An Assessment of and Access to NASA CERES Hourly Solar Irradiance Data Products Using POWER Web Services

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Abstract

The NASA Prediction Of Worldwide Energy Resources (POWER) project targets three user communities: Renewable Energies (RE), Sustainable Buildings (SB), Agroclimatology (AG). The Clouds and the Earth's Radiant Energy System (CERES) SYN1deg (Ed4.1) hourly all-sky global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI), which span from March 2000 to within a few months of real time, are now the source data provided through POWER Web Services Suite (WSS). Although the SYN1deg (Ed4.1) hourly DHI and direct horizontal irradiance (DirHI) sum to the GHI that agree reasonably well with matching Baseline Surface Radiation Network (BSRN) measurements, the DHI and DirHI components show appreciable positive and negative biases, respectively, relative to the BSRN data. The direct normal irradiance (DNI) derived by dividing the DirHI by the cosine of the solar zenith angle [cos(Z)] is, therefore, also appreciably biased relative to the BSRN data. In this report, we present a simple bias-based correction scheme. We perform the correction in the following procedure: 1) Correct the GHI and DHI according to the biases that are expressed as functions of cos(Z); 2) Compute the GHI-DHI difference to get the corrected DirHI; 3) Divide the corrected DirHI by cos(Z) to get the DNI. In addition, when Z is larger than 75°, the derived DNI can sometimes become unrealistically large as cos(Z) approaches 0 without considering refraction effects. We correct the cos(Z) by adding a linear component to it to prevent cos(Z) from becoming infinitesimally small. The results from the scheme agree better with the BSRN than that from the DirIndex model.

Keywords: POWER, CERES SYN1deg, Diffuse horizontal irradiance, Direct horizontal irradiance, Direct normal irradiance, Bias-based correction

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1 Introduction

The NASA POWER surface meteorology and solar energy Version 6.0 (SSE V6.0) database is being superseded by the one based on the CERES SYN1deg (Ed4.1) hourly data. The SSE V6.0 dataset was derived from the NASA GEWEX SRB Release 3.0 monthly mean solar GHI and DHI that were derived from 3-hourly means spanning the time from July 1983 to December 2007. The method for deriving the monthly mean DNI was based on the regression analysis of the BSRN data that cover the years from 1992 to 2005, and the details of the regression analysis are available in Appendix A in Zhang et al. (2014). The monthly mean solar irradiance on surfaces tilted equatorward at various angles were derived using the method of Liu and Jordan (1960), the isotropic model (Duffie and Beckman, 2013) and the monthly average day (Klein, 1977).

Zhang et al. (2014) applied the DirIndex model to the GEWEX SRB Release 3.0 3-hourly GHI, and the resulting monthly mean DNI agree with the BSRN data better than those of SSE V6.0. The DirIndex model requires input of hourly all-sky and clear-sky GHI, surface pressure, sea-level pressure, aerosol optical depth (AOD) at 700 nm, atmospheric column water vapor and elevation angle of the Sun. So it is an overstretch of the model to apply it to 3-hourly data. Part of the reason that the model was applied to only the 6 years from 2000 to 2005 was that, at that time, the AOD data were available for only those 6 years.

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The CERES SYN1deg (Ed4.1) hourly solar irradiance dataset start from March 2000 and span to near present (Loeb et al., 2018; Rose et al., 2013; Rutan et al., 2015). In addition to GHI, the dataset also provides hourly DHI and direct horizontal irradiance (DirHI) along with hourly solar zenith angle (Z) which is derived such that the top-of-atmosphere hourly DirHI divided by cos(Z) is equal to the solar constant. The surface hourly DNI is then derived by dividing the hourly DirHI by cos(Z), namely DirHI/cos(Z), and the daily and monthly mean DNI are computed by arithmetically averaging the hourly DNI. Comparison with the BSRN data show, however, that the DNI derived as such are significantly negatively biased against the BSRN data. Further investigations show that the SYN1deg (Ed4.1) DHI are significantly positively biased against the BSRN while the DirHI are significantly negatively biased against the BSRN, though the sum of DHI and DirHI, namely the resuling GHI, agree with the BSRN fairly well.

We then applied the DirIndex model to the SYN1deg (Ed4.1) hourly GHI to derive the hourly, daily and monthly mean DNI and compared the results with BSRN. It was found that, although the DNI computed from the original SYN1deg (Ed4.1) data and simple division, namely, DirHI/cos(Z), are significantly biased against the BSRN, the uncertainty as represented by the root-mean-square error and standard deviation is much smaller than that of the results from the DirIndex model. In addition, we analyzed the biases of DHI and DirHI as functions of cos(Z), and found both exhibit simple, near-linear relation with cos(Z). This suggests to us that a simple bias-based correction according to cos(Z) can provide results better than that from the DirIndex model. In other words, this scheme can produce a dataset that is not only less biased but depicts the spatiotemporal variability better.

To be specific, the correction scheme is as follows: 1) Correct the GHI; 2) Correct the DHI; 3) Compute the corrected DirHI by subtracting result from Step 2) from result from Step 1); 4) Divide results from Step 3) by cos(Z) to get the corrected DNI.

In Section 2, the details of the bias-based correction will be given; in Section 3, the original CERES SYN1deg (Ed4.1) adjusted hourly GHI, DHI, DirHI and the derived DHI, or DirHI/cos(Z), will be compared with their BSRN counterparts; in Section 4, the corrected version will be presented; the conclusions will be given in Section 5.

2 The Solar Irradiance Data Based on the CERES SYN1deg (Ed4.1)

The Clouds and the Earth's Radiant Energy System (CERES) Mission flies instruments on multiple platforms to measure and monitor the Earth's Radiation Budget and its variability (Wielicki et al., 1996; Loeb et al, 2016). One of the CERES data products provides both the top-of-atmosphere and surface radiative fluxes, but using a radiative transfer model, together with Geosynchronous satellite observations and multiple ancillary inputs to compute the surface radiative fluxes (Rose et al., 2013; Rutan et al., 2015) globally gridded to 1°x1° resolution. This product, called the SYN1deg (Ed4.1), provides estimates of the surface hourly solar irradiance data spanning the period from March 2000 to within a few months of near present time and are now the source data for the POWER Web Services Suite (WSS). Two versions of the CERES SYN1deg (Ed4.1) hourly irradiances are available, the initial and adjusted. Based on comparisons with the BSRN data, we found that the "adjusted" GHI agree somewhat better with the BSRN than the initial one. The overall bias/σ of the adjusted version are -2.91/83.44 W m^{-2} and of the initial version are -4.51/82.44 W $m^{-2}$where σ stands for standard deviation; in a 20-bin analysis of the cos(Z), we found that except in a few extreme bins, the adjusted version is slightly better than the initial version in most of the bins. So we decided to use the adjusted version. Henceforth, all SYN1deg data refer to the adjusted version. Beside the hourly global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI), the POWER WSS derives the direct normal irradiance (DNI) by dividing the direct horizontal irradiance (DirHI) by the cosine of the solar zenith angle [cos(Z)], namely, DirHI/cos(Z). However, we found that, although the original SYN1deg (Ed4.1) DHI and DirHI sum to the GHI that agree reasonably well with the Baseline Surface Radiation Network (BSRN) data, the DHI and DirHI show appreciable positive and negative biases, respectively, against the BSRN data and, therefore, the derived DNI, or DirHI/cos(Z) also show significant biases against the BSRN data. To be precise, the overall bias/σ of the DHI are 30.58 W m^{-2}, and in the 20 bins of cos(Z), the bias increases steadily from -2.29 to 116.22 W m^{-2}, or from -21.78% to 41.75% of the mean BSRN DHI; the overall bias/σ of the DirHI are -37.09/116.48 W m^{-2}, and in the 20 bins of cos(Z), the bias changes from -2.18 to -90.40 W m^{-2}, or from -45.54% to -16.64% of the mean BSRN DirHI; the overall bias/σ of the derived DNI, or DirHI/cos(Z), are -54.32/196.35 W m^{-2}, and in the 20 bins of cos(Z) goes from 40.17 to -93.94 W m^{-2}, or from 89.97% to -16.79% of the mean BSRN DNI (Oumura et al., 1998).

So we decided to make a correction of the data. We have previously applied the DirIndex model to the GEWEX SRB GSW(V3.0) 3-hourly GHI to derive the 3-hourly DNI (Zhang et al., 2014; Ineichen, 2008), since the solar energy community is particularly interested in the DNI. The DirIndex model requires the inputs of the all-sky and clear-sky GHI along with surface pressure, aerosol optical depth at 700 nm, the atmospheric water vapor and so on. The DirIndex model has been found to be one of the two best global-to-beam models from among 140 separation models (Gueymard and Ruiz-Arias, 2016). More recently, we applied the DirIndex model to the CERES SYN1deg (Ed4.0) hourly data to get the SYN1deg-based hourly DNI (Zhang et al. 2017), and the overall bias/σ are found to be 8.54/228.81 W m^{-2}. The σ, or standard deviation, represents the magnitude of uncertainty, and this σ is about 17% larger than that of the DNI derived from the original SYN1deg (Ed4.1) DirHI, or DirHI/cos(Z). This implies that the DNI derived from the original SYN1deg (Ed4.1) hourly DirHI, albeit significantly biased in a systemic way, captures the spatiotemporal variability of the DNI than the DirIndex model does, and in addition, it is possible to perform a simple bias-based correction to get a set of DNI with a smaller uncertainty than that of the DirIndex model.

3 Comparison of the original CERES SYN1deg (Ed4.1) hourly irradiances with BSRN

Figs. 1-3 show the comparison of the original CERES SYN1deg (Ed4.1) hourly GHI, DHI, and DNI, or DirHI/cos(Z), with their respective BSRN counterparts. The hourly DirHI, which is biased on the opposite side of DHI at the same magnitude, is not shown due to limited space.

In terms of the overall statistics, the GHI agree with the BSRN reasonably well. In most of the 20 bins of the cos(Z), the biases are negative; in the five bins approaching the zenith, or the overhead position of the Sun, the biases are positive, and in the last bin, the bias maximizes at 24.04 W m^{-2}. The DHI, on the other hand, shows a positive overall bias of a significant magnitude, and in the 20 bins of cos(Z), the bias shows an unmistakable near-linear increasing trend on both the absolute and relative scales as shown in Fig. 2c-d. The DirHI, not shown here due to limited space, is biased equally significantly, though on the opposite side of DHI, because DirHI and DHI sum to GHI which agrees with the BSRN reasonably well. For this reason, the derived DNI, or DirHI/cos(Z), shows notable biases in the bins of cos(Z). The GHI, DHI, DirHI and DNI comparison statistics are summarized in Table 1.

The unambiguous near-linear pattern of the biases of DHI and DirHI in the bins of cos(Z) suggest that the biases are not just stochastic, but might be systemic, or deterministic. In addition, although the overall bias of DNI is considerable, the σ, or standard deviation, that represents the uncertainty of DNI, is still appreciably smaller than the DNI from the DirIndex model. These facts suggest that a simple bias-based correction can produce a set of DNI with an uncertainty smaller than that from the DirIndex model.

Table 1. CERES SYN1deg (ED4.1)-BSRN hourly all-sky GHI, DHI, DirHI and DNI comparison statistics from 2000-03 to 2020-07 before and after the correction. The DNI from the DirIndex model in the last line for comparison.

All-Sky Hourly	Bias	RMS	P	σ	μ_{DATA}	N
Original CERES SYN1deg (Ed4.1)						
GHI	-2.91	83.49	0.9566	83.44	341.63	3,331,148
DHI	30.58	85.86	0.8306	80.23	168.33	3,450,473
DirHI	-37.09	122.24	0.8881	116.48	192.60	3,009,959
DNI, or DirHI/cos(Z)	-54.32	203.73	0.8224	196.35	342.79	3,009,963
After Correction						
GHI	0.01	83.19	0.9567	83.19	344.54	3,331,148
DHI	0.01	65.70	0.8300	65.70	137.88	3,450,473
DirHI, or GHI-DHI	-0.02	106.45	0.9058	106.45	222.64	3,107,945
DNI, or DirHI/cos(Z)	0.72	182.15	0.8509	182.15	386.06	3,107,969
DNI from the DirIndex Model						
DNI from DirIndex Model[*1]	8.54	228.81	0.7580	228.65	444.91	2,195,000

*1. The DNI from the DirIndex model covers the period from 2000-04 to 2016-12 only.

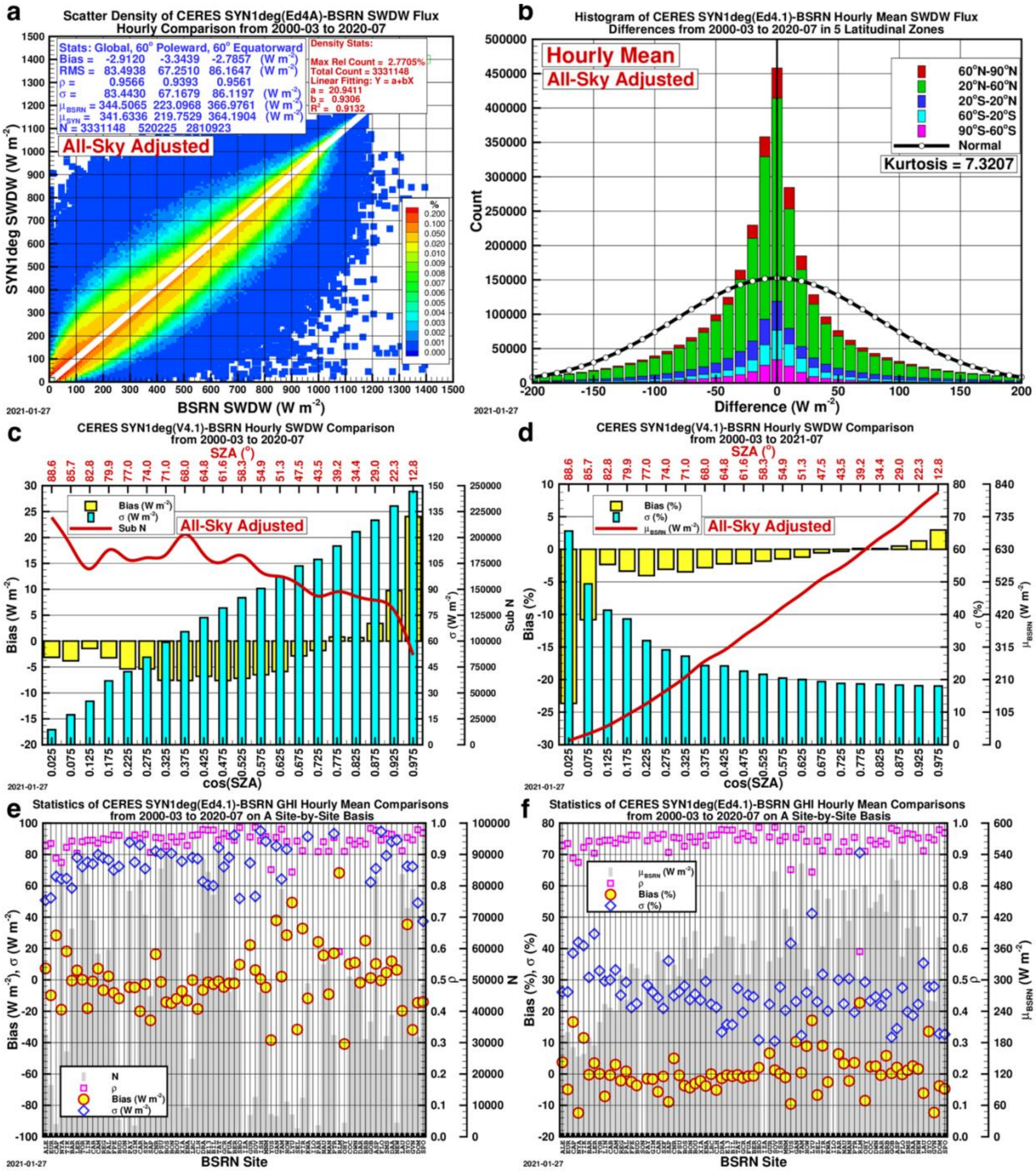

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Fig. 1. Comparison of the *original* CERES SYN1deg (Ed4.1) hourly GHI with the BSRN data from 2000-03 to 2020-07. a) The scatter density of the hourly GHI. The statistics shown are categorized as "Global" that includes all data points, "60° Poleward" and "60° Equatorward"; ρ stands for correlation coefficient, ρ standard deviation, μ_{BSRN} the BSRN mean, and N the total number of data points. b) Histogram of the SYN1deg (Ed4.1)-BSRN hourly GHI differences. c) and d) The biases in 20 bins of cos(Z) on absolute and relative scale, respectively. e) and f) The bias, σ and p on a site-by-site basis.

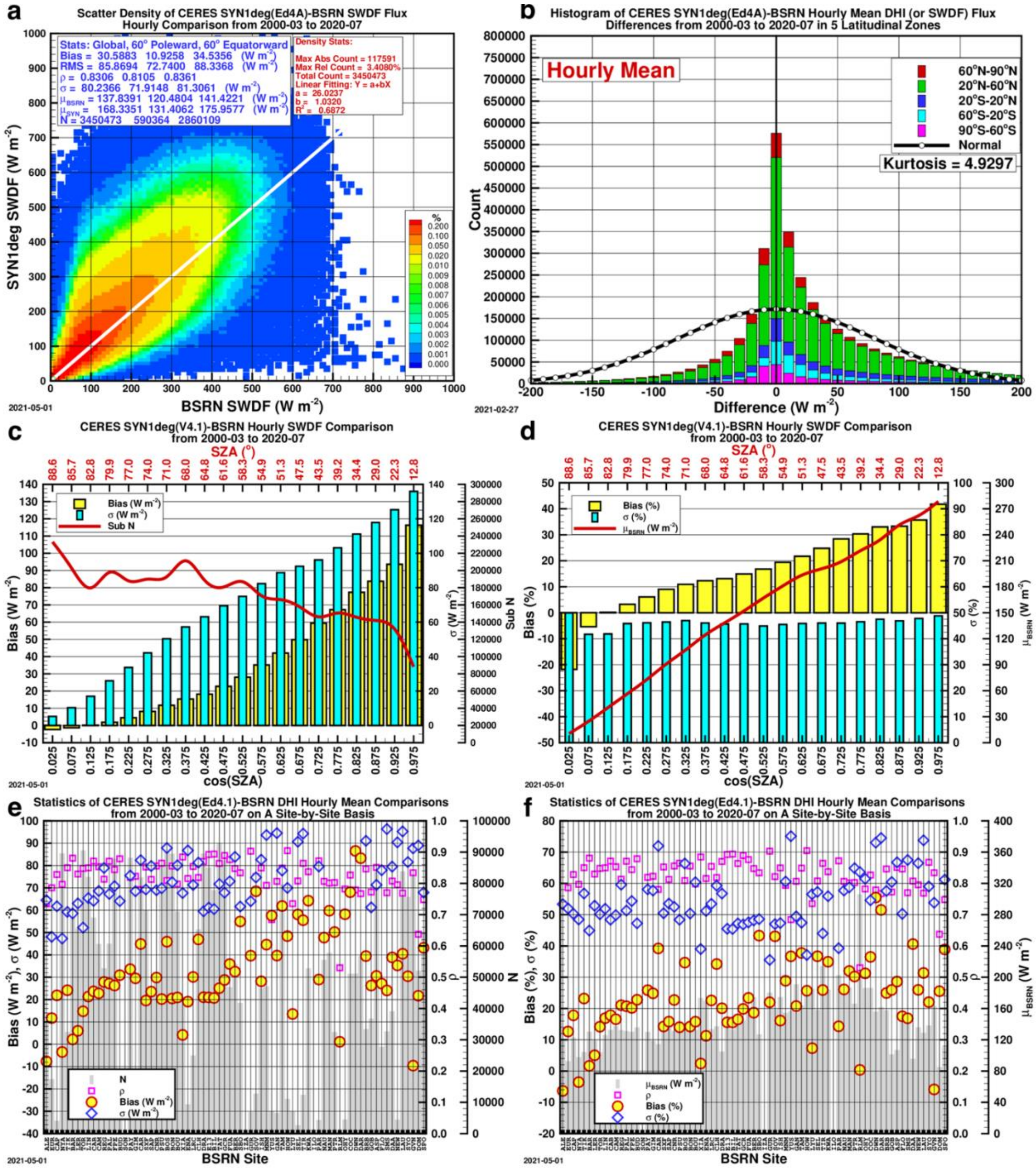

Fig. 2. Same as Fig. 1 except for DHI.

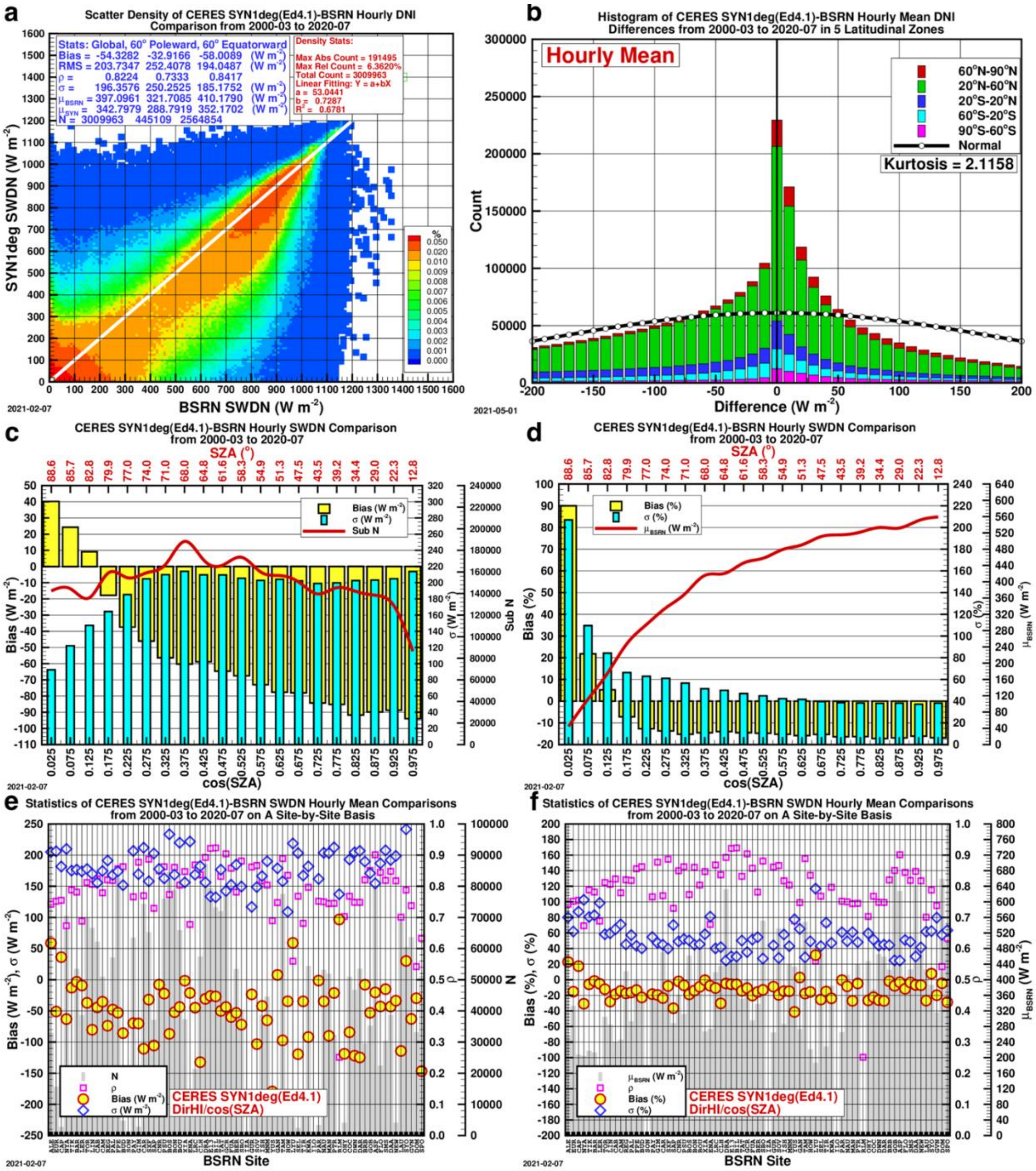

Fig. 3. Same as Fig. 1 except for DNI, or DirHI/cos(Z).

4 The Correction Methodology

4.1 The bias correction

The bias-based correction scheme is as follows: 1) Apply the bias-based correction to the DHI and GHI as well; 2) Subtract the DHI from the GHI to get a corrected version of DirHI; 3) Divide the DirHI by cos(Z) to get DNI. Note that the hourly solar zenith angle, Z, is part of the CERES SYN1deg (Ed4.1) data, and it is determined such that the top-of-atmosphere (TOA) DirHI divided by the cos(Z) is equal to the solar constant.

To perform the correction of DHI, the SYN1deg-BSRN hourly DHI biases are first calculated in 100 bins of cos(Z), as opposed to 20 bins in Figs. 1-3. In each bin, the bias is calculated on the absolute scale, $Bias$, in W m^{-2}, and on relative scale, R_{Bias} as percentage of the mean SYN1deg (Ed4.1) hourly DHI, as opposed to the BSRN hourly mean DHI, the bias is considered to represent the center of the bin. Now both $Bias$ and R_{Bias} are functions of cos(Z). For any given hourly DHI, I_{DH}, its corresponding cos(Z) is first used to determine its bias through linear interpolation; if the $Bias$ or R_{Bias} is negative, then the corrected DHI, $I_{DH}^c = I_{DH} - Bias$; if the the $Bias$ or R_{Bias} is positive, then the corrected DHI, $I_{DH}^c = I_{DH} \cdot (1 - R_{Bias})$. The scheme keeps or reduces the random variability of the original data.

The correction of GHI is similarly performed. The difference between the corrected GHI and corrected DHI is the corrected DirHI.

4.2 The modification of cos(Z)

Effective hourly solar zenith angle that correctly relates hourly direct horizontal irradiance and hourly direct normal irradiance has been studied (Blanc and Wald, 2016), and the CERES hourly solar zenith angle, Z, which is based on the relation between the hourly DirHI and DNI, or solar constant, at TOA, is one of the six methods studied. According to the study, the best result is based on a surface clear-sky model that computes clear-sky hourly DirHI and DNI.

Here, however, we will only modify the cos(Z) by adding a linear component for large Z values to prevent cos(Z) from getting too small. When $Z > 75°$, the value cos(Z) approaches 0 infinitesimally as the DirHI also approaches 0 and, and the error becomes a more and more significant part of the DirHI value. Consequently, the derived DNI, or DirHI/cos(Z) becomes haphazardly, or unphysically, large. The following correction of cos(Z) for $Z > 75°$ is proposed.

Let μ stand for cos(Z), and μ_{eff} for effective cos(SZA). If $Z \leq 75°$, then $\mu_{eff} = \mu$; if $Z > 75°$, then $\mu_{eff} = \mu + \mu_A$, where $\mu_A = -\frac{k}{\mu_{75d}}\mu + k$, $\mu_{75d} = \cos 75°$, and k is an adjustable parameter, and when $k = 0.045$, the biases are minimized for $Z > 75°$. In fact, the biases in all twenty 0.05-sized bins become one digit.

The corrected DHI, DirHI and derived DNI therefrom as compared to BSRN are shown in Figs. 4-6. The corrected GHI is not shown here due to limited space; it looks similar to Fig. 1 except with even smaller biases and other statistics, and the biases in all bins of cos(Z) are close to zero. Note that the BSRN data have been quality-checked, and Zhang et al. (2013) details the quality-check procedure.

Although the lower panels in Figs. 4-6 show that the site-by-site biases scatter around 0 over wide ranges, 43 sites of 70 in Fig. 6f are actually within ±10%. The larger biases at other sites do not necessarily mean bad data. Schwarz et al. (2018) studied how the BSRN point observations represent their larger surroundings, and they found that 26 sites out of 47 sites in the range from 50°S to 55°N are representative of their larger surroundings according to different metrics. Therefore, caution is advised when interpreting the differences between satellite-based and ground-based data.

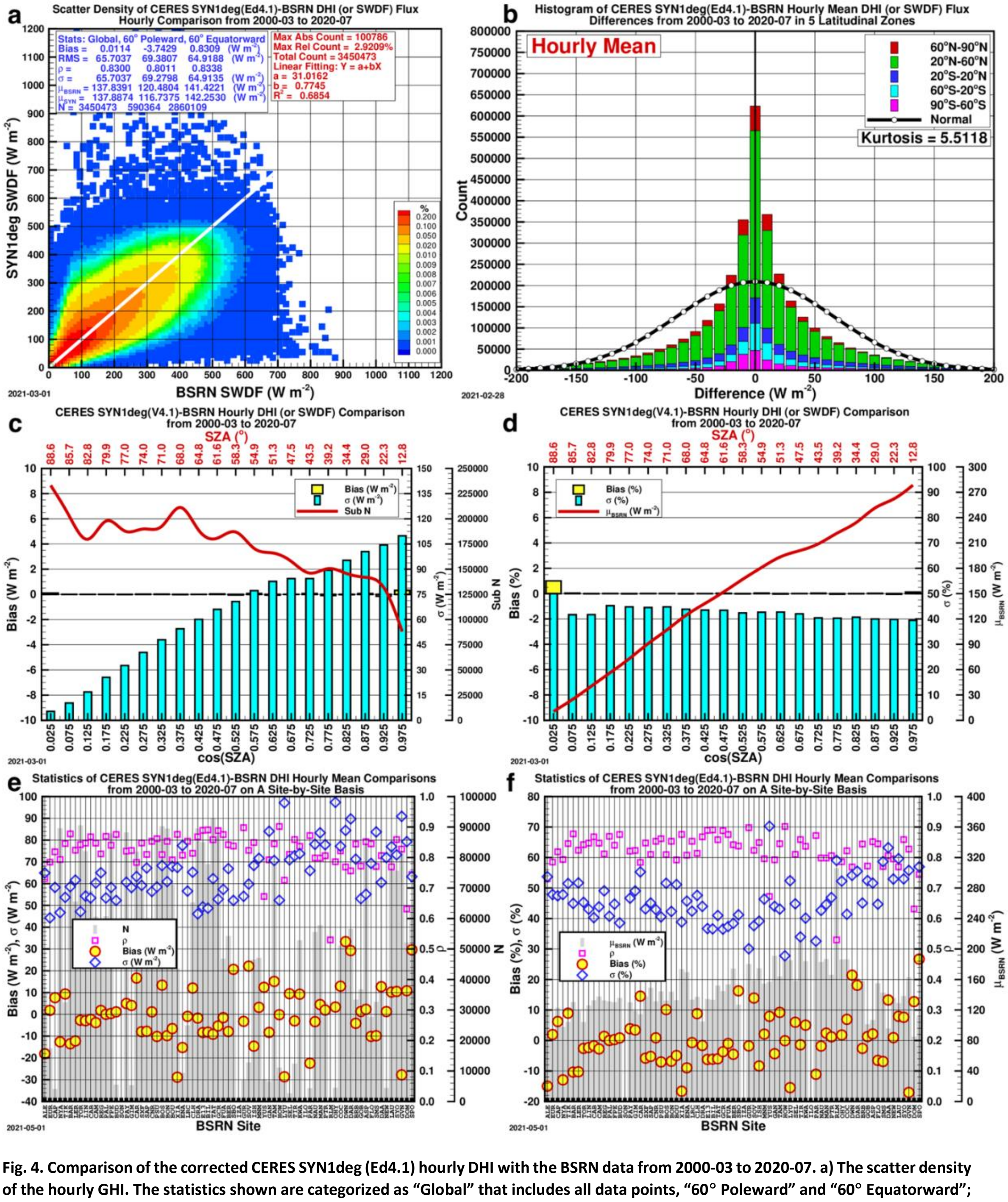

Fig. 4. Comparison of the corrected CERES SYN1deg (Ed4.1) hourly DHI with the BSRN data from 2000-03 to 2020-07. a) The scatter density of the hourly GHI. The statistics shown are categorized as "Global" that includes all data points, "60° Poleward" and "60° Equatorward"; ρ stands for correlation coefficient, ρ standard deviation, μBSRN the BSRN mean, and N the total number of data points. b) Histogram of the SYN1deg (Ed4.1)-BSRN hourly GHI differences. c) and d) The biases in 20 bins of cos(Z) on absolute and relative scale, respectively. e) and f) The bias, σ and p on a site-by-site basis.

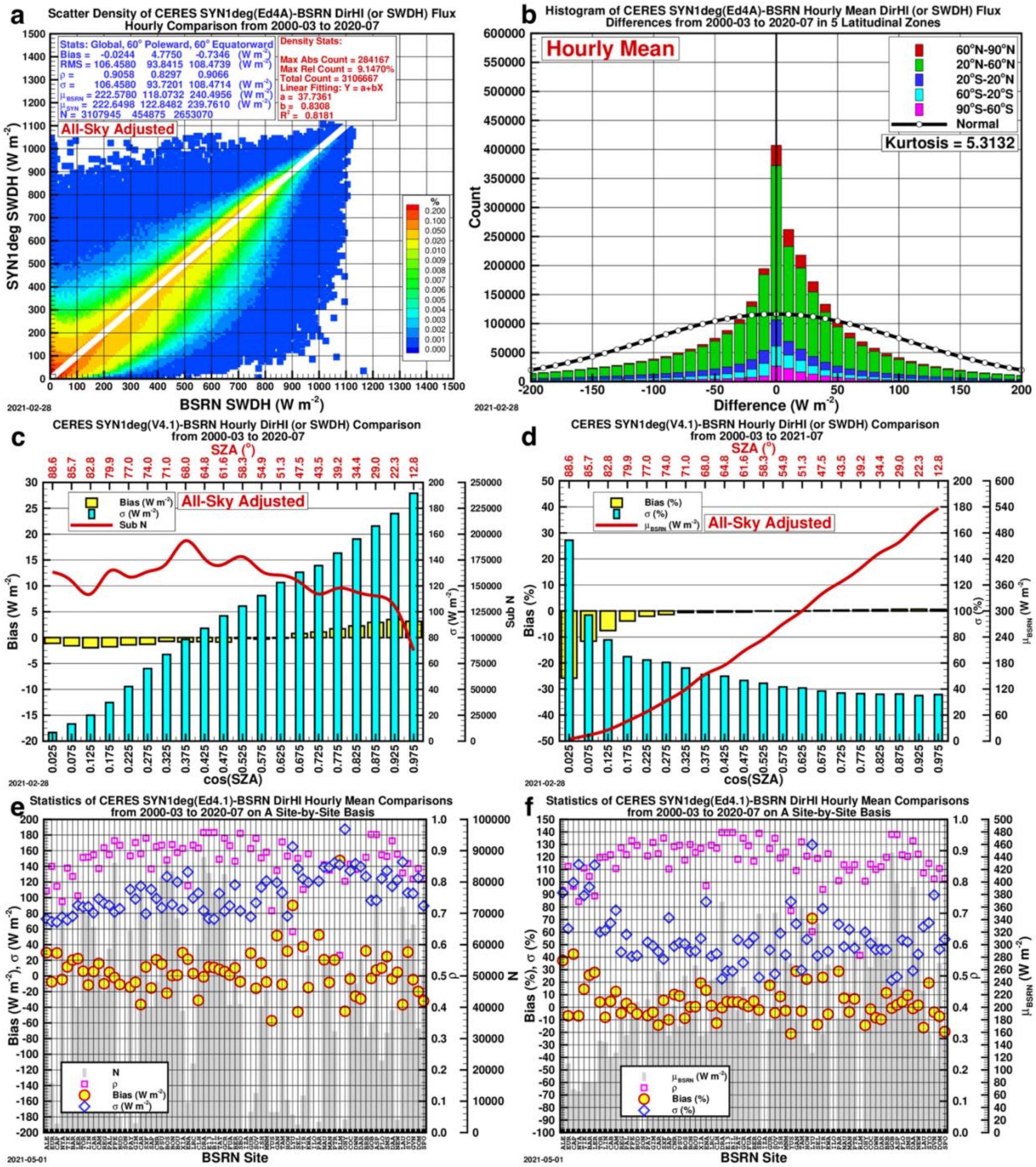

Fig. 5. Same as Fig. 4 except for DirHI, which is the difference between GHI and DHI, or GHI-DHI.

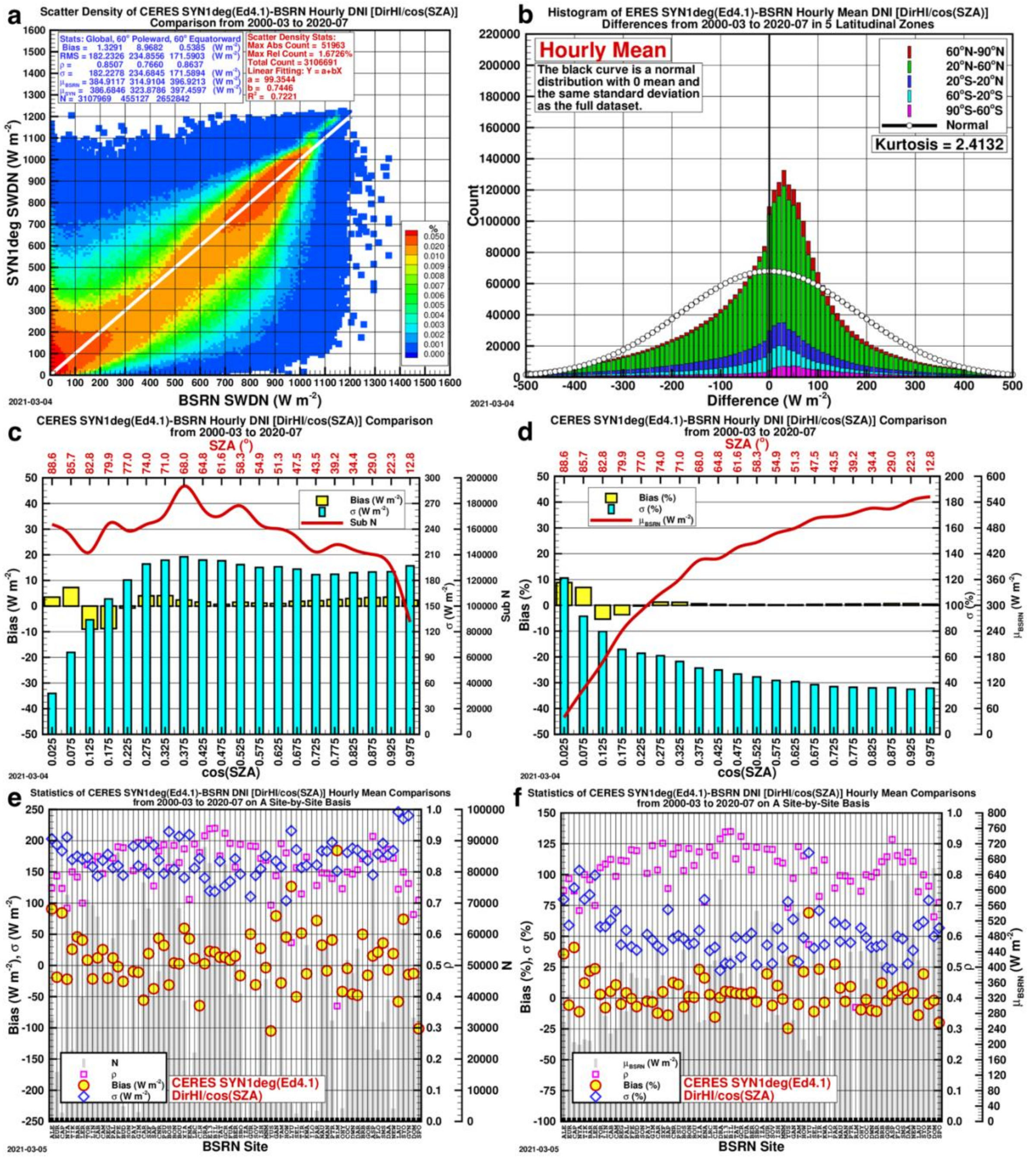

Fig. 6. Same as Fig. 5 except for corrected DNI, or DirHI/cos(Z).

5 Summary and Conclusions

The POWER WSS project needs GHI, DHI and, in particular, DNI. The CERES SYN1deg (Ed4.1) has hourly GHI and DHI, but not DNI, and instead, it has DirHI. However, it has been found that the DHI is positively biased against BSRN and, the DirHI is negatively biased against BSRN, and the biases become more and more pronounced as cos(Z) increases. Consequently, the derived DNI, or DirHI/cos(Z), is also negatively biased. In addition, the cos(Z) value approaches 0 infinitesimally toward sunset, and the derived DNI becomes haphazardly and unphysically large. Therefore, we performed a bias-based correction of the GHI and DHI, and use their difference, GHI-DHI as corrected DirHI, and the cos(Z) is modified by adding a linear component to cos(Z) when $Z > 75°$. The corrected DNI shows an overall minimal bias, and in all the 20 bins of cos(Z), the biases are all 1-digit on both the absolute and relative scales. More importantly, the overall standard deviation of the differences, or uncertainty, is significantly smaller than that of the DNI computed using the DirIndex model. To access the POWER solar data, visit https://power.larc.nasa.gov, select DATA ACCESS, then click POWER DATA ACCESSS VIEWER, click Access Data, select Renewable Energy, and the follow steps to select the data parameters and temporal averaging for a particular location. A complete Application Programing Interface is also provided as well as limited image services. Please see the main homepage for details.

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