 545.02, 8739.17
MAE: 13.85, 47.13
RMSE: 23.35, 93.48
FF$_{V4A}$ - CRS$_{Ed4}$
XGB - CRS$_{Ed4}$
Fraction of CERES Footprints per bin
ΔSW ↓ [W m^{-2}]

Summary & Outlook

- CRS generally outperforms SOFA parameterizations available on the CERES/FLASH SSF products (Ed4A, v4A)
  - Based upon comprehensive validation & comparisons to SOFA Models A, B, & C at a network of 40 surface sites
  - CRS SW↓ & LW↓ fluxes show lower RMS**Δ** & higher corr. w/ measurements – independent of sky conditions & surface type
  - In some places/conditions, CRS is often but not always less biased, highlighting a need to refine the CRS flux algorithm
  - Comparisons with remote polar field measurements in the Arctic & Antarctica show impressive performance

- Scott, R. C., F. G. Rose, P. W. Stackhouse, Jr., N. G. Loeb, S. Kato, D. R. Doelling, D. A. Rutan, P. C. Taylor, W. L. Smith, Jr. (2022), Clouds & the Earth's Radiant Energy System (CERES) Cloud Radiative Swath (CRS) Edition 4 Data Product, *Journal of Atmospheric & Oceanic Technology, in review*

- We've successfully tuned machine learning model hyperparameters & developed a scalable method to provide CRS-quality surface ↓ radiative fluxes in near real-time on the FLASHFlux SSF
  - Need near real-time fluxes during May 2022? Use models trained on CRS computations for May 2021
  - Tuned XGBoost SW↓ & LW ↓ fluxes are > 50% closer (global MAE, RMSE) to CRS than FF SSF Model B fluxes are
  - Beginning to work w/ FLASHFlux team to integrate models into production
  - *Next steps:* (1) predict fluxes in near real-time using FLASHFlux-derived meteorological predictors $\mathbf{X}_{\mathbf{FLASH}}$
    (2) validate the fluxes to confirm performance enhancements & refine algorithms as necessary

- CRS data will be released (ahead of schedule) as part of Ed4 for a 5-year period (2017-2021)
  - Terra FM1 & Aqua FM3 data will be accompanied by the above publication & Data Quality Summary (in progress)
  - Thank You!

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Extra Slides

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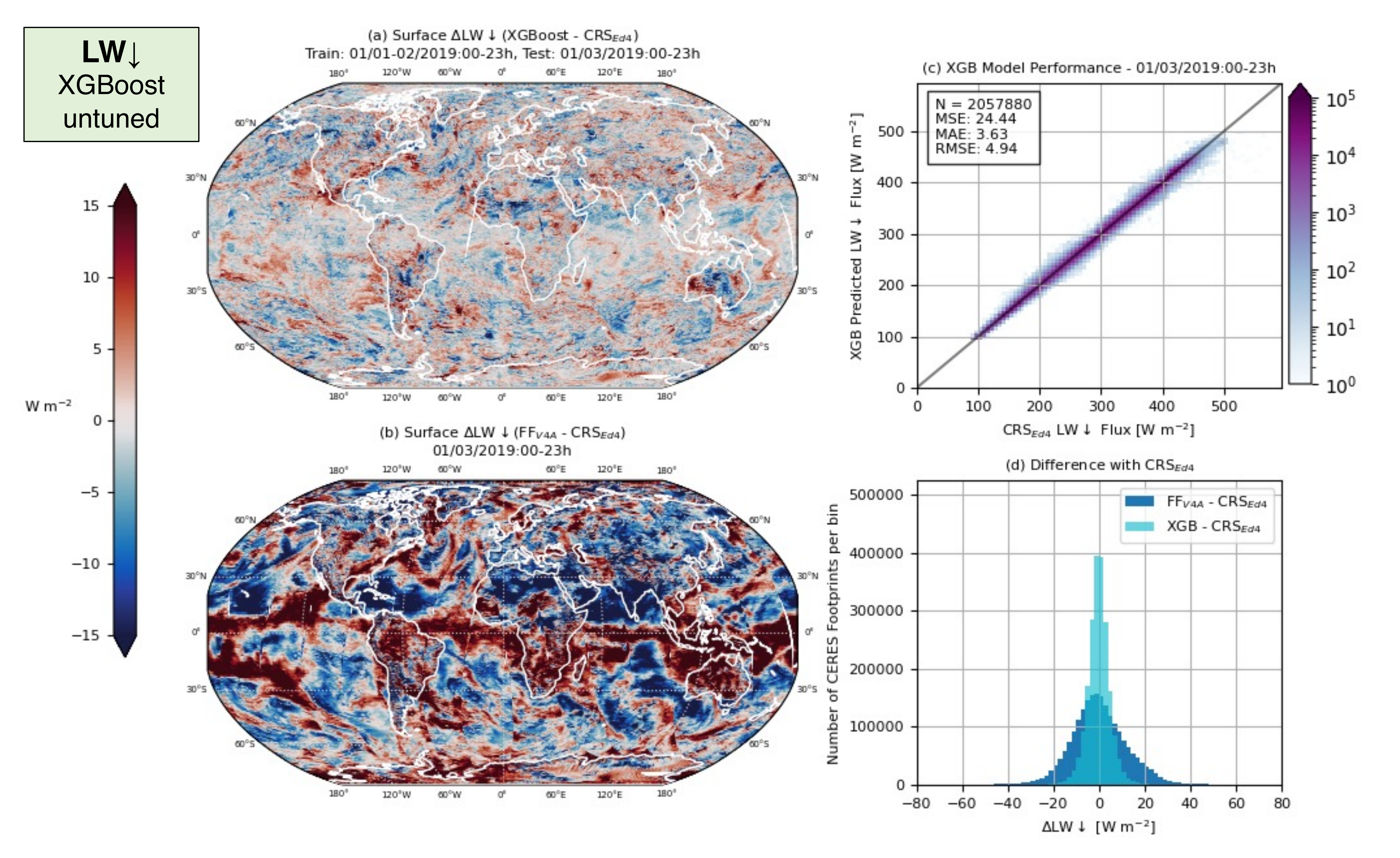
LW↓
XGBoost
untuned
(a) Surface ΔLW ↓ (XGBoost - CRS$_{Ed4}$)
Train: 01/01-02/2019:00-23h, Test: 01/03/2019:00-23h
(b) Surface ΔLW ↓ (FF$_{V4A}$ - CRS$_{Ed4}$)
01/03/2019:00-23h
W m^{-2}
15
10
5
0
−5
−10
−15
(c) XGB Model Performance - 01/03/2019:00-23h
N = 2057880
MSE: 24.44
MAE: 3.63
RMSE: 4.94
XGB Predicted LW ↓ Flux [W m^{-2}]
CRS$_{Ed4}$ LW ↓ Flux [W m^{-2}]
(d) Difference with CRS$_{Ed4}$
FF$_{V4A}$ - CRS$_{Ed4}$
XGB - CRS$_{Ed4}$
Number of CERES Footprints per bin
ΔLW ↓ [W m^{-2}]
CERES

LW↓
XGBoost
tuned