

Calibration and validation of global horizontal irradiance clear sky models against McClear clear sky model in Morocco

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Abstract: The study calibrates and compares the capabilities of hourly global horizontal irradiance (GHI) clear sky models for six Moroccan locations, using the McClear clear sky model as a reference. Complex clear sky models namely: Bird, Simplified Solis, Ineichen & Perez; Simple clear sky models namely: Adnot-Bourges-Campana-Gicquel (ABCG), Berger-Duffie and Haurwitz; SOLCAST satellite-based dataset estimates were validated against McClear clear sky model. Pvlib-python was used to configure the models, and ERA5 hourly fractional cloud cover was used to identify clear sky days. The study period was from 2014 to 2021 and the study sites were in different climatic regions in Morocco. Bar graphs, tables and the quantitative statistical metrics namely relative Mean Bias Error (rMBE), relative Root Mean Square Error (rRMSE), relative Mean Absolute Error (rMAE) and the coefficient of determination (R^2) were used to quantify the skill of the clear sky model at different sites. The overall rMBE was negative in 5/6 sites, indicating consistent overestimation of GHI, and positive in Tantan (14.4%), indicating frequent underestimation of GHI. Overall rRMSE varied from 6–22% suggesting a strong agreement between clear sky models and McClear clear sky model. The overall correlation was greater than 0.96, indicating a very strong relationship. Overall, the Bird clear sky model proved to be the most feasible. Complex clear sky models outperformed simple clear sky models. The SOLCAST satellite-based dataset and ERA5 cloud fraction information could well be used with quantifiable certainty as an accurate clear sky model in the study region and in other areas where complex clear sky models' inputs are not available.

Keywords: Clear sky model; global horizontal irradiance; calibration, validation; solar energy applications; Pvlib-python, SOLCAST, Fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5); statistical metrics.

Citation: Mendyl, A.; Mabasa, B.; Bouzghiba, H.; Weidinger, T. Calibration and Validation of Global Horizontal Irradiance Clear Sky Models against McClear Clear Sky Model in Morocco. *Appl. Sci.* **2023**, *13*, 320. <https://doi.org/10.3390/app13010320>

Academic Editors: Harry D. Kambezidis and Basil Psiloglou

Received: 19 October 2022

Revised: 19 December 2022

Accepted: 22 December 2022

Published: 27 December 2022



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Table S1. Clear sky model predicted irradiance versus McClear model prediction at Marrakech station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation mean	Model mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R ²
Bird	518.06	501.4	-16.67	-3.22	21.72	4.19	17.68	3.41	0.999
Solis	518.06	489.82	-28.24	-5.45	36.78	7.1	28.25	5.45	0.997
Ineichen & Perez	518.06	471.66	-46.40	-8.96	51.99	10.04	46.61	8.99	0.998
SOLCAST	518.06	496.29	-21.77	-4.2	28.2	5.44	23.23	4.48	0.999
Haurwitz	518.06	494.14	-23.92	-4.62	39.82	7.69	32.14	6.2	0.995
Berger-Duffie	518.06	475.41	-42.65	-8.23	69.24	13.36	56.02	10.81	0.994
ABCG	518.06	443.15	-74.91	-14.46	90.29	17.43	76.08	14.69	0.994

Table S2. Clear sky model predicted irradiance versus McClear model prediction at Fes station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation	Model Mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R ²
Bird	494.69	482.84	-11.85	-2.4	14.96	3.02	12.65	2.56	0.999
Solis	494.69	484.59	-10.1	-2.04	16.56	3.35	11.62	2.35	0.999
Ineichen & Perez	494.69	474.13	-20.56	-4.16	28.17	5.69	22.7	4.59	0.999
SOLCAST	494.69	495.02	0.33	0.07	48.84	9.87	35.28	7.13	0.985
Haurwitz	494.69	464.66	-30.03	-6.07	39.69	8.02	32.64	6.6	0.997
Berger-Duffie	494.69	449.76	-44.93	-9.08	68.91	13.93	55.18	11.16	0.997
ABCG	494.69	494.69	78.67	18.91	92.36	22.20	79.01	18.99	0.996

Table S3. Clear sky model predicted irradiance versus McClear model prediction at Agadir station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation Mean	Model Mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R2
Bird	485.91	468.64	-17.26	-3.55	28.63	5.89	19.41	3.99	0.997
SOLIS	485.91	443.38	-42.52	-8.75	61.67	12.69	42.52	8.75	0.988
Ineichen & Perez	485.91	465.69	-20.21	-4.16	30.31	6.24	24.54	5.05	0.997
SOLCAST	485.91	461.29	-24.62	-5.07	39.09	8.04	25.84	5.32	0.995
Haurwitz	485.91	468.77	-17.13	-3.53	37.35	7.69	30.02	6.18	0.994
Berger-Duffie	485.91	452.92	-32.98	-6.79	63.47	13.06	50.93	10.48	0.993
ABCG	485.91	419.79	-66.11	-13.61	83.81	17.25	68.53	14.10	0.993

Table S4. Clear sky model predicted irradiance versus McClear model prediction at Tangier station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation	Model mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R2
Bird	545.24	525.21	-20.02	-3.67	22.76	4.17	20.51	3.76	0.999
Solis	545.24	516.61	-28.62	-5.25	34.62	6.35	28.63	5.25	0.999
Ineichen & Perez	545.24	533.11	-12.13	-2.22	21.48	3.94	17.94	3.29	0.999
SOLCAST	545.24	526.32	-18.92	-3.47	23.24	4.26	19.57	3.59	0.999
Haurwitz	545.24	532.79	-12.45	-2.28	29.72	5.45	23.37	4.29	0.997
Berger-Duffie	545.24	516.61	-28.62	-5.25	34.62	6.35	28.62	5.25	0.999
ABCG	545.24	480.12	-65.11	-11.94	79.57	14.59	66.49	12.19	0.996

Table S5. Clear sky model predicted irradiance versus McClear model prediction at Ouarzazate station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation	Model mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R ²
Bird	518.26	463.56	-54.7	-10.55	64.8	12.50	56.95	10.99	0.994
Solis	518.26	450.71	-67.56	-13.03	77.63	14.98	68.69	13.25	0.995
Ineichen & Perez	518.26	461.6	-56.66	-10.93	67.64	13.05	59.09	11.40	0.995
SOLCAST	518.26	450.27	-67.99	-13.12	105.55	20.37	71.97	13.89	0.963
Haurwitz	518.26	454.86	-63.40	-12.23	81.37	15.70	69.23	13.36	0.987
Berger-Duffie	518.26	440.97	-77.3	-14.91	104.2	20.11	87.16	16.82	0.987
ABCG	518.26	407.34	-110.92	-21.40	130.81	25.24	113.26	21.85	0.98

Table S6. Clear sky model predicted irradiance versus McClear model prediction at Tantan station, with validation metrics. The colours in the table are used to indicate the clear model skill in estimating GHI based statistical metrics with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Model	Observation	Model mean	MBE	rMBE	RMSE	rRMSE	MAE	rMAE	R ²
Bird	379.50	452.26	72.75	19.17	97.49	25.69	82.61	21.77	0.968
Solis	379.50	423.04	43.54	11.47	89.27	23.52	74.32	19.58	0.948
Ineichen & Perez	379.50	445.26	65.76	17.33	88.83	23.41	75.15	19.8	0.971
SOLCAST	379.50	460.85	81.35	21.44	106.04	27.94	90.49	23.84	0.966
Haurwitz	379.50	439.83	60.33	15.89	81.17	21.39	67.02	17.66	0.975
Berger-Duffie	379.50	428.39	48.89	12.88	75.42	19.87	60.12	15.84	0.973
ABCG	379.50	392.44	12.94	3.41	54.91	14.47	43.86	11.56	0.977

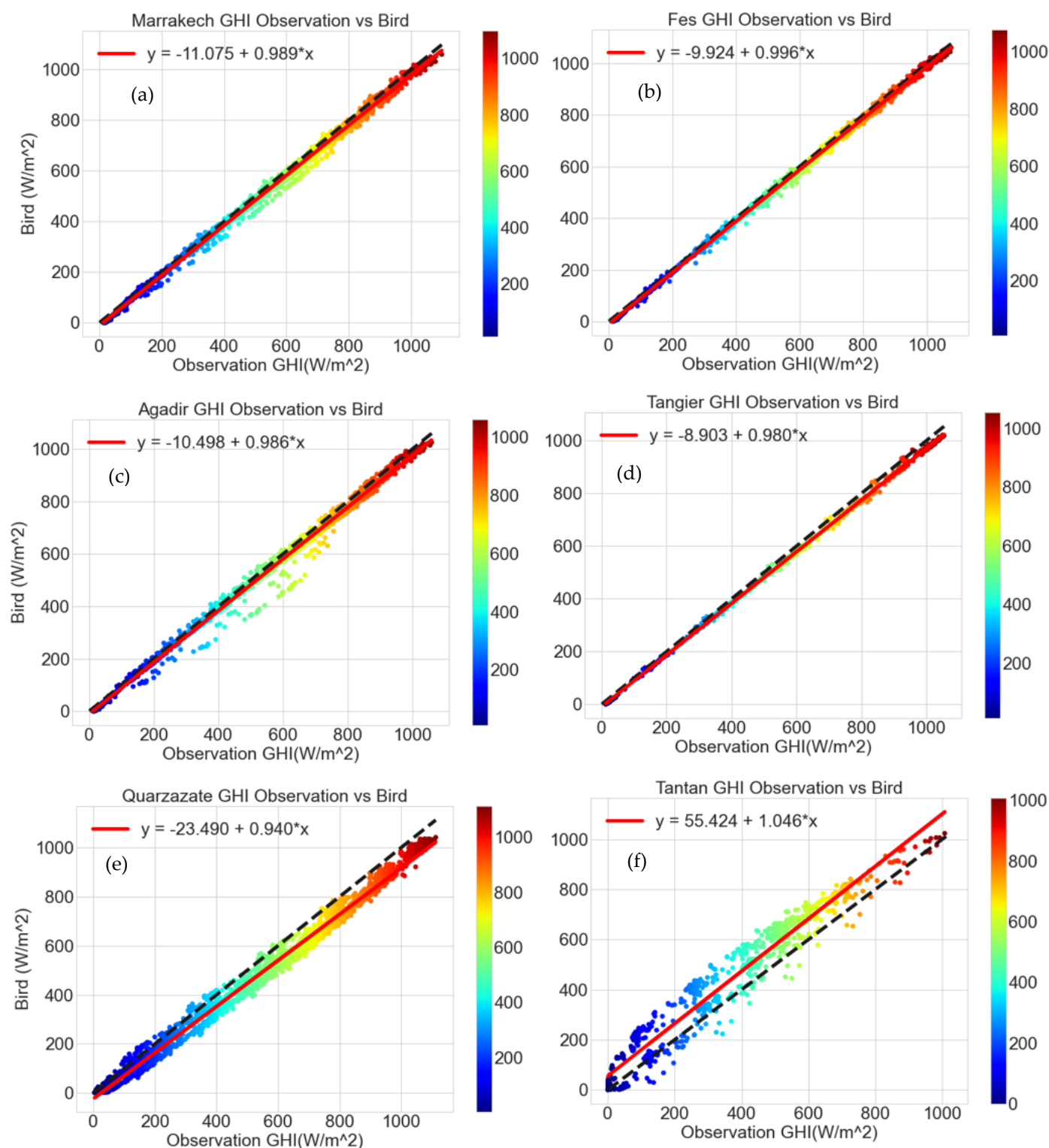


Figure S1. Scatter plot of McClear modelled hourly GHI and Bird clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

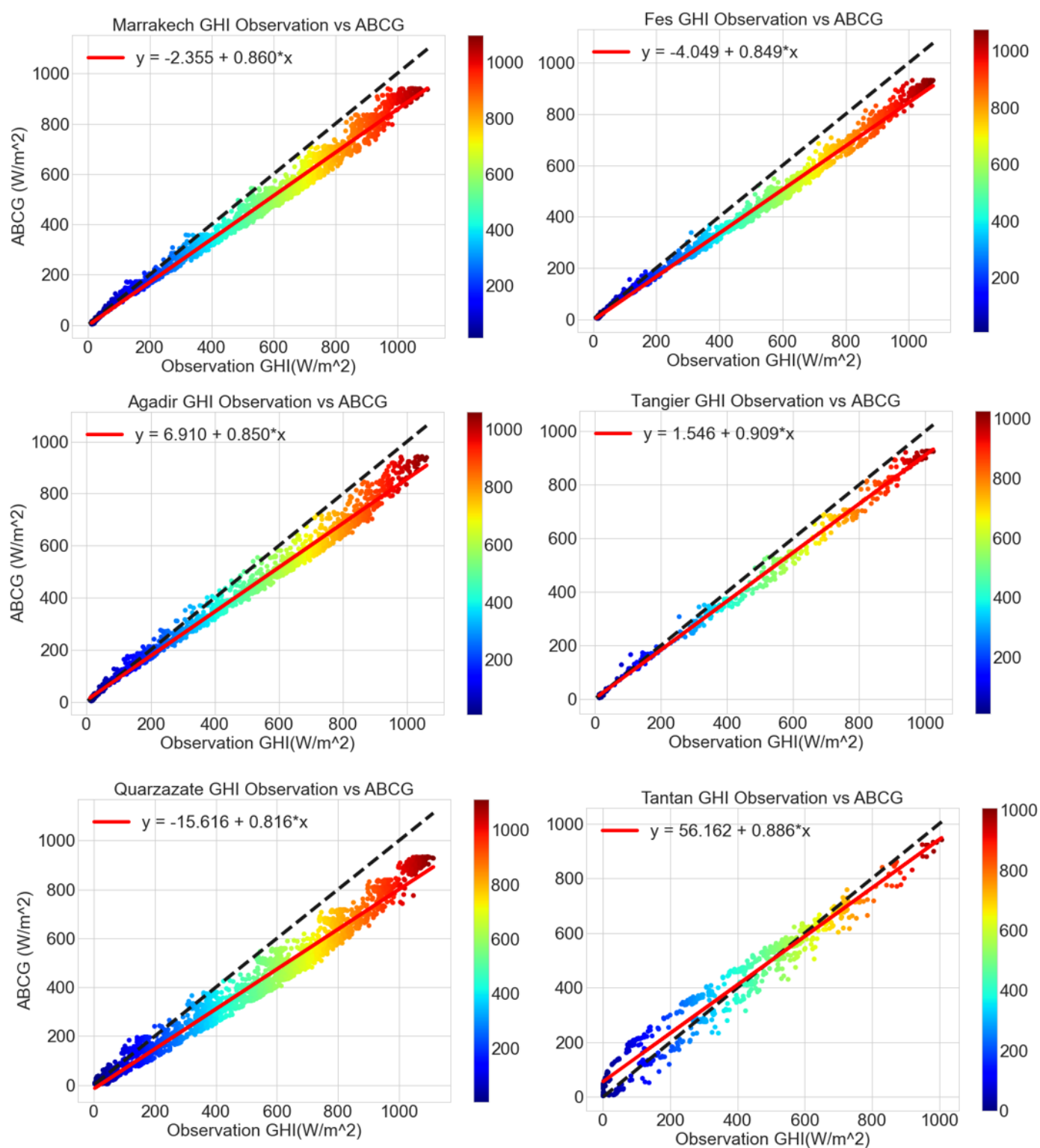


Figure S2. Scatter plot of McClear modelled hourly GHI and Adnot-Bourges-Campana-Gicquel (ABCG) clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

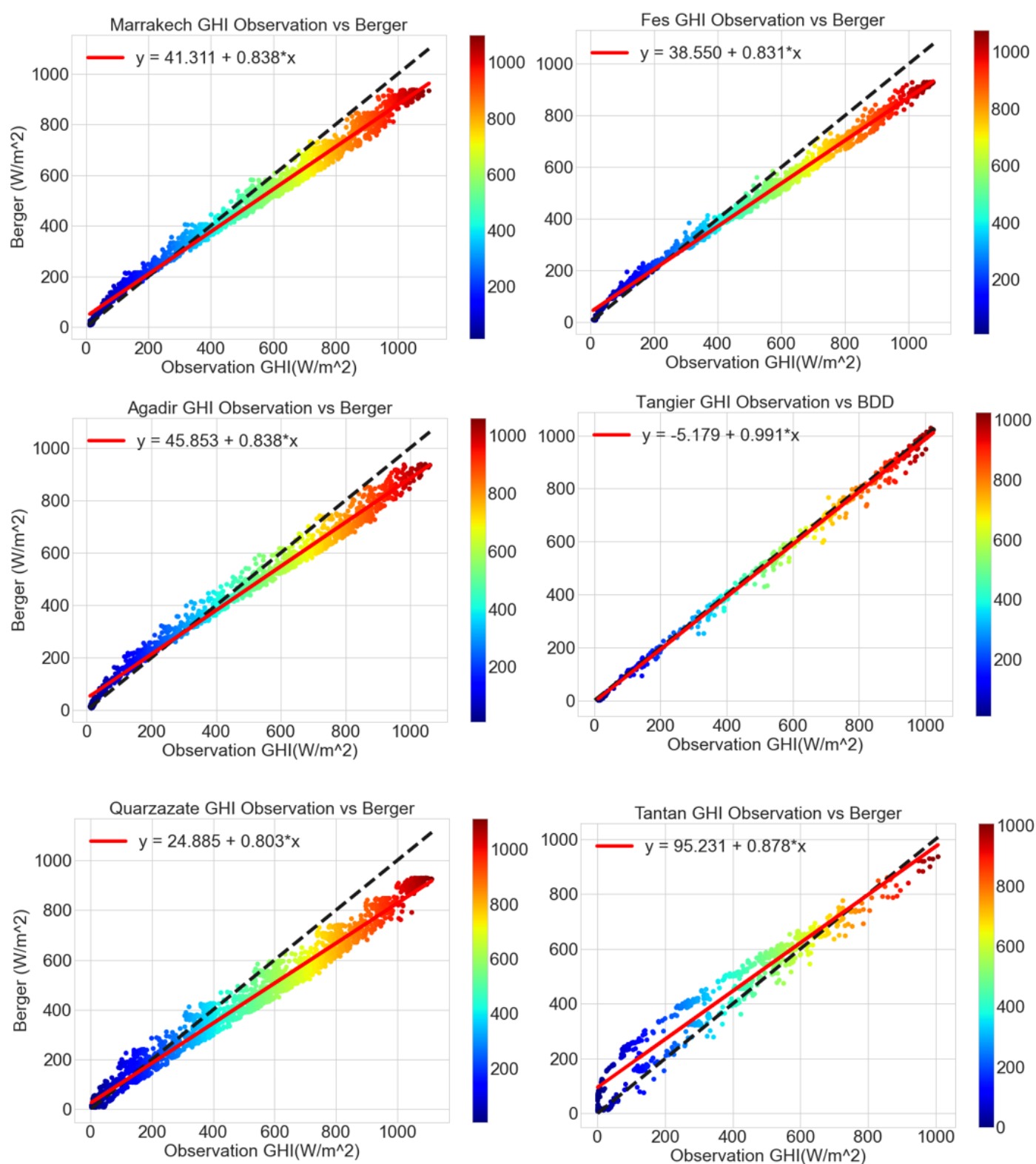


Figure S3. Scatter plot of McClear modelled hourly GHI and Berger-Duffie clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

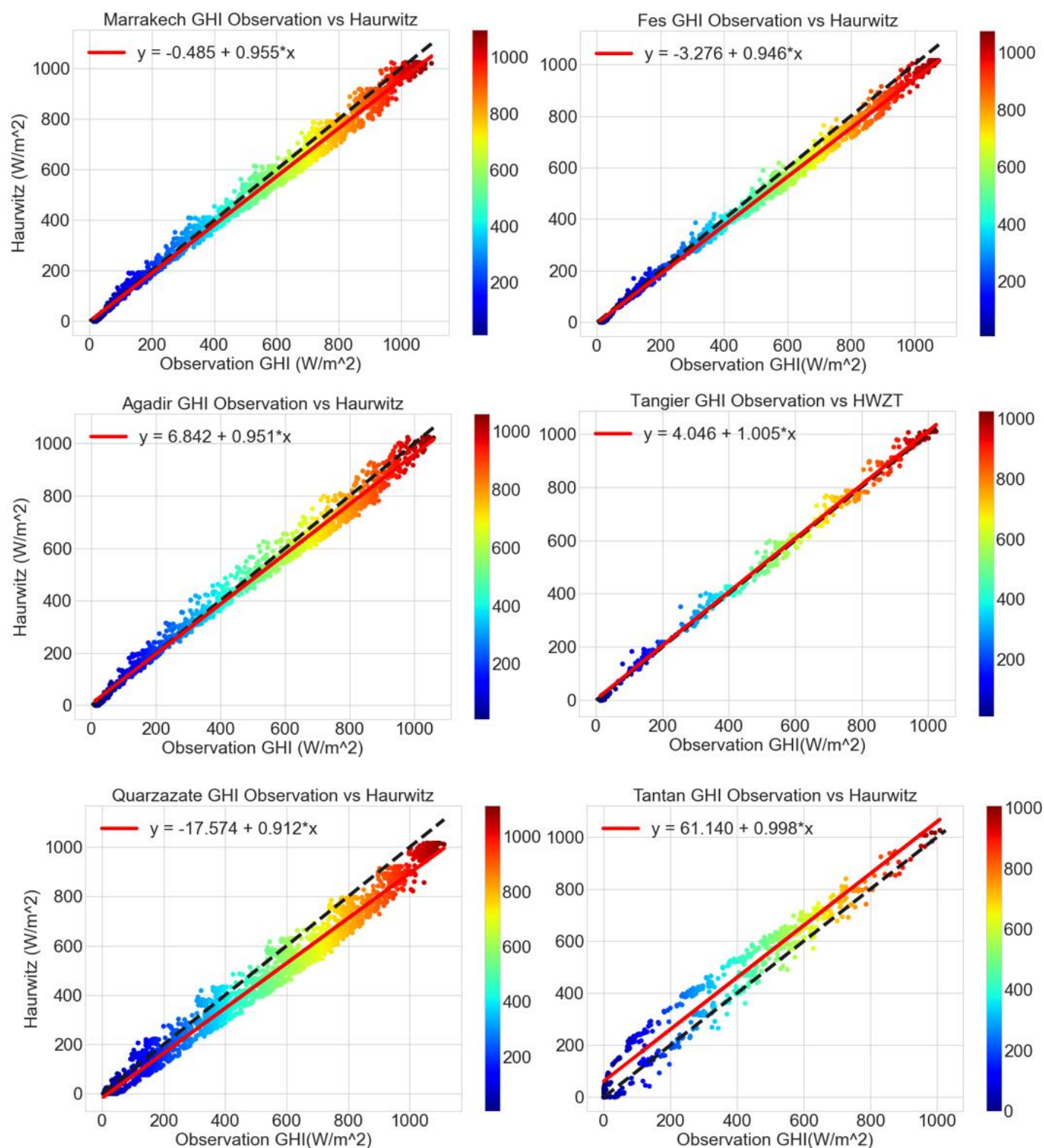


Figure S4. Scatter plot of McClear modelled hourly GHI and Haurwitz clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

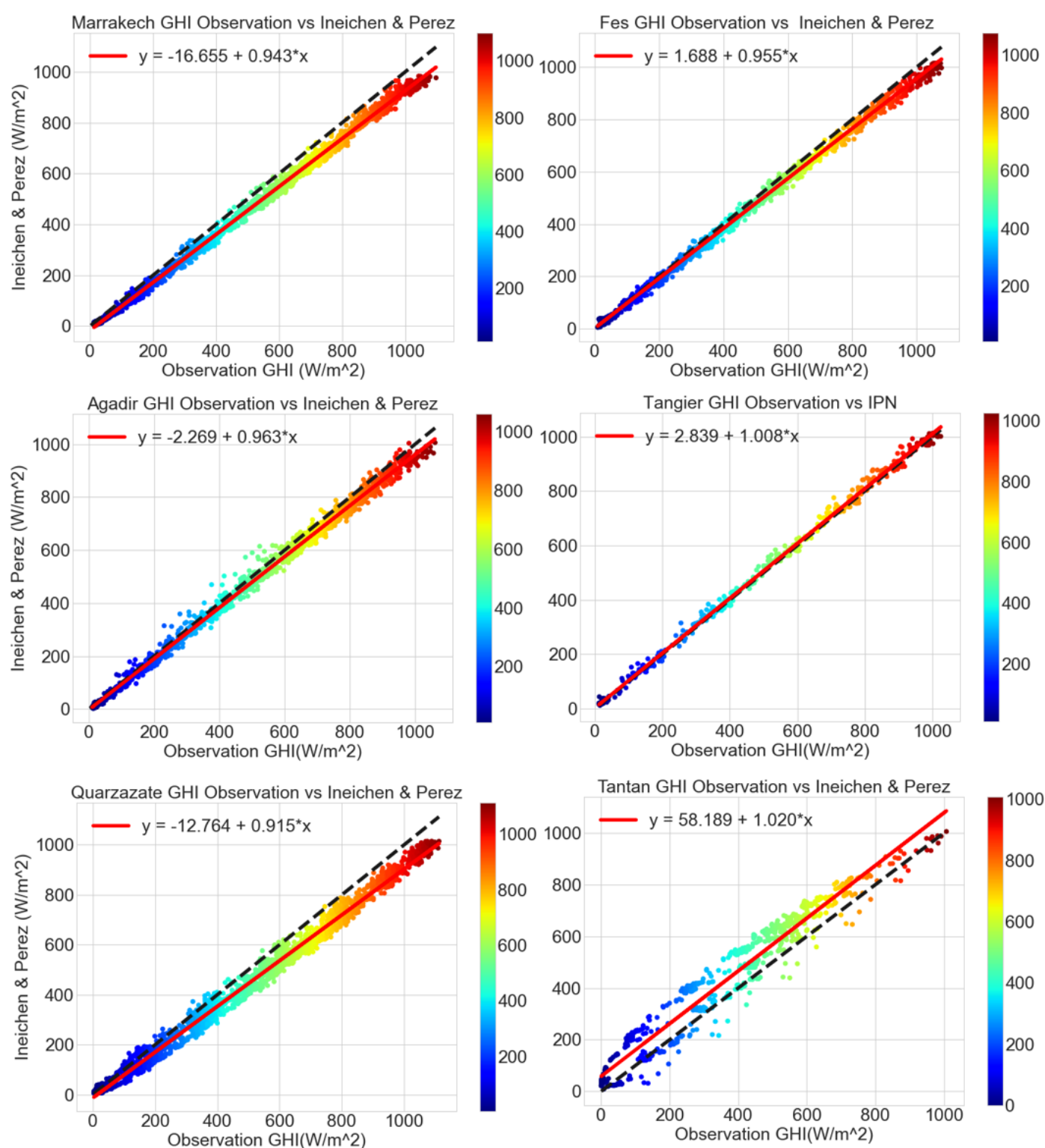


Figure S5. Scatter plot of McClear modelled hourly GHI and Ineichen & Perez (IPN) clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

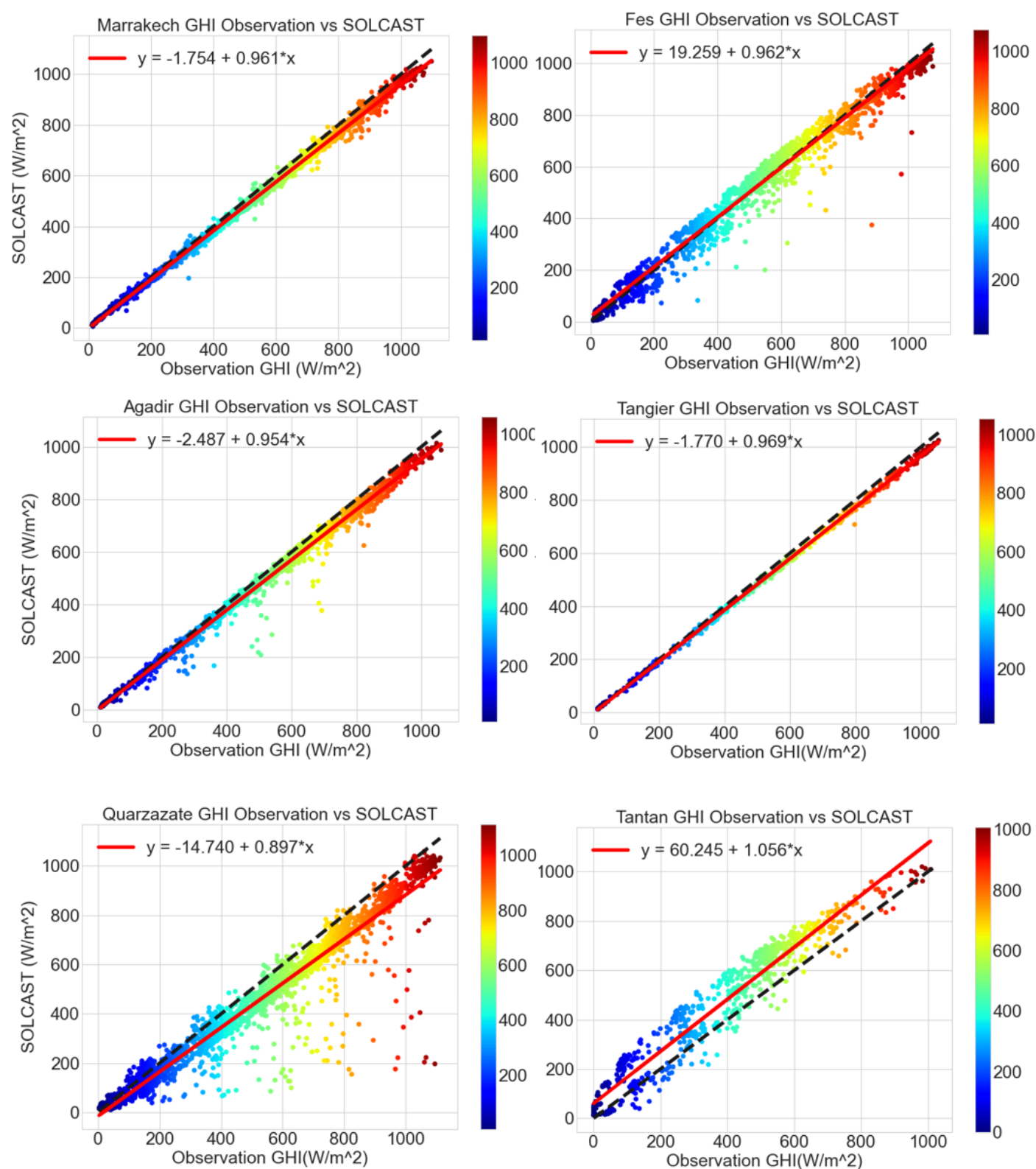


Figure S6. Scatter plot of McClear modelled hourly GHI and SOLCAST clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.

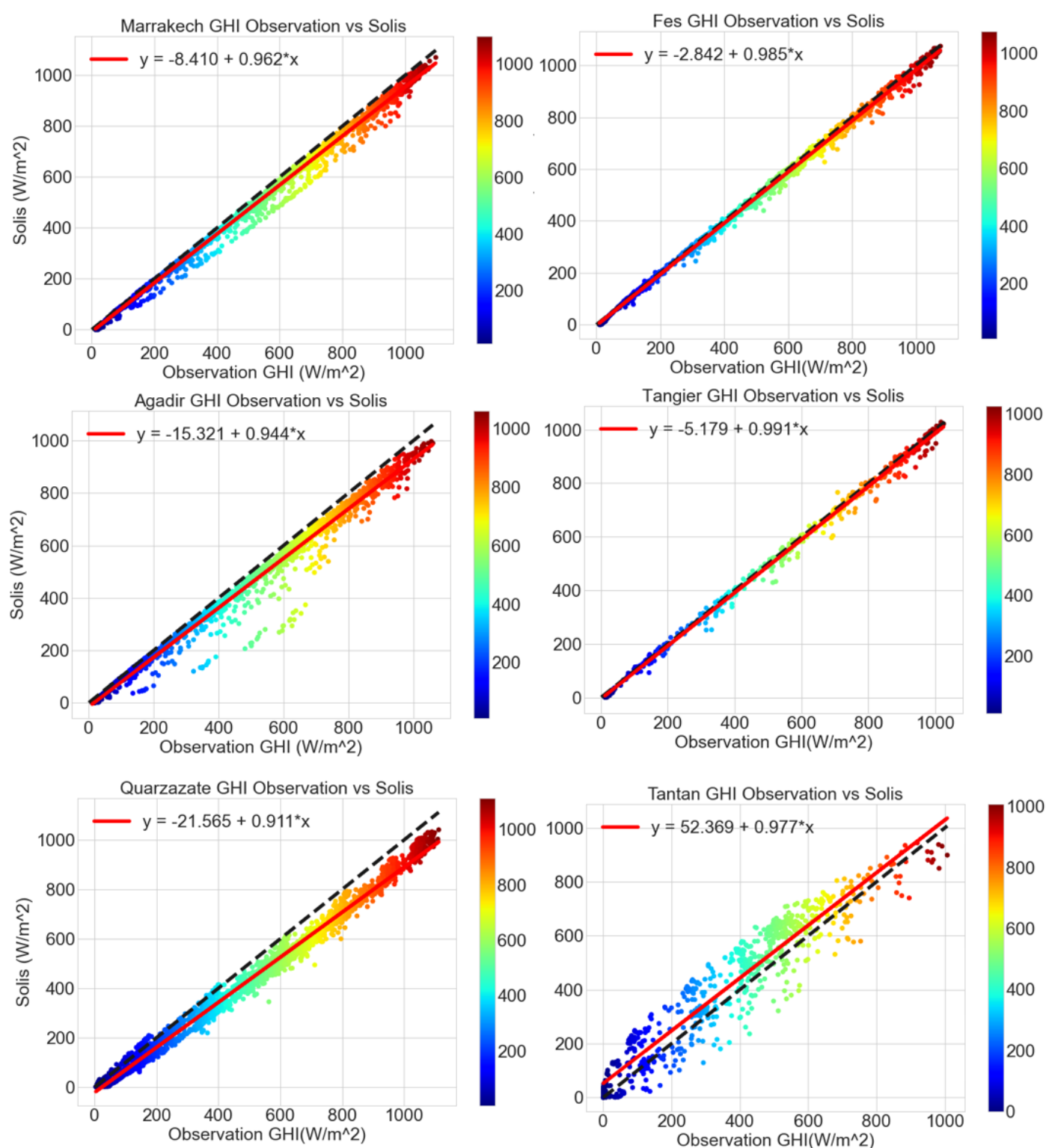


Figure S7. Scatter plot of McClear modelled hourly GHI and Solis clear sky modelled hourly GHI at (a) Marrakech station, (b) Fes station, (c), Agadir station, (d) Quarzazate station, (e) Tangier and (f) Tantan.