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The Performance Assessment of Six Global Horizontal Irradiance Clear Sky Models in Six Climatological Regions in South Africa

Brighton Mabasa [1,2,*], Meena D. Lysko [2,3], Henerica Tazvinga [1], Nosipho Zwane [1] and Sabata J. Moloi [2]

[1] Research & Development Division, South African Weather Service, Pretoria 0001, South Africa; Henerica.Tazvinga@weathersa.co.za (H.T.); Nosipho.Zwane@weathersa.co.za (N.Z.)
[2] Department of Physics, University of South Africa, UNISA Preller Street, Muckleneuk, Pretoria 0001, South Africa; mlysko@gmail.com (M.D.L.); moloisj@unisa.ac.za (S.J.M.)
[3] Move Beyond Consulting (Pty) Ltd., Pretoria 0001, South Africa
* Correspondence: brighton.mabasa@weathersa.co.za; Tel.: +27-12-367-6088

Abstract: This study assesses the performance of six global horizontal irradiance (GHI) clear sky models, namely: Bird, Simple Solis, McClear, Ineichen–Perez, Haurwitz and Berger–Duffie. The assessment is performed by comparing 1-min model outputs to corresponding clear sky reference 1-min Baseline Surface Radiation Network quality controlled GHI data from 13 South African Weather Services radiometric stations. The data used in the study range from 2013 to 2019. The 13 reference stations are across the six macro climatological regions of South Africa. The aim of the study is to identify the overall best performing clear sky model for estimating minute GHI in South Africa. Clear sky days are detected using ERA5 reanalysis hourly data and the application of an additional 1-min automated detection algorithm. Metadata for the models' inputs were sourced from station measurements, satellite platform observations, reanalysis and some were modelled. Statistical metrics relative Mean Bias Error (rMBE), relative Root Mean Square Error (rRMSE) and the coefficient of determination (R^2) are used to categorize model performance. The results show that each of the models performed differently across the 13 stations and in different climatic regions. The Bird model was overall the best in all regions, with an rMBE of 1.87%, rRMSE of 4.11% and R^2 of 0.998. The Bird model can therefore be used with quantitative confidence as a basis for solar energy applications when all the required model inputs are available.

Keywords: clear sky model; global horizontal irradiance; performance evaluation; climatological regions; solar energy applications; European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)'s Satellite Application Facility on Climate Monitoring (CM SAF); Fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5); Solar Radiation Data (SoDa); Copernicus Atmosphere Monitoring Service Aerosol Optical depth (CAMS-AOD) ; statistical metrics

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Table S1. Bird clear sky model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance. Grey colour represents results from other literature studies.

Station	Latitude	Altitude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	505.81	1.79	4.69	0.996
Polokwane	−23.86	1233	498.90	494.99	−0.78	2.78	0.999
Bethlehem	−25.25	1688	471.68	460.74	−2.32	5.38	0.995
Nelspruit	−25.39	870	485.19	478.57	−1.36	4.96	0.995
Mahikeng	−25.81	1289	512.03	501.06	−2.14	5.30	0.995
Irene	−25.91	1524	493.23	488.26	−1.01	3.70	0.998
Upington	−28.48	848	589.77	569.47	−3.44	4.59	0.998
Durban	−29.61	91	443.56	433.99	−2.16	3.82	0.998
Prieska	−29.68	989	606.53	597.22	−1.54	2.71	0.999
De Aar	−30.67	1284	570.57	560.25	−1.81	3.73	0.998
Mthatha	−31.55	744	453.34	448.13	−1.15	3.19	0.998
George	−34.01	192	491.98	479.45	−2.55	3.63	0.999
Cape Point	−35.35	86	585.88	546.49	−6.72	10.95	0.984
Adelaide	−34.95	2	284.8		5.22	5.35	0.992
Alice Springs	−23.8	546	538.3		3.66	6.26	0.987
Kalgoorlie	−30.78	365	465.2		1.85	3.45	0.996
Learmonth	−22.24	5	364.2		3.98	7.57	0.993
Mildura	−34.54	50	438.4		1.2	4.06	0.995
Mt Gambier	−37.75	63	284.9		4.44	6.99	0.991
Rockhampton	−23.38	10	387.4		5.23	5.3	0.991
Wagga	−35.16	212	398.3		2.94	4.47	0.994
Reunion Island	−20.89	4	821		1.3	3.4	0.99

Table S2. McClear clear sky model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance. Grey colour represents results from other literature studies.

Station	Latitude	Altitude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	472.60	−4.90	7.07	0.994
Polokwane	−23.86	1233	498.90	460.80	−7.64	8.97	0.995
Bethlehem	−25.25	1688	471.68	491.29	4.16	6.34	0.995
Nelspruit	−25.39	870	485.19	505.78	4.24	6.52	0.995
Mahikeng	−25.81	1289	512.03	527.79	3.08	5.77	0.994
Irene	−25.91	1524	493.23	517.69	4.96	5.93	0.998
Upington	−28.48	848	589.77	593.44	0.62	2.63	0.999
Durban	−29.61	91	443.56	461.01	3.94	5.16	0.998
Prieska	−29.68	989	606.53	623.12	2.74	3.35	0.999
De Aar	−30.67	1284	570.57	580.76	1.79	4.24	0.997
Mthatha	−31.55	744	453.34	475.84	4.96	5.84	0.998
George	−34.01	192	491.98	502.21	2.08	2.74	0.999
Cape Point	−35.35	86	585.88	577.03	−1.51	2.76	0.999
Alice Springs	−23.8	547	715		2	3	0.99

Reunion Island	−20.89	4	821	0.8	3	0.99

Table S3. Simple Solis model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance. Grey colour represents results from other literature studies.

Station	Latitude	Altitude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	503.31	1.28	4.78	0.995
Polokwane	−23.86	1233	498.90	499.53	0.13	2.79	0.999
Bethlehem	−25.25	1688	471.68	468.44	−0.69	4.93	0.995
Nelspruit	−25.39	870	485.19	481.19	−0.82	5.56	0.994
Mahikeng	−25.81	1289	512.03	505.52	−1.27	5.20	0.995
Irene	−25.91	1524	493.23	495.81	0.52	3.65	0.998
Upington	−28.48	848	589.77	555.87	−5.75	7.29	0.997
Durban	−29.61	91	443.56	428.03	−3.50	5.29	0.998
Prieska	−29.68	989	606.53	596.39	−1.67	3.27	0.998
De Aar	−30.67	1284	570.57	563.45	−1.25	4.04	0.998
Mthatha	−31.55	744	453.34	449.29	−0.89	3.40	0.998
George	−34.01	192	491.98	479.08	−2.62	4.12	0.999
Cape Point	−35.35	86	585.88	542.22	−7.45	11.77	0.983
Adelaide	−34.95	2	284.8		−1.65	4.97	0.993
Alice Springs	−23.8	546	538.3		−1.7	6.1	0.987
Kalgoorlie	−30.78	365	465.2		−3.16	4.47	0.994
Learmonth	−22.24	5	364.2		−2.89	8.49	0.991
Mildura	−34.54	50	438.4		−5.01	6.35	0.987
Rockhampton	−23.38	10	387.4		−2.18	3.98	0.995
Wagga	−35.16	212	398.3		−1.94	4.9	0.993
Reunion Island	−20.89	4	821		1.2	4.8	0.97

Table S4. Ineichen –Perez model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance. Grey colour represents results from other literature studies.

Station	Latitude	Altitude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	490.77	−1.24	4.28	0.996
Polokwane	−23.86	1233	498.90	514.39	3.11	4.46	0.998
Bethlehem	−25.25	1688	471.68	498.41	5.67	8.04	0.994
Nelspruit	−25.39	870	485.19	492.81	1.57	5.70	0.993
Mahikeng	−25.81	1289	512.03	515.81	0.74	5.17	0.994
Irene	−25.91	1524	493.23	515.75	4.57	6.10	0.997
Upington	−28.48	848	589.77	548.80	−6.95	8.26	0.997
Durban	−29.61	91	443.56	457.00	3.03	4.88	0.997
Prieska	−29.68	989	606.53	573.93	−5.38	6.15	0.998
De Aar	−30.67	1284	570.57	560.56	−1.75	4.34	0.997
Mthatha	−31.55	744	453.34	467.96	3.23	4.86	0.997
George	−34.01	192	491.98	470.90	−4.29	6.08	0.998

Cape Point	−35.35	86	585.88	543.41	−7.25	11.39	0.984
Adelaide	−34.95	2	284.8		−5.65	5.84	0.99
Alice Springs	−23.8	546	538.3		0.06	4.98	0.992
Kalgoorlie	−30.78	365	465.2		−3.68	4.26	0.994
Learmonth	−22.24	5	364.2		1.04	5.09	0.997
Mildura	−34.54	50	438.4		−3.13	4.74	0.993
Rockhampton	−23.38	10	387.4		−3.3	3.93	0.995
Wagga	−35.16	212	398.3		−4.88	5.8	0.99

Table S5. Haurwitz model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Station	Latitude	Alti-tude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	510.00	2.63	5.10	0.996
Polokwane	−23.86	1233	498.90	494.33	−0.92	4.31	0.998
Bethlehem	−25.25	1688	471.68	452.98	−3.96	7.47	0.994
Nelspruit	−25.39	870	485.19	489.38	0.86	5.55	0.994
Mahikeng	−25.81	1289	512.03	491.88	−3.94	7.71	0.993
Irene	−25.91	1524	493.23	484.78	−1.71	5.89	0.996
Upington	−28.48	848	589.77	546.90	−7.27	10.29	0.996
Durban	−29.61	91	443.56	468.88	5.71	7.82	0.995
Prieska	−29.68	989	606.53	566.88	−6.54	8.42	0.998
De Aar	−30.67	1284	570.57	530.77	−6.98	11.92	0.987
Mthatha	−31.55	744	453.34	452.61	−0.16	4.20	0.997
George	−34.01	192	491.98	479.29	−2.58	6.17	0.998
Cape Point	−35.35	86	585.88	544.49	−7.07	12.04	0.983

Table S6. Berger-Duffie model predicted irradiance versus measured, with validation metrics. The colours in the table are used to visualize the model skill in addition to statistical thresholds with blue representing excellent performance, green good performance, yellow average performance and pink poor performance.

Station	Latitude	Altitude (m)	Measured (Wm^{-2})	Predicted (Wm^{-2})	*rMBE* (%)	*rRMSE* (%)	R^2
Thohoyandou	−23.08	619	496.94	490.76	−1.24	8.39	0.996
Polokwane	−23.86	1233	498.90	477.13	−4.36	10.00	0.997
Bethlehem	−25.25	1688	471.68	441.14	−6.47	12.30	0.993
Nelspruit	−25.39	870	485.19	472.93	−2.53	9.79	0.994
Mahikeng	−25.81	1289	512.03	475.14	−7.20	12.92	0.993
Irene	−25.91	1524	493.23	468.85	−4.94	11.53	0.996
Upington	−28.48	848	589.77	523.92	−11.17	16.59	0.996
Durban	−29.61	91	443.56	455.23	2.63	9.72	0.994
Prieska	−29.68	989	606.53	539.94	−10.98	15.31	0.998
De Aar	−30.67	1284	570.57	508.96	−10.80	16.58	0.996
Mthatha	−31.55	744	453.34	441.08	−2.70	9.10	0.997
George	−34.01	192	491.98	464.12	−5.66	12.54	0.997
Cape Point	−35.35	86	585.88	520.53	−11.15	17.32	0.982

S4.4 Scatter plots of measured and modelled clear sky global horizontal irradiance

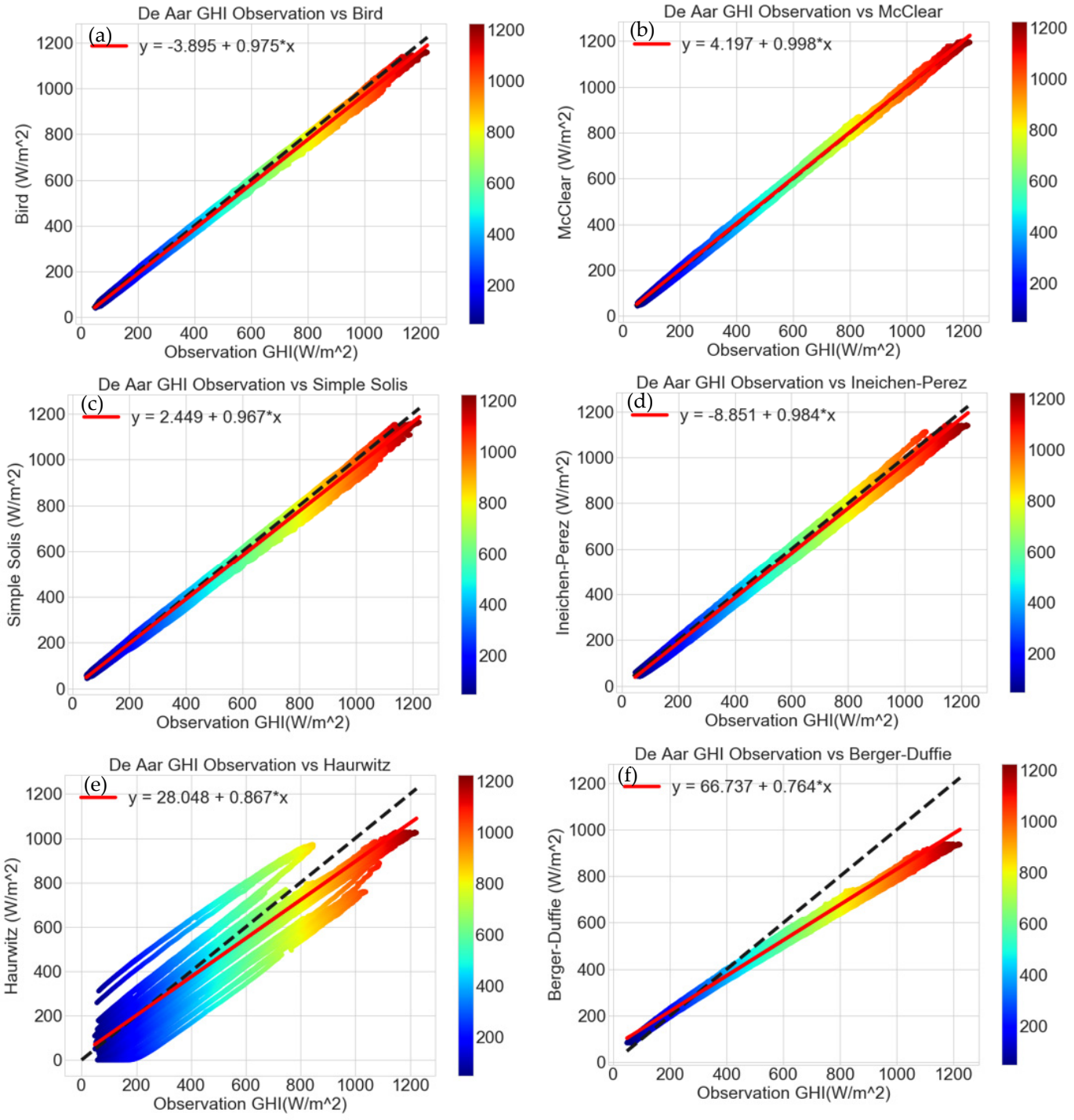

Figure S1. Scatter plot of measured and modelled clear sky global irradiance at De Aar for Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz model (**e**) and Berger-Diffie model (**f**).

From scatter plots in Figure S1 show the correlation between measured clear sky GHI and corresponding modelled GHI at De Aar station. Complex models show a very good correlation between measured and observed GHI (the data is close to the 1:1 (black dotted) line). For simple models, there is poor correlation between measured and modelled GHI data.

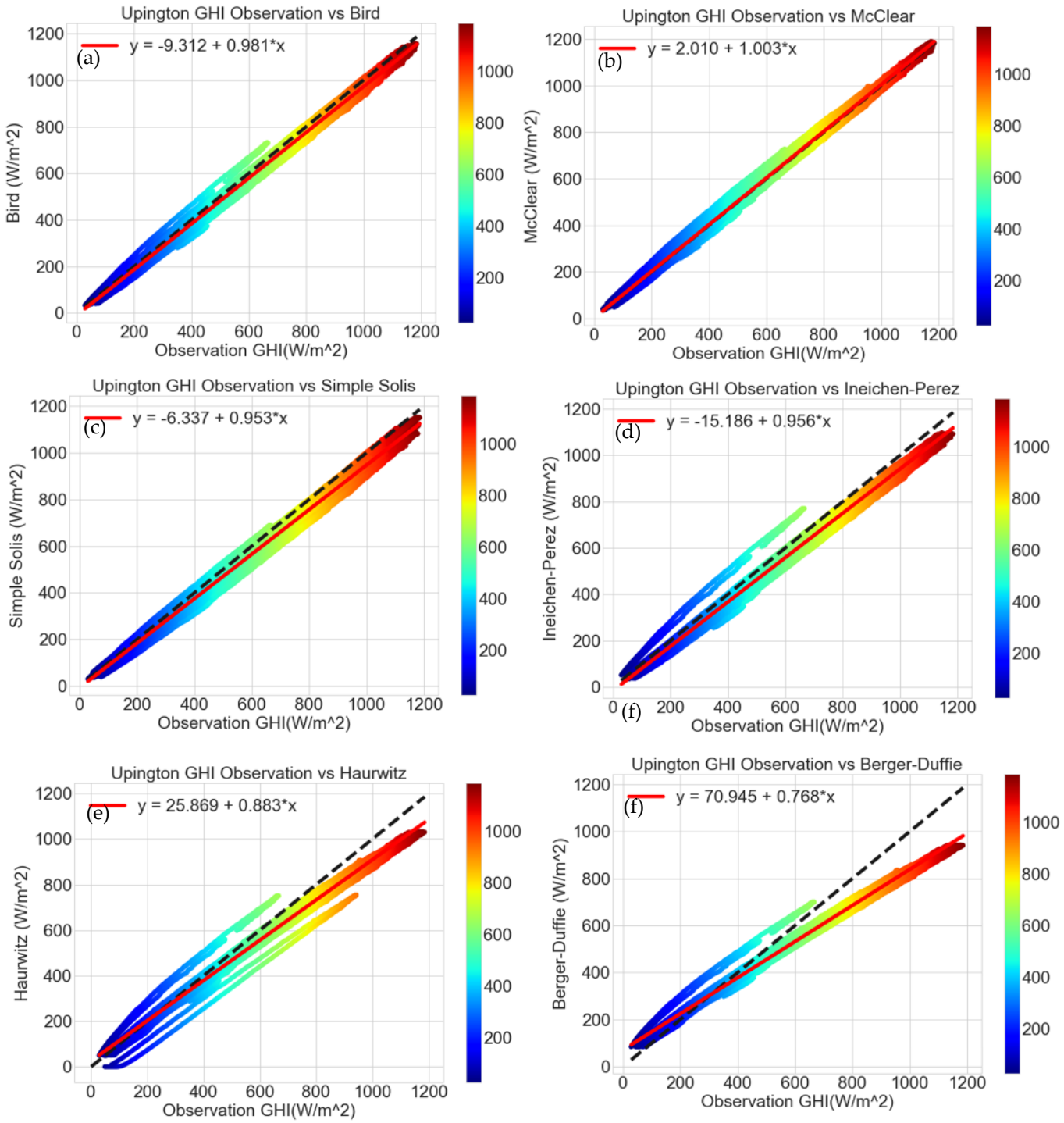

Figure S2. Scatter plot of measured and modelled clear sky global irradiance at Upington station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S2, which show the correlation between measured clear sky GHI and corresponding modelled GHI at Upington station. Bird, Simple Solis and McClear models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Ineichen-Perez, Haurwitz and Berger-Duffie models there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

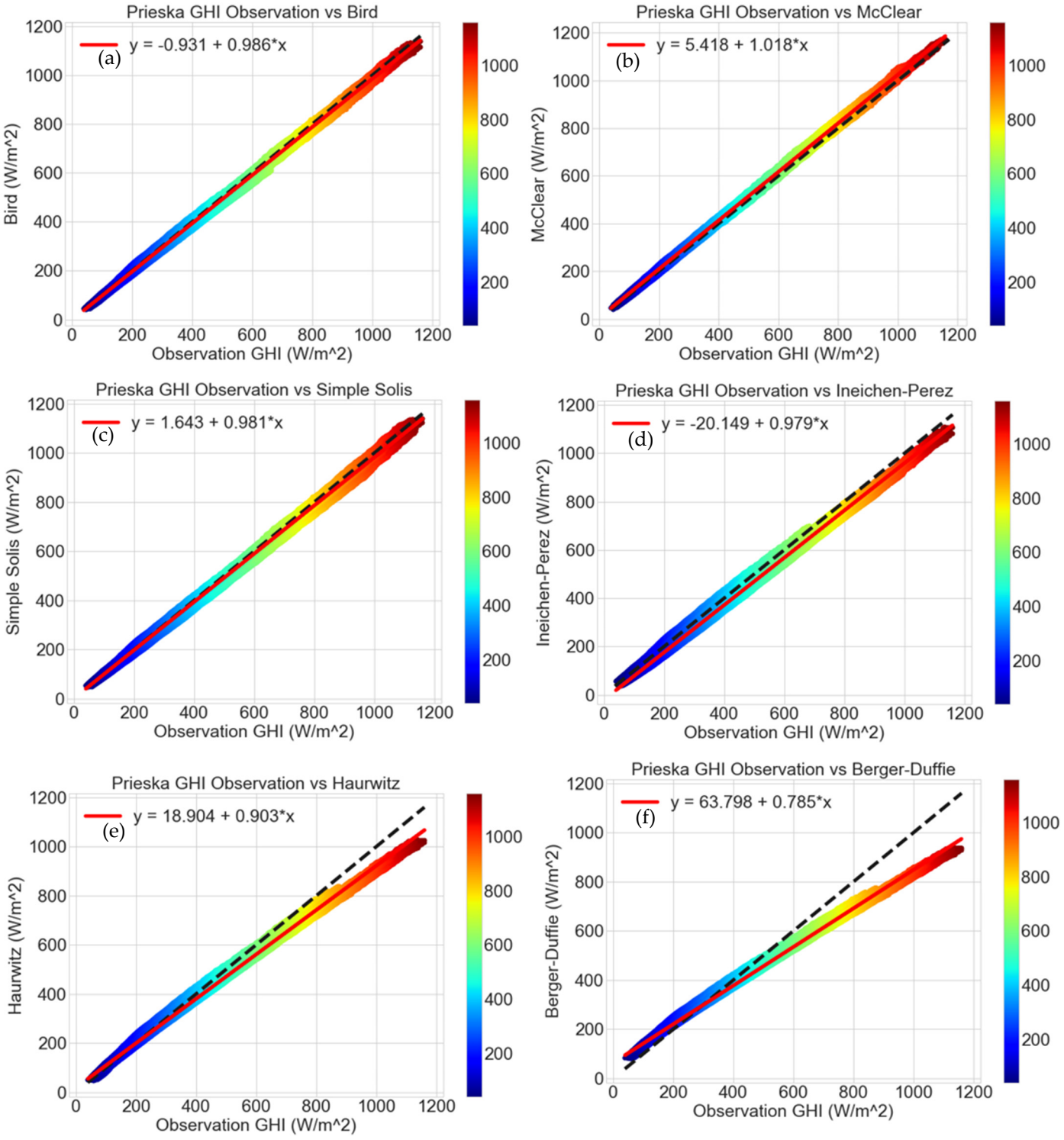

Figure S3. Scatter plot of measured and modelled clear sky global irradiance at Prieska station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S3, which show the correlation between measured clear sky GHI and corresponding modelled GHI at Prieska station. Bird, Simple Solis, McClear and Ineichen-Perez models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Haurwitz and Berger-Duffie models there is poor correlation between measured and modelled GHI data, the

data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

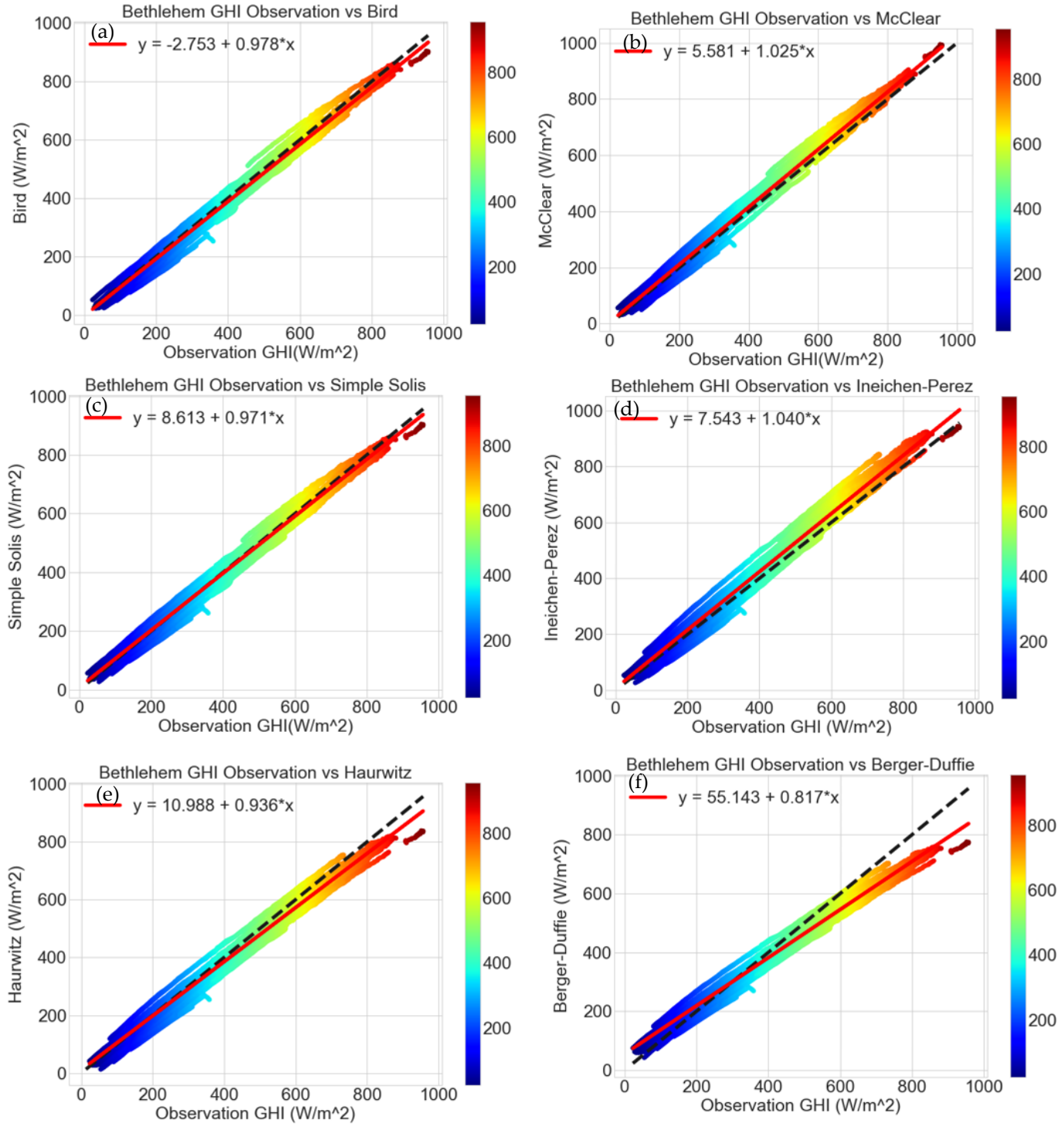

Figure S4. Scatter plot of measured and modelled clear sky global irradiance at Bethlehem station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S4 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Bethlehem station. Bird, Simple Solis, McClear and Haurwitz models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Ineichen-Perez and

Berger-Duffie models there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

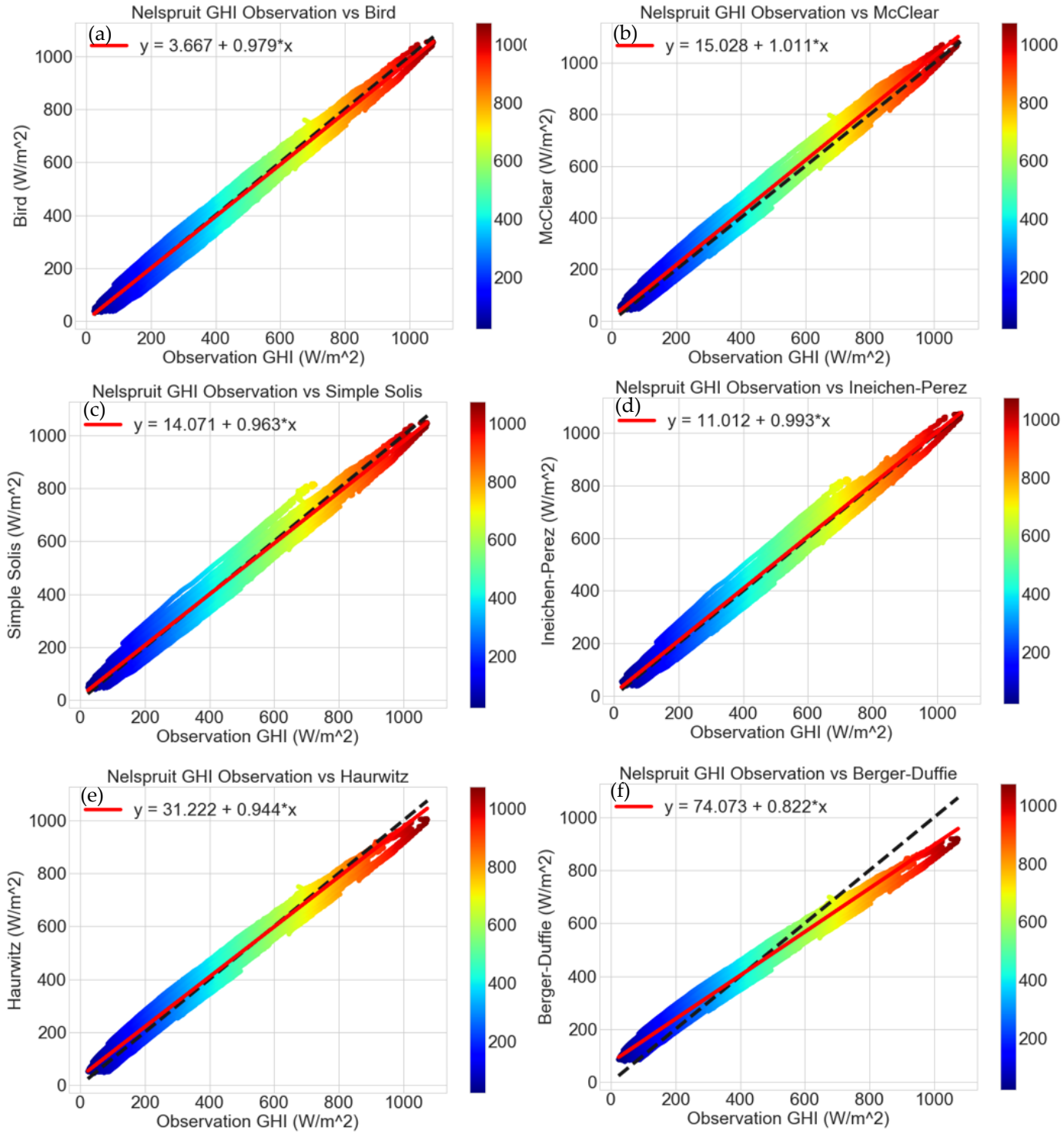

Figure S5. Scatter plot of measured and modelled clear sky global irradiance at Nelspruit station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S5 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Nelspruit station. Bird, Simple Solis, McClear, Ineichen-Perez and Haurwitz models show a very good correlation between

measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Berger-Duffie model there is poor correlation between measured and modelled GHI data when irradiance values are high, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

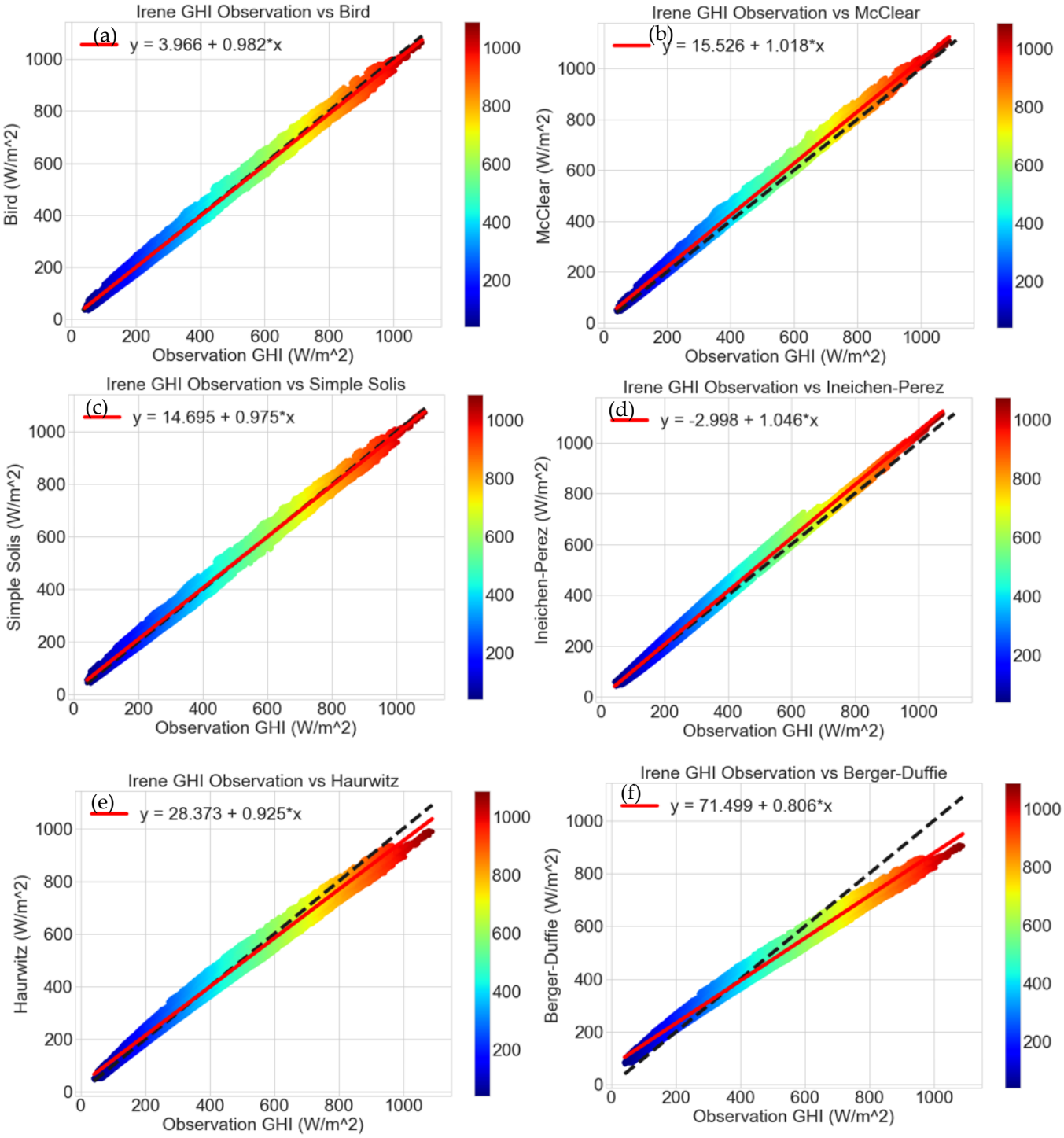

Figure S6. Scatter plot of measured and modelled clear sky global irradiance at Irene station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S6 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Irene station. Bird, Simple Solis, McClear,

Ineichen-Perez and Haurwitz models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Berger-Duffie model there is poor correlation between measured and modelled GHI data when irradiance values are high, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

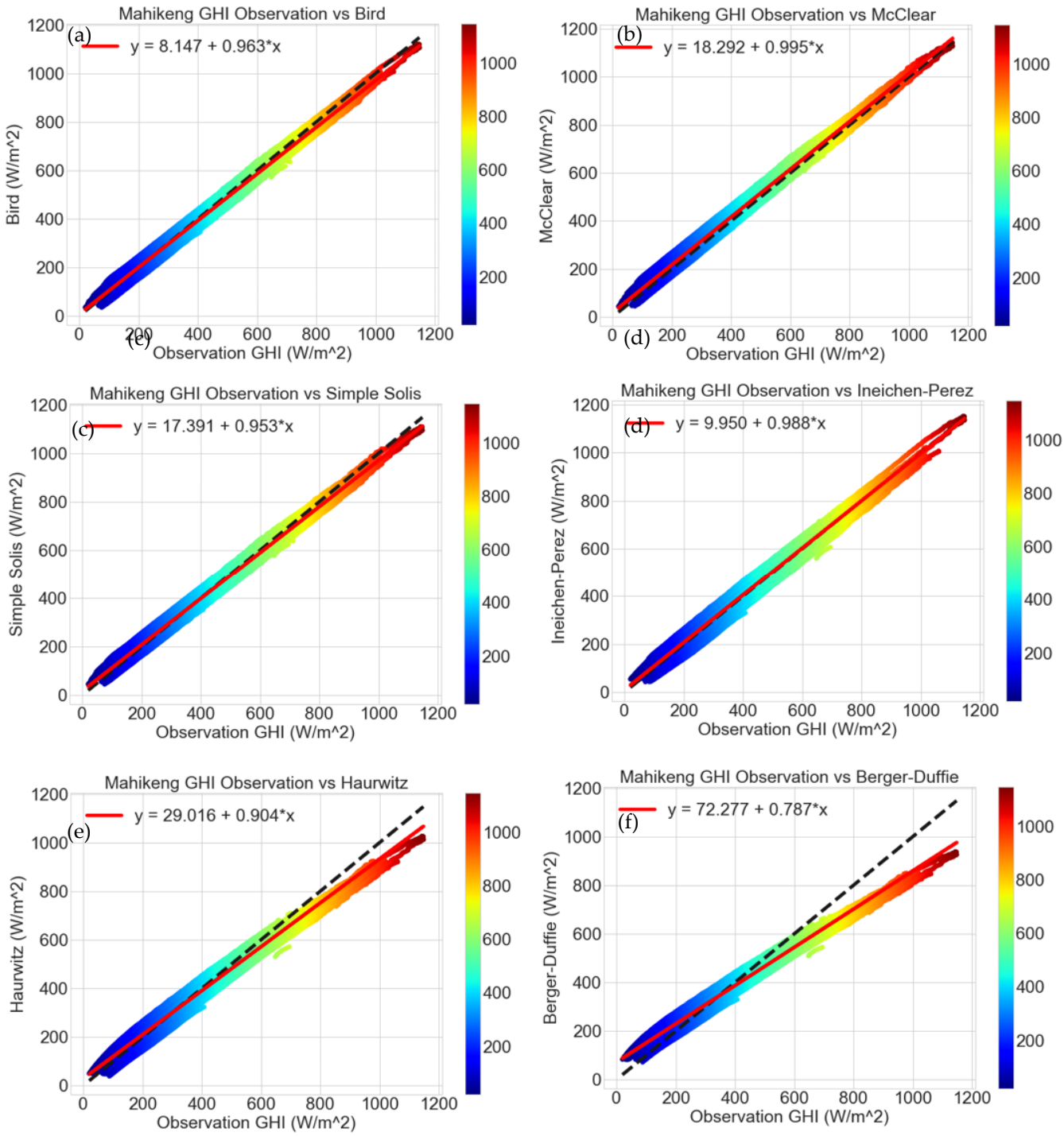

Figure S7. Scatter plot of measured and modelled clear sky global irradiance at Mahikeng station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S7 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Mahikeng station. Bird, Simple Solis,

McClear and Ineichen-Perez models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Haurwitz and Berger-Duffie models there is poor correlation between measured and modelled GHI data when irradiance values are high, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

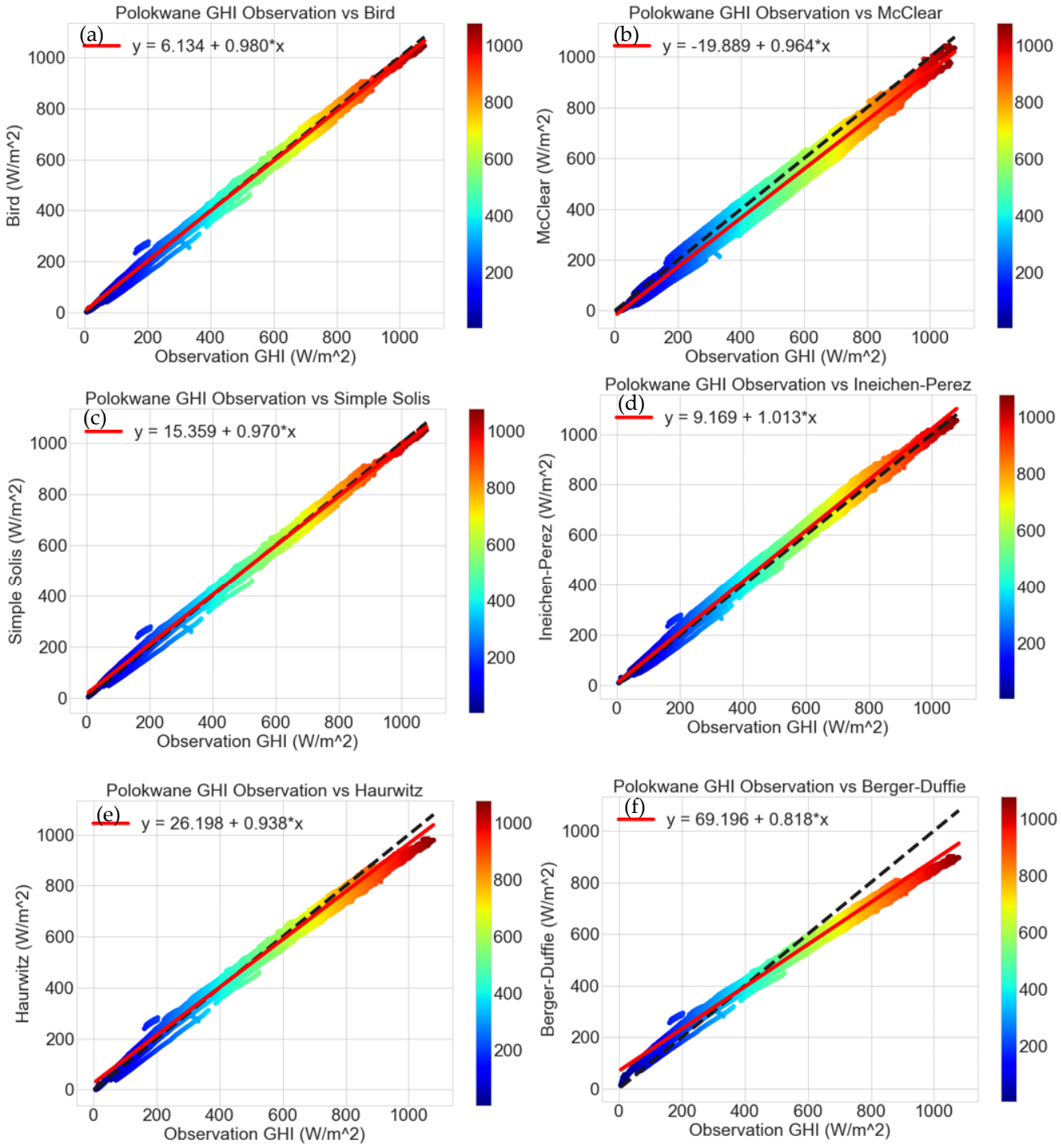

Figure S8. Scatter plot of measured and modelled clear sky global irradiance at Polokwane station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S8 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Polokwane station. Bird, Simple Solis,

Ineichen-Perez and Haurwitz models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for McClear and Berger-Duffie models there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

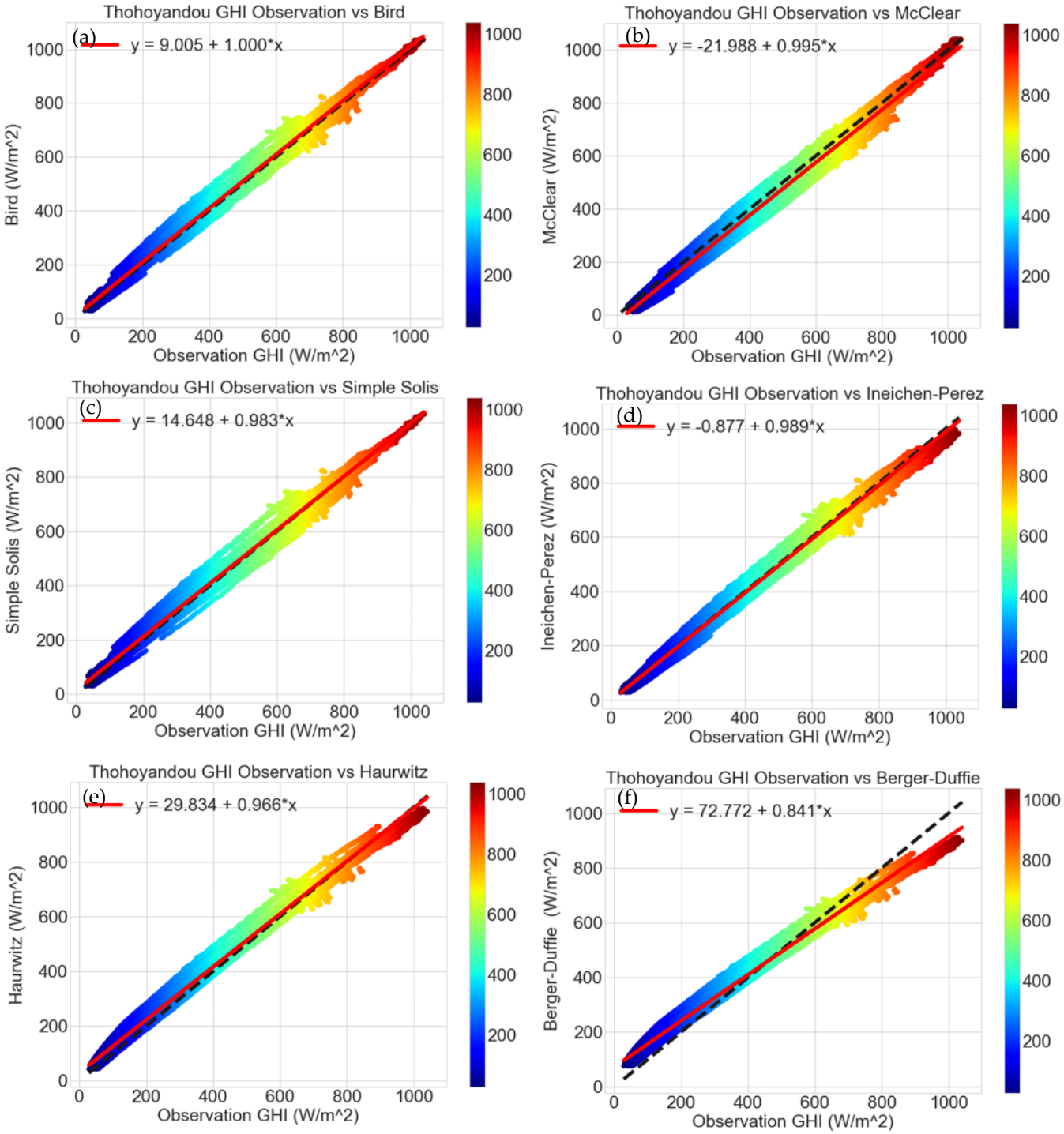

Figure S9. Scatter plot of measured and modelled clear sky global irradiance at Thohoyandou station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S9 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Thohoyandou station. Bird, Simple Solis,

Ineichen-Perez and Haurwitz models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for McClear and Berger-Duffie models there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

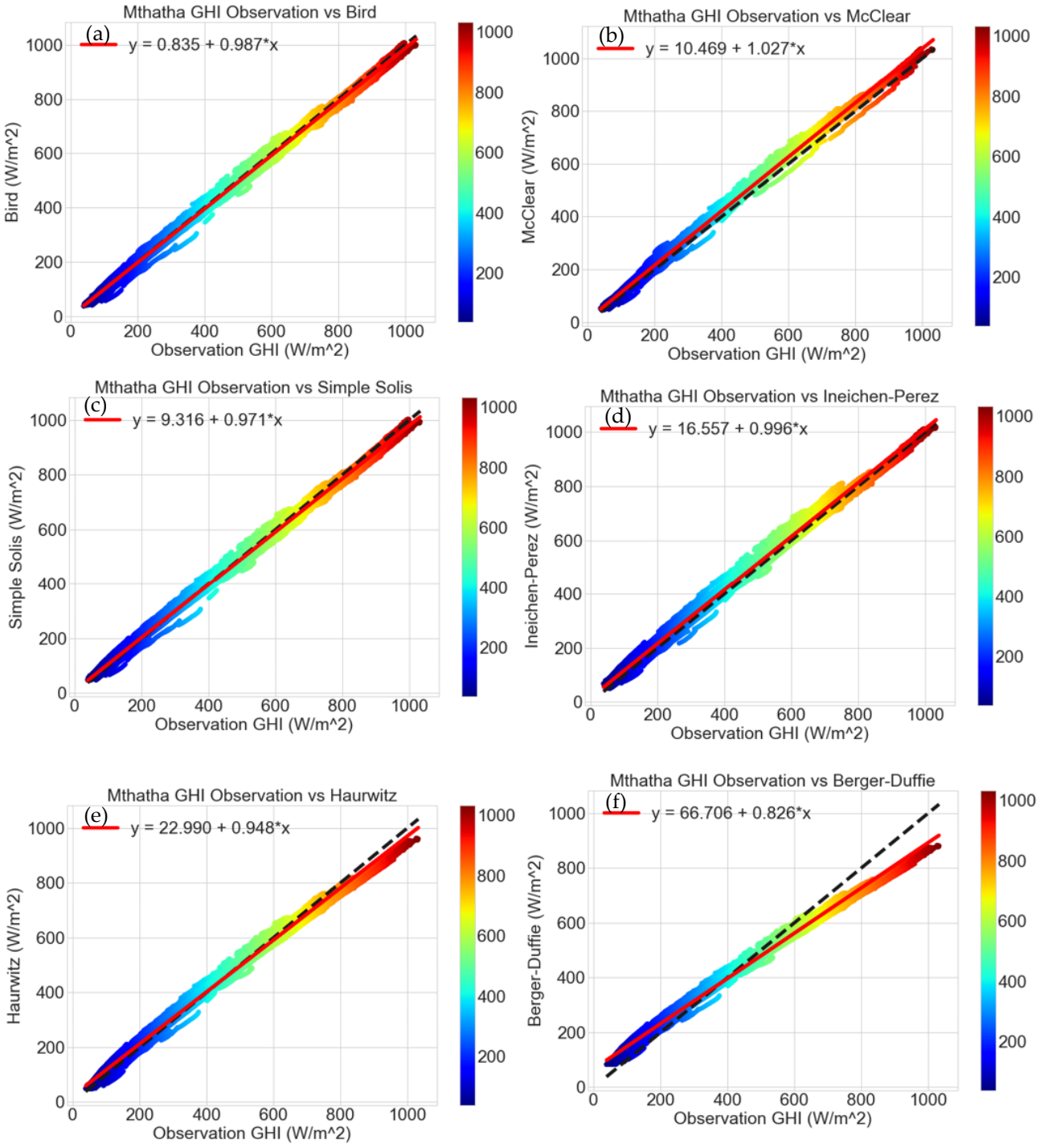

Figure S10. Scatter plot of measured and modelled clear sky global irradiance at Mthatha station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S10 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Mthatha station. Bird, Simple Solis,

McClear, Ineichen-Perez and Haurwitz models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Berger-Duffie model there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

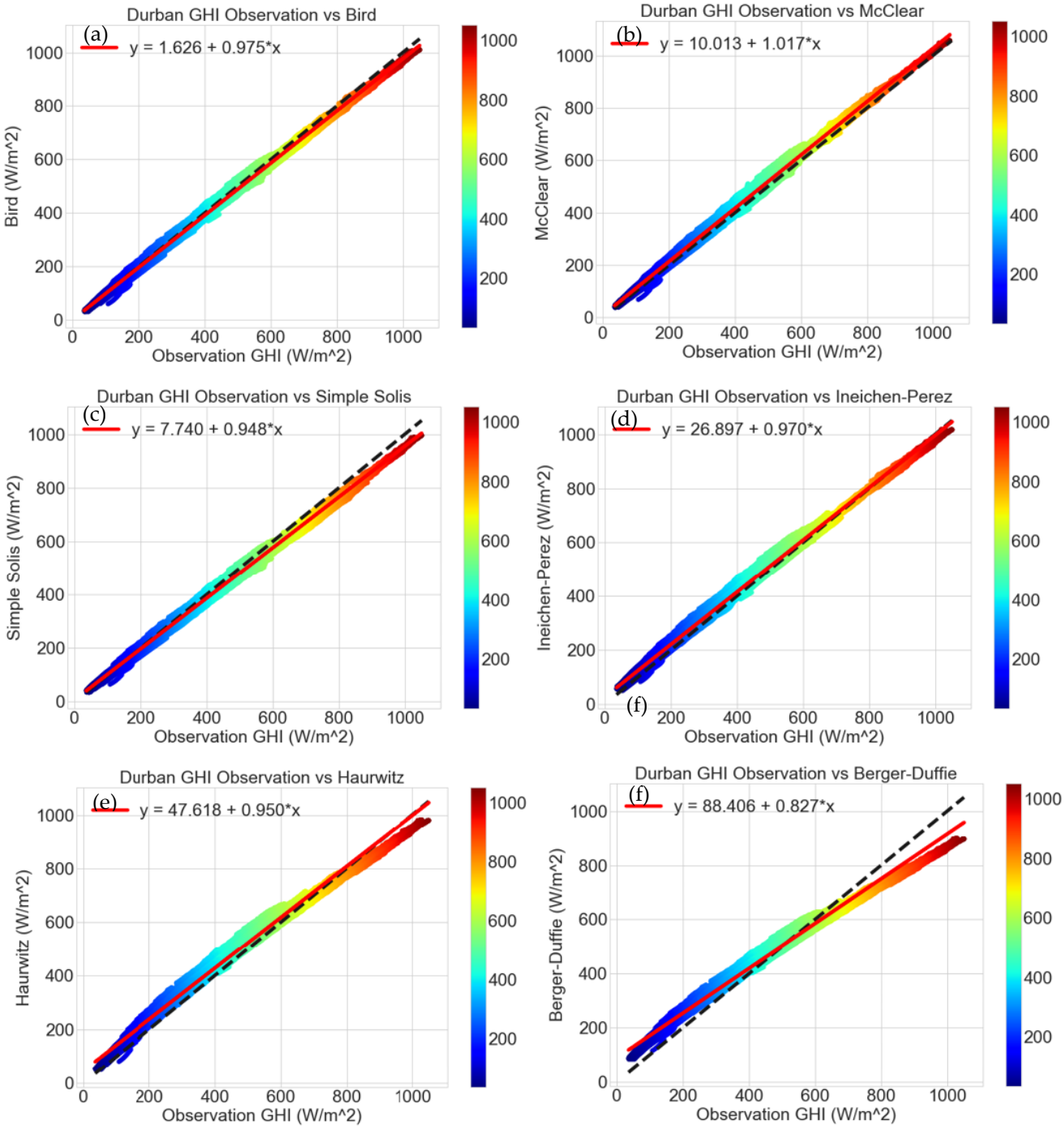

Figure S11. Scatter plot of measured and modelled clear sky global irradiance at Durban station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S11 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Durban station. Bird, Simple Solis, McClear, Ineichen-Perez and Haurwitz models show a very good correlation between measured

and observed GHI the data is close to the 1:1 (black dotted) line, while for Berger-Duffie model there is poor correlation between measured and modelled GHI data, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

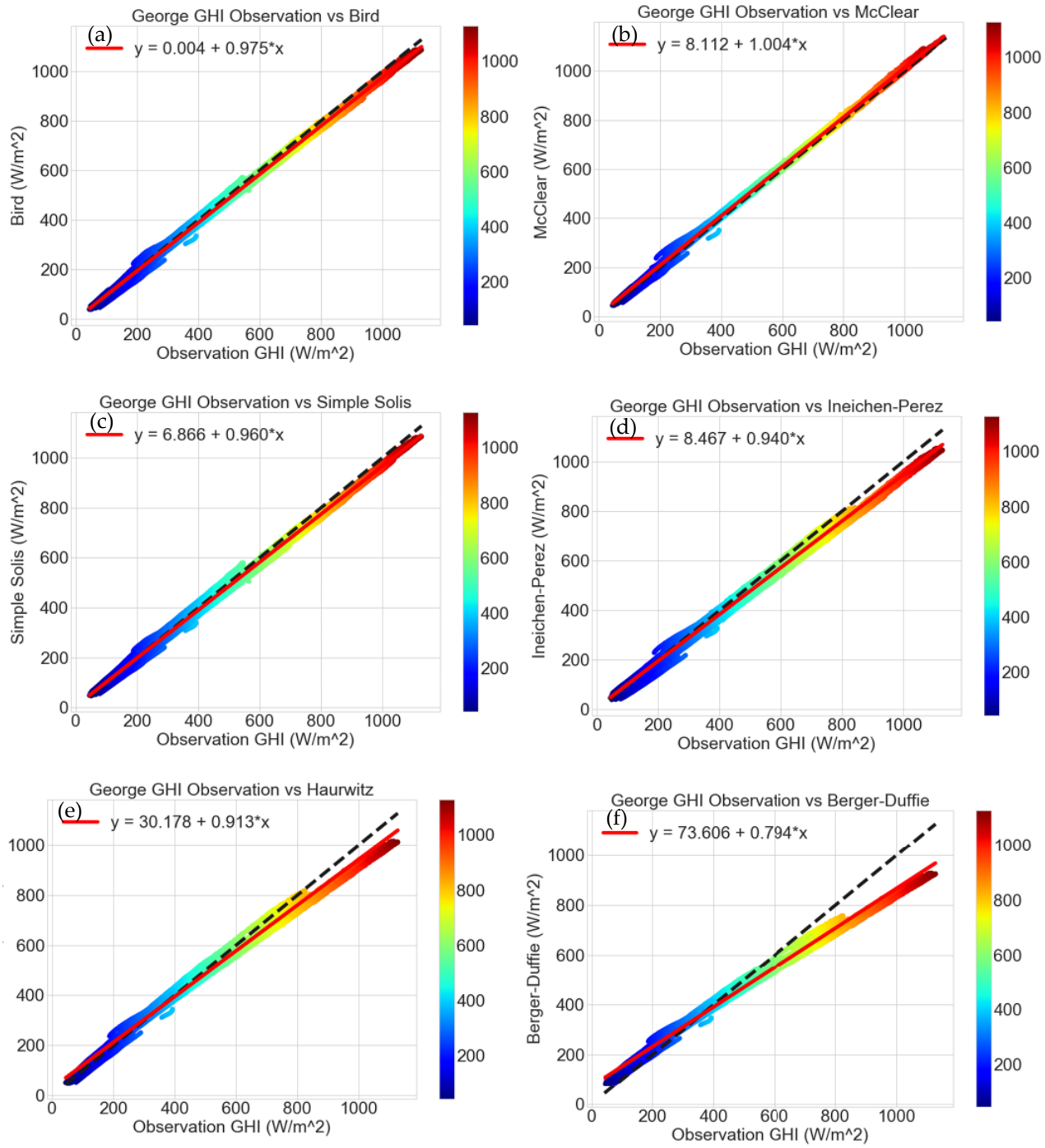

Figure S12. Scatter plot of measured and modelled clear sky global irradiance at George station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

Figure S12**.** which show the correlation between measured clear sky GHI and corresponding modelled GHI at George station. Bird, Simple Solis and McClear models show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Ineichen-Perez, Haurwitz and Berger-Duffie models there is

poor correlation between measured and modelled GHI data when irradiance values are high, the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.

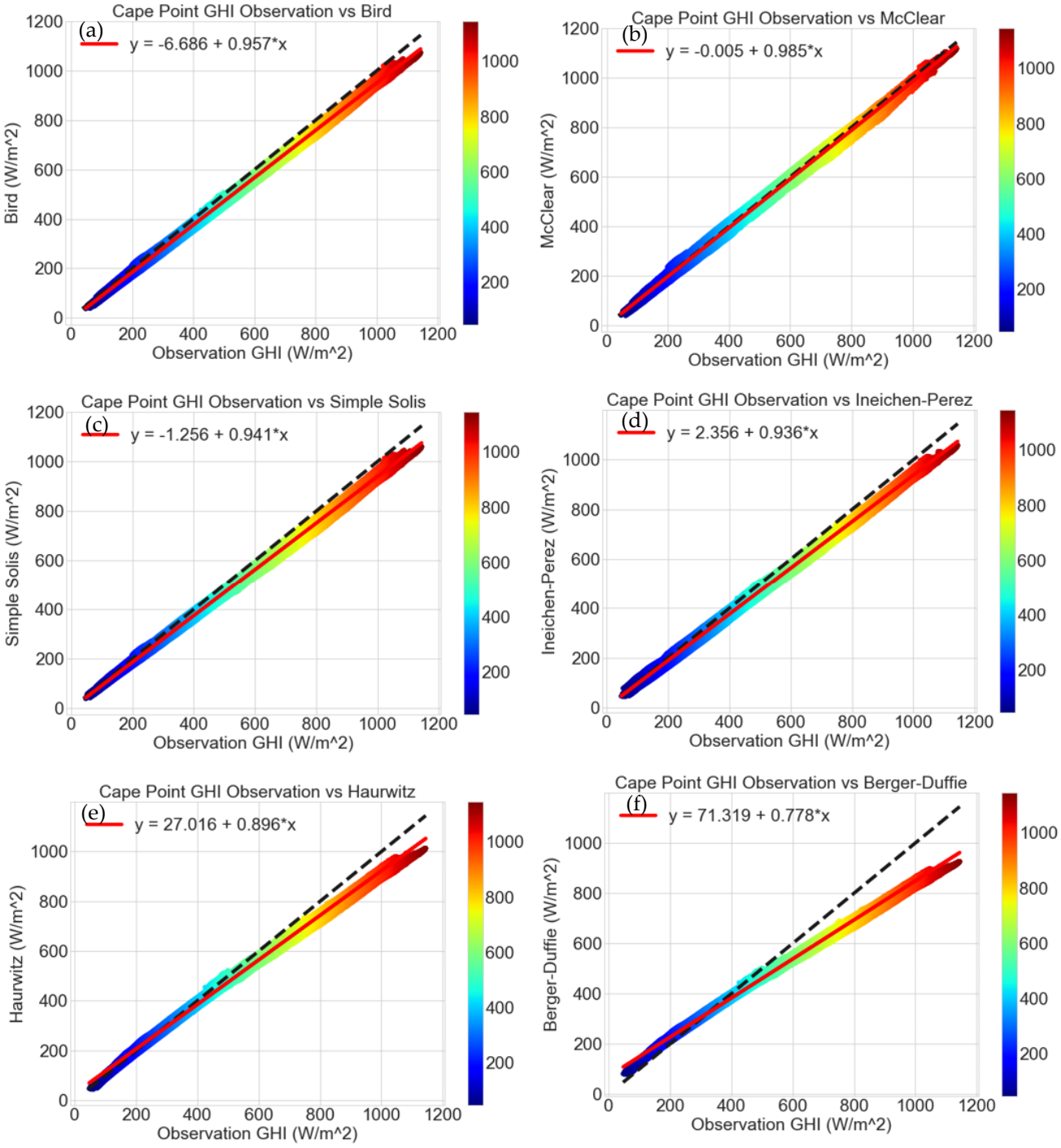

Figure S13. Scatter plot of measured and modelled clear sky global irradiance at Cape Point station, Bird model (**a**), McClear model (**b**), Simple Solis model (**c**), Ineichen-Perez model (**d**), Haurwitz (**e**) and Berger-Duffie (**f**).

From scatter plot in Figure S13 which show the correlation between measured clear sky GHI and corresponding modelled GHI at Cape Point station. and McClear model show a very good correlation between measured and observed GHI the data is close to the 1:1 (black dotted) line, while for Bird, Simple Solis, Ineichen-Perez, Haurwitz and Berger-Duffie models there is poor correlation between measured and modelled GHI data,

the data diverged from the 1:1 line, the correlation shown here agrees with the statistics from table S1 to S5.