

Evaluation of satellite and reanalysis products of downward surface solar radiation over East Asia: Spatial and seasonal variations

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[1] Surface solar radiation plays a crucial role in surface energy and water budgets, and it is also an important forcing for land hydrological models. In this study, the downward surface solar radiation (DSSR) from two satellite products, the Fengyun-2C satellite (FY-2C) and the Fast Longwave and Shortwave Radiative Fluxes project (FLASHFlux), and two reanalysis datasets, NCEP-DOE and ERA-Interim, was evaluated against ground-based observations (OBS) from 94 stations over mainland China during July 2006 to June 2009. It is found that the mean DSSR derived from FY-2C is comparable to OBS, with small positive biases of 3.0 Wm^{-2} for daily data and 3.5 Wm^{-2} for monthly data and moderate RMSEs of 49.3 Wm^{-2} (daily) and 31.9 Wm^{-2} (monthly). These results are comparable to those for FLASHFlux, which has the lowest RMSEs (43.2 Wm^{-2} and 30.5 Wm^{-2} for daily and monthly data, respectively) and the strongest correlations with OBS ($r=0.90$ and 0.93 for daily and monthly data, respectively) among the four products. The DSSR from the reanalyses has much larger RMSEs and generally lower correlations with OBS than the satellite products, especially for the NCEP-DOE products. Results also show that daily DSSR values are sensitive to the averaging grid size, while monthly mean DSSR is largely insensitive to the averaging scale. The DSSR from the four datasets over East Asia shows similar spatial patterns with large seasonal variations but differs in magnitude. In summer, high DSSR is observed over western China, while low DSSR is seen primarily over South Asia and the Sichuan Basin associated with extensive cloud cover (CC) and large precipitable water (PW). In winter, the high DSSR center shifts to South Asia due to decreased CC and PW, and the DSSR decreases from the South to the North. Deficiencies in the parameterizations of clouds, aerosols, and water vapor, as well as errors in atmospheric and surface properties for the retrieval algorithms contribute to the lower correlation of the DSSR derived from FY-2C ($r=0.82$ and 0.90 for daily and monthly data) with OBS than those from FLASHFlux product. Further improvements to the representation of clouds and aerosols in the FY-2C retrieval algorithm are needed.

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1. Introduction

[2] Surface solar radiation plays a crucial role in the energy and water cycles in the Earth's climate system. Quantitatively, it is a key driver of land surface hydrological models [Shi *et al.*, 2010], and it also affects the accuracy of land data assimilation [Jia *et al.*, 2009; Tian *et al.*, 2010]. Information regarding the spatial and temporal variations of downward surface solar radiation (DSSR) is needed for understanding the exchange of heat, water, and momentum across the land-atmosphere interface [Li *et al.*, 1995; Xia *et al.*, 2006]. Direct measurements of DSSR are sparse over most of the globe, especially in highland and mountainous regions. As a result, several approaches for estimating DSSR have

been developed, including satellite remote sensing retrieval [Pinker *et al.*, 1995], single-layer [Qiu, 2002] and multi-layer [Berk *et al.*, 1989; Li *et al.*, 1993; Pawlak *et al.*, 2004] radiative transfer modeling, empirical modeling based on surface meteorological data [Ehnberg and Bollen, 2005; Yang *et al.*, 2006], and using DSSR from both general circulation models (GCM) [Wild *et al.*, 2005] and reanalysis products [Kalnay *et al.*, 1996; Uppala *et al.*, 2005].

[3] The study by Wild [2009] showed that space-borne sensors with wide footprints offer an alternative approach to quantifying regional and global DSSR variations, as satellite-derived DSSR products have better spatial coverage than in situ measurements. However, satellite sensors do not measure DSSR directly but only record the fraction of solar radiation reflected back to the satellite. Several methods have been developed to derive DSSR indirectly from satellite-observed radiances and atmospheric and surface variables [Pinker *et al.*, 1995; Zhang *et al.*, 1995, 2004; Wang and Pinker, 2009] using either empirical or physical radiative transfer models together with information from satellite-derived atmospheric properties, the most important of which is clouds. Recently, several global products of surface solar radiation fluxes have been produced based on satellite observations [Zhang *et al.*, 2004; Stackhouse *et al.*, 2008]. For example, the NASA Goddard Institute for Space Studies (GISS) produced a 25-year (1983–2007) global dataset of radiative fluxes [Rossow and Schiffer, 1999] based on the International Satellite Cloud Climatology Project (ISCCP), known as ISCCP-FD [Zhang *et al.*, 2004]; the Global Energy and Water Cycle Experiment Surface Radiation Budget (GEWEX-SRB) project released various versions of global datasets of shortwave and longwave radiative fluxes [Pinker *et al.*, 2003]; and NASA's Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) project [Stackhouse *et al.*, 2008] provides near real-time surface and top-of-atmosphere (TOA) radiative fluxes derived from measurements by the Terra and Aqua satellites.

[4] Current satellite products of surface solar radiation, including DSSR, are likely to contain large uncertainties. In particular, changes in satellites and their orbits over time may induce spurious long-term changes that could hamper their application for assessing long-term trends in surface solar radiation [Pinker *et al.*, 2005]. Indeed, Wild [2009] pointed out that different satellite-derived DSSR products show inconsistent trends. Therefore, it is necessary to compare these products and understand their discrepancies. Masuda [2004] compared the monthly mean DSSR products from the GEWEX-SRB, ISCCP-FD and the University of Maryland Surface Radiation Budget (UMD-SRB) for Asia and Oceania, and found that the three products showed similar agreement with in situ measurements except for the Tibetan Plateau. Yang *et al.* [2008] made in-depth comparisons of the DSSR data from these products over the Tibetan Plateau and found that the UMD-SRB dataset, which has higher spatial and temporal resolutions, compared more favorably with surface measurements than the ISCCP-FD and GEWEX-SRB products. In addition, Hicke [2005] compared DSSR from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis [Kalnay *et al.*, 1996] and ISCCP-FD; Xia *et al.* [2006] analyzed DSSR

Table 1. Characteristics of the Five-Channel Visible and Infrared Spin Scan Radiometer (VISSR) on the FY-2C Satellite

Channel	Spectral Band (μm)	Spatial Resolution (km)	FOV (μrad)	Dynamic Range (K)
VIS	0.55–0.90	1.25	0–98%	35
IR1	10.30–11.30	5.00	180–330 K	140
IR2	11.50–12.50	5.00	180–330 K	140
IR3	3.50–4.00	5.00	180–330 K	140
WV	6.30–7.60	5.00	180–280 K	140

FOV = field of view; VIS = visible; IR = infrared; WV = water vapor.

from ground observations, NCEP/NCAR, ISCCP-FD, and UMD-SRB; and Qin *et al.* [2006] compared DSSR measurements from the Geostationary Meteorological Satellite series GMS-5 visible/infrared spin-scan radiometer (VISSR) with that from NCEP/NCAR, the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis (ERA40), and Japanese 25-year reanalysis (JRA25). They found that the reanalysis datasets significantly overestimated DSSR compared to the satellite estimates. However, little effort has been devoted to develop multi-decadal, high temporal-spatial resolution datasets of DSSR that can be used for land surface modeling. One high-resolution DSSR dataset (hourly, 0.1° $\times$ 0.1°) since June 2005 has been produced by the first of the Fengyun-2 series (FY-2C) of geostationary meteorological satellites operated by the China Meteorological Administration (CMA) [Yuan, 2005; Shi, 2008]. However, FY-2C-based DSSR product has not been evaluated extensively and is not known to the international community.

[5] The goal of this study is to evaluate and compare the DSSR data from the FY-2C and FLASHFlux satellite products and two recent reanalysis datasets using surface in situ observations and to quantify and investigate the spatial and seasonal variations of DSSR over East Asia. The DSSR products examined here have not been similarly evaluated either by Xia *et al.* [2006] or in other studies over East Asia.

[6] The FY-2C DSSR retrieval algorithm and a brief description of the other DSSR datasets used in this study are given in Section 2. Section 3 compares the DSSR from the various sources, and Section 4 discusses the DSSR over East Asia. A discussion of the causes of the discrepancies among different DSSR data sets is provided in Section 5. A summary is presented in Section 6.

2. Data and Evaluation Measures

2.1. FY-2C Retrievals of DSSR

[7] The FY-2 series of geostationary meteorological satellites, operated by CMA, are devoted to monitoring the environment and preventing meteorological disasters by observing and tracking extreme weather events. These satellites also provide valuable data for studying the climate of East Asia [Xu *et al.*, 2002; Zhang *et al.*, 2006; Lu *et al.*, 2008]. The FY-2C, launched on 19 October 2004, was the first operational satellite of the FY-2 series [Jin *et al.*, 2009]. Its geostationary orbit is located over the equator at 105° E. The major payload in FY-2C is a five-channel visible/infrared spin scan radiometer (VISSR) for detecting visible, infrared, and water vapor images of the Earth [Xu *et al.*, 2002; Lu *et al.*, 2008]. The characteristics of the VISSR instrument are listed in Table 1. FY-2C provides images with a high temporal resolution

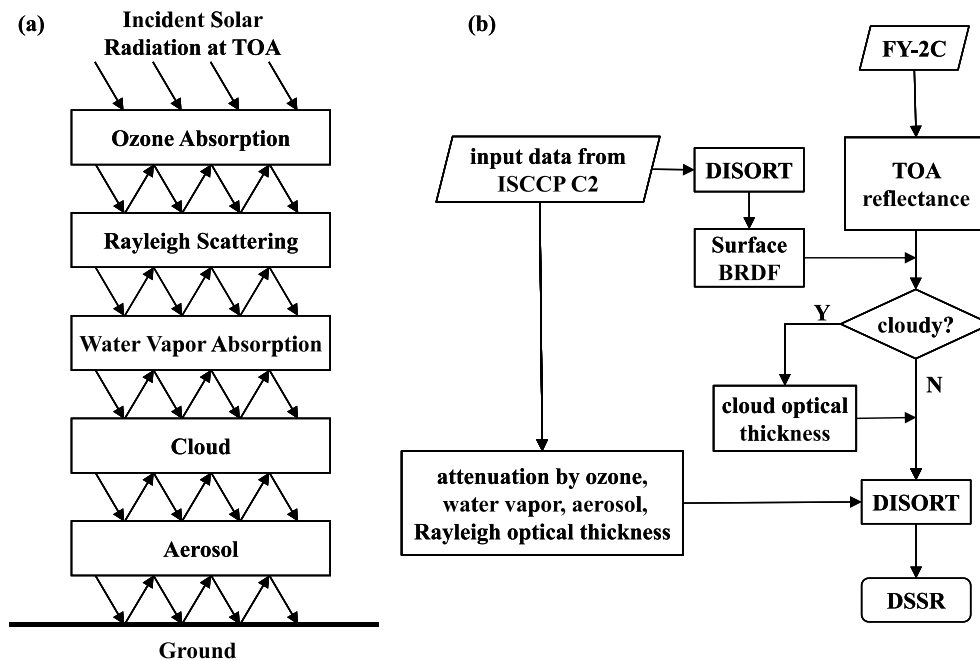


Figure 1. (a) Five main physical processes and (b) the flowchart of the retrieval algorithm of downward surface solar radiation (DSSR) from FY-2C satellite.

(48 observations per day during the crop growing season in China and 24 per day in other seasons) and a spatial resolution of $0.04^\circ \times 0.04^\circ$ [Jin *et al.*, 2009].

[8] The DSSR retrieval derived from FY-2C measurements with the visible channel uses the discrete ordinates radiative transfer program for a multi-layered plane-parallel medium (DISORT) method [Stamnes *et al.*, 1988] for radiative transfer calculations with the climatological monthly data from the ISCCP C2 product [Rossow *et al.*, 1991]. The plane-parallel atmospheric model with five vertical layers was selected for calculation of the atmospheric radiative transfer equation (Figure 1a) [Yuan, 2005]. As the incoming solar radiation destined for Earth's surface passes through the atmosphere, it is subject to five main physical processes: ozone absorption [Lacis and Hansen, 1974], Rayleigh molecular scattering [Marggraf and Griggs, 1969], scattering and absorption of cloud droplets [Pinker and Laszlo, 1992], water vapor absorption [Lacis and Hansen, 1974], and scattering and absorption of aerosols [Darnell *et al.*, 1988]. The scattering, absorption, and reflection of solar radiation were calculated for five solar spectral ranges (0.2–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, and 0.7–4.0 μm). The retrieval algorithm was described by Yuan [2005] and Shi [2008], which is summarized as follows (Figure 1b):

1. Calculation of surface bidirectional reflectance distribution function (BRDF) under clear skies. The solar zenith angle, satellite zenith angle, and relative azimuth angle between the Sun and the satellite are calculated first by the real measurement time onboard FY-2C; the solar absorption by the ozone and water vapor and the Rayleigh optical thickness are calculated using the methods of Lacis and Hansen [1974] and Marggraf and Griggs [1969], respectively, with input data of climatological monthly atmospheric precipitable water, ozone amount, surface visible

reflectance, surface pressure and atmospheric temperature from the ISCCP C2 data set. These atmospheric and surface properties were then used to drive the DISORT model to obtain the surface BRDF under clear skies. We realize that the use of the ISCCP C2 climatological properties (instead of real-time states) may induce substantial errors in the retrieved DSSR.

2. Determination of the presence of cloud in pixels: the real reflectance at TOA based on the radiance reflected toward the FY-2C satellite observation direction is calculated and then compared with the surface BRDF from Step 1. If the latter is smaller, the sky is considered as cloudy; otherwise, clear sky is assumed.

3. Retrieval of cloud optical thickness from the DISORT model using the data sets from Step 1 and real TOA reflectance from Step 2 and a fast approximation method.

4. Calculation of DSSR using DISORT model driven by the data sets from Step 1 under clear skies or both the data sets from Step 1 and the cloud optical thickness from Step 3.

[9] FY-2C observations are available for the period from June 2005 to November 2009. In this study, data from July 2006 to June 2009 are used. The study area is from 15°N – 55°N and 70°E – 140°E , which includes most East Asia. The DSSR product from FY-2C was created hourly with a high spatial resolution of $0.1^\circ \text{lon} \times 0.1^\circ \text{lat}$. To facilitate quantitative comparison with ground measurements, we used both the daily and monthly means, where the daily values were obtained using total solar radiation from sunrise to sunset calculated using a cumulative trapezoidal method [Yeh and Kwan, 1978] and then divided by 24 hours, and the monthly values were then calculated by averaging the daily mean values for each month (requiring a minimum of

27 days of observations). Outliers (outside the ± 3 SD range) in the daily DSSR were removed in the analysis. This method for the removal of the outliers was also applied to other three products (FLASHFlux, ERA-Interim, and NCEP-DOE), which are detailed below.

2.2. FLASHFlux Data

[10] The other satellite product of the DSSR used for comparison in this study is FLASHFlux from NASA [Stackhouse *et al.*, 2008; <http://flashflux.larc.nasa.gov/index.php>]. The FLASHFlux provides surface radiative fluxes on a near real-time basis using the Langley parameterized shortwave algorithm described in Gupta *et al.* [2001] and the Clouds and Earth's Radiant Energy System (CERES) and Moderate Resolution Imaging Spectro-radiometer (MODIS) measurements from NASA's Terra and Aqua satellites. The Time Interpolation and Spatial Averaging (TISA) data product of FLASHFlux is used in this study covering the period July 2006 to June 2009 inclusive. The FLASHFlux radiative estimates are provided globally at 1.0° spatial resolution and are available at hourly, daily, and monthly time steps.

2.3. NCEP-DOE and ERA-Interim Reanalysis Data

[11] This study also uses the monthly mean DSSR from July 2006 to June 2009 from two well-known reanalysis datasets: the NCEP-DOE AMIP-II reanalysis (NCEP-DOE) [Kanamitsu *et al.*, 2002] and the ERA-Interim reanalysis [Dee *et al.*, 2011] for comparison with the satellite DSSR data. The NCEP-DOE reanalysis data are available (<http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html>) globally at 6-hourly, daily, and monthly intervals since 1979, with a spatial resolution of T62 Gaussian grid ($\sim 1.875^\circ$). The ERA-Interim covers the period from 1989 to present, and we used the DSSR monthly data on a 1.5° grid obtained from http://data-portal.ecmwf.int/data/d/interim_daily.

2.4. Ground Observations

[12] The surface solar radiation data collected in Xianghe County (39.753°N , 116.961°E) were obtained to validate the four DSSR products. These in situ data have been quality controlled using the Baseline Surface Radiation Network (BSRN) quality control procedure [Xia *et al.*, 2007; Li *et al.*, 2007]. This site, which began operating on 21 September 2004, is located about 80 km southeast of central Beijing in northern China. The site is equipped with Kipp-Zonen CM21 and CM11 radiometers to measure global radiation and two other radiometers, an Eppley Normal Incidence Pyrheliometer (NIP) and a black-and-white radiometer (B&W) to measure the direct and diffuse components of radiation separately. Radiation measurements were taken at 1-min intervals [Li *et al.*, 2007]. Due to the limitations of the CM21 and CM11 radiometers [Xia *et al.*, 2007], in this study, the global radiation was calculated from the sum of the direct and diffuse radiation measurements by the NIP and B&W, which had an estimated uncertainty of $\sim 6\%$ [Stoffel, 2005].

[13] In addition, a dataset of daily and monthly solar radiation from ground observations (OBS) at 122 stations over China using thermopile pyranometers was obtained from the China Meteorological Data Sharing Service System (CMDSSS, <http://cdc.cma.gov.cn>) of the CMA and used

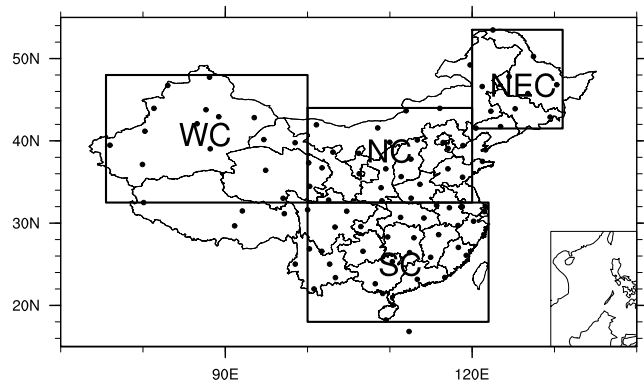


Figure 2. Distributions of 94 ground stations with measurements of global radiation in China. SC=South China; NC=North China; NEC=Northeast China; WC=West China.

to evaluate the DSSR products. Regular calibrations of the instruments and a basic quality control on this dataset had been performed by CMA [CMA, 1996]. However, the quality control done by CMA only required that both the direct and diffuse radiation components be lower than the global radiation for daily data. Therefore, additional quality assessments of the CMA dataset are needed. Due to lack of other radiation observations, we used the quality assessment (QA) scheme from Shi *et al.* [2008] to eliminate the poor-quality data points in the CMA dataset. This scheme includes a physical threshold test and a sunshine duration test for daily and monthly global radiation. Since only three-years of data were used in this study, we did not do the standard deviation test for annually averaged global radiation time series. As mentioned in Shi *et al.* [2008], the goal of the QA is to reject those data points that are physically unreasonable so that the errors of the solar radiation measurements would not exceed the 5% accuracy of the thermopile pyranometers. It should be noted that the measurement errors in the monthly averaged DSSR should be much smaller than this. After disregarding some stations because of incomplete or poor-quality records, 94 sites from the original 122 stations were selected to cover the target area of this study (Figure 2). The station measurements were sampled every 20 seconds and then averaged to derive daily mean values, from which the monthly values were derived by averaging the daily mean values. In this study, only the global radiation observations from this CMA data set (equivalent to DSSR) were used for comparison with the satellite and reanalysis DSSR values.

2.5. Issues Related to Data Resolution

[14] Inconsistency of the spatial resolution among different data sets is often an issue in dataset comparisons. For example, the point value of global radiation from a station may differ from that averaged over a grid box of $1\text{--}2^\circ$, especially for daily values. For monthly mean, spatial coherence in solar radiation is likely to have a longer distance than for daily data so that this inconsistency is less of an issue. Furthermore, although the FY-2C has a nominal resolution of 0.1° , its actual resolution is likely to be lower since its

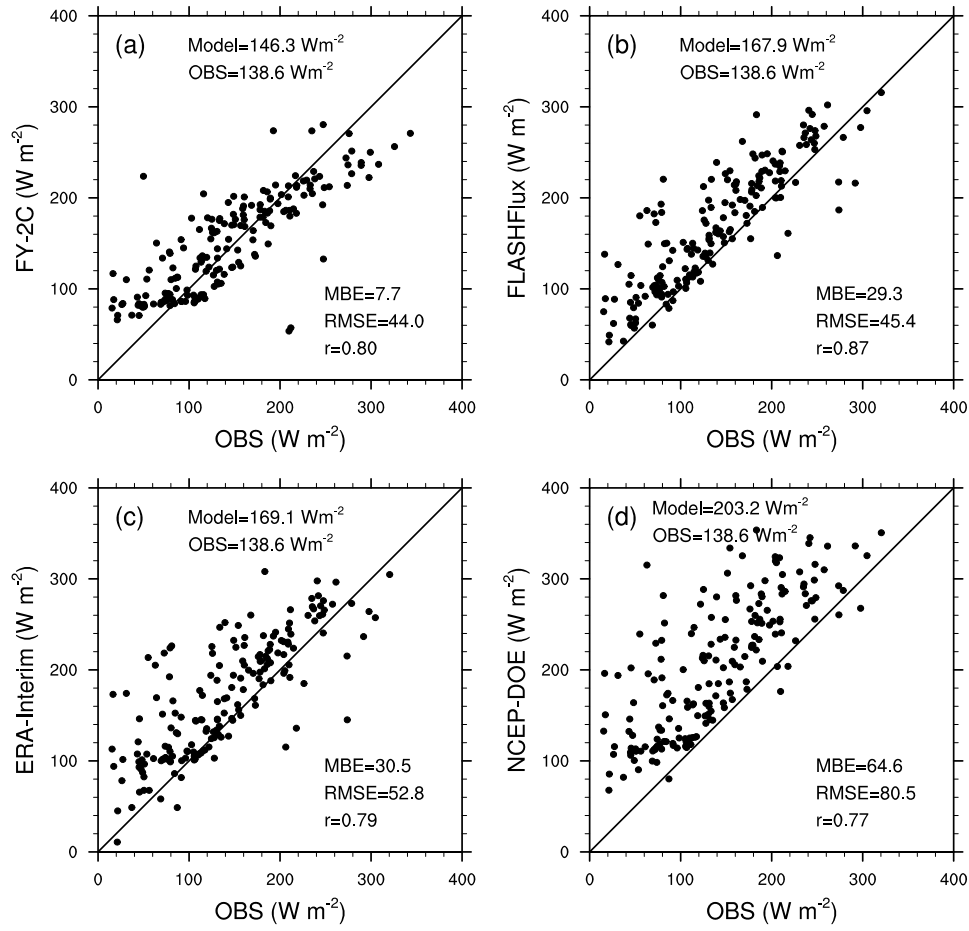


Figure 3. Comparison of daily DSSR from satellite and reanalysis products on the 2.5° collocated grid boxes, with in situ measurements at Xianghe site from 1 July to 31 December 2006. MBE = mean bias error; RMSE = root mean square error; r = correlation coefficient.

retrieval algorithm used input data from the ISCCP C2 data set, which is at 2.5° resolution. To minimize the effect of the different spatial resolutions among the satellite and reanalysis products, we first re-gridded all the original DSSR datasets onto a $2.5^\circ \text{ lat} \times 2.5^\circ \text{ lon}$ grid using a distance-weighted interpolation before comparing them with surface observations. In section 3.3, we attempt to quantify the effect of data resolution on the comparison. We emphasize that some of the differences discussed below may result from the incomparable spatial resolution of the data.

2.6. Performance Measures

[15] To quantify the performance of the various DSSR products in comparison with surface observations (OBS), we computed the mean bias error (MBE), the root mean square error (RMSE), the correlation coefficient (r), the normalized standard deviation (NSD), and the centered RMSE (cRMSE). They are defined as follows:

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (\mathbf{S}_i - \mathbf{O}_i), \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\mathbf{S}_i - \mathbf{O}_i)^2}, \quad (2)$$

$$r = \frac{\frac{1}{n} \sum_{i=1}^n (\mathbf{S}_i - \bar{\mathbf{S}})(\mathbf{O}_i - \bar{\mathbf{O}})}{\sigma_{\mathbf{S}} \sigma_{\mathbf{O}}}, \quad (3)$$

$$\text{NSD} = \sigma_{\mathbf{S}} / \sigma_{\mathbf{O}}, \quad (4)$$

$$\text{cRMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [(\mathbf{S}_i - \bar{\mathbf{S}}) - (\mathbf{O}_i - \bar{\mathbf{O}})]^2}, \quad (5)$$

where $\mathbf{S}$ is DSSR from either satellite or reanalysis dataset, $\mathbf{O}$ is surface observation of DSSR, $\sigma_{\mathbf{S}}$ and $\sigma_{\mathbf{O}}$ are the corresponding standard deviations related to $\mathbf{S}$ and $\mathbf{O}$, respectively.

3. Evaluation of Satellite and Reanalysis DSSR Products

3.1. Evaluation of Daily Satellite and Reanalysis Products

[16] We first compared the daily mean DSSR of the four products from the collocated 2.5° grid box with ground measurements at the Xianghe site from 1 July to 31 December 2006. The comparison (Figure 3) shows MBEs of 7.9 W m^{-2} (FY-2C), 29.3 W m^{-2} (FLASHFlux), 30.5 W m^{-2} (ERA-Interim), and 64.6 W m^{-2} (NCEP-DOE). The two satellite products have lower RMSEs ($\approx 45 \text{ W m}^{-2}$) than both of the reanalysis datasets (53 W m^{-2}).

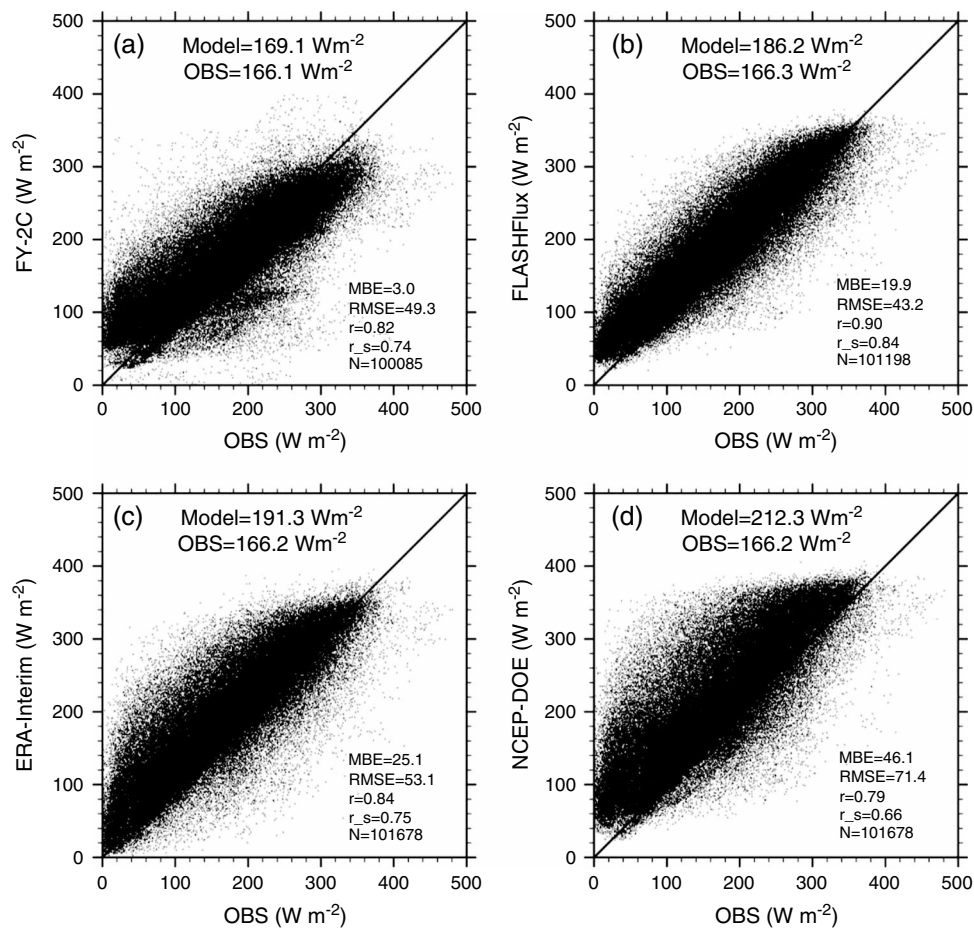


Figure 4. Same as Figure 3 but for the 94 sites (Figure 2) from 1 July 2006 to 30 June 2009. r_s = correlation coefficient with the annual cycle removed, N = total collocated data points.

for ERA-Interim and 81 W m^{-2} for NCEP-DOE). FLASHFlux is most closely correlated with the ground measurements ($r=0.87$); the other three products have similar correlation coefficients of $0.77\sim 0.80$.

[17] Daily DSSR data from the collocated 2.5° grid boxes from the four products from 1 July 2006 to 30 June 2009 were then compared with CMA ground-observed global radiation data (Figure 4). Of the four products, the FY-2C daily DSSR produces the lowest bias, with a MBE of 3.0 W m^{-2} and a moderate RMSE of 49.3 W m^{-2} , but relatively low correlation with OBS (correlation= 0.82 and 0.74 with (r) and without (r_s) the annual cycle, respectively). In contrast, FLASHFlux agrees most closely with OBS, with the lowest RMSE (43.2 W m^{-2}) and highest correlation coefficients ($r=0.90$ and $r_s=0.84$). The two reanalysis products, on the other hand, clearly overestimate the DSSR, with a bias $> 46 \text{ W m}^{-2}$ and $\text{RMSE} > 71 \text{ W m}^{-2}$ for NCEP-DOE. The result is consistent with the findings of *Betts et al.* [2006], who pointed out that a significant underestimation of cloudiness by the NCEP-DOE was the main reason for the large positive biases over the northern continents. The relatively poor performance of the two reanalysis products is especially true for North China (Table 3).

3.2. Evaluation of Monthly Satellite and Reanalysis Products

[18] Figure 5 shows the comparisons between the monthly satellite and reanalysis products and OBS at the 94 sites from the CMA between 1 July 2006 and 30 June 2009. Consistent with the daily data comparison, the monthly DSSR from the two satellite datasets agrees relatively well with the surface observations, with MBEs of 3.5 W m^{-2} (FY-2C) and 19.5 W m^{-2} (FLASHFlux) and RMSEs of 31.9 and 30.5 W m^{-2} , respectively. The two reanalysis products again overestimate the DSSR, with large MBEs of 25.1 W m^{-2} (ERA-Interim) and 46.1 W m^{-2} (NCEP-DOE) and RMSEs of 37.1 W m^{-2} and 56.5 W m^{-2} , respectively. The FLASHFlux DSSR has the highest correlation coefficient ($r=0.93$) of the four products. FY-2C and ERA-Interim products have lower correlations with OBS ($r=0.90$). The NCEP-DOE reanalysis compares relatively poorly with OBS, producing the lowest correlation coefficient ($r=0.88$). The main reasons for the discrepancies between the different DSSR products are discussed in section 5 below.

3.3. Effect of Spatial Resolution on the Comparison

[19] To investigate whether some of the differences shown in Figures 4 and 5 might have resulted from the different spatial resolutions of the DSSR products, the

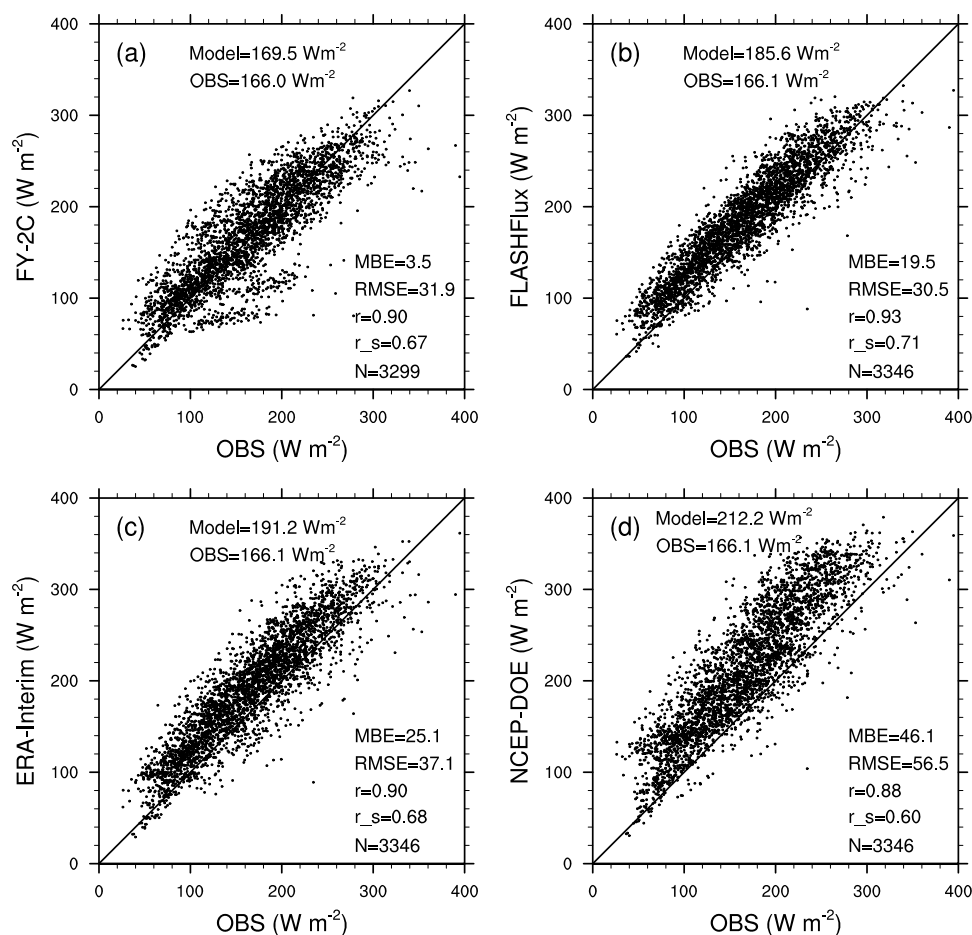


Figure 5. Same as Figure 4 but for the monthly DSSR.

high-resolution FY-2C DSSR data were averaged to lower resolutions and compared with OBS at daily and monthly scales for the period from 1 July 2006 to 30 June 2009 (Figure 6). It is clear that the monthly results are insensitive to the spatial resolution. However, for daily DSSR, the correlation and RMSE are considerably worse at 2.5° resolution than the cases of higher resolutions. This suggests that the mismatch in DSSR data resolutions between OBS and any of the four products may contribute to the differences between daily DSSR from OBS and the four products, although this mismatch with OBS is similar among the four products and thus should not contribute to the different performances among the four products shown in Figures 3 and 4. To gain further insights into the errors related to scale mismatch in the DSSR data, we made a comparison between two satellite retrievals of daily and monthly DSSR using the method proposed by *Li et al.* [2005], with the results shown in Table 2. One retrieval is the FY-2C satellite-simulated “point measurements” over $0.1^\circ \times 0.1^\circ$ grid boxes (from the original FY-2C product), each containing one of the 94 ground stations (Figure 2), while the other is the areal mean DSSR from the FY-2C DSSR product at different spatial resolutions (0.25° , 0.5° , 1.0° , and 2.5°). Since the two sets of DSSR data were retrieved from the same FY-2C satellite observations using the same algorithm,

the difference between the “point measurements” and the grid-box mean DSSR provides a measure of the errors due to the mismatch in the spatial scales represented by the types of the DSSR data. Table 2 shows that, as the grid size increases, the RMSE increases and the correlation coefficient decreases for both daily and monthly data. This suggests that the mismatch error increases as the scale difference increases, which is expected. However, the RMSE for monthly mean DSSR is substantially lower than that for daily DSSR, and it remains very small (less than 7 W m^{-2}) even as the scale difference increases. This result is consistent with the findings of *Li et al.* [2005], who showed that averaging over periods greater than 5 days reduced the sampling error to less than 15 W m^{-2} for the surface net solar radiation data derived from the Geostationary Operational Environmental Satellite.

3.4. Performances of Satellite and Reanalysis Products Over Different Subregions

[20] To examine regional differences in the performance of the FY-2C and other products, four subregions over China are defined (Figure 2) and evaluated (Table 3). These are similar to the divisions in the study by *Xia et al.* [2006], except that in this study, each region covers more area to include more in situ sites. Table 3 shows

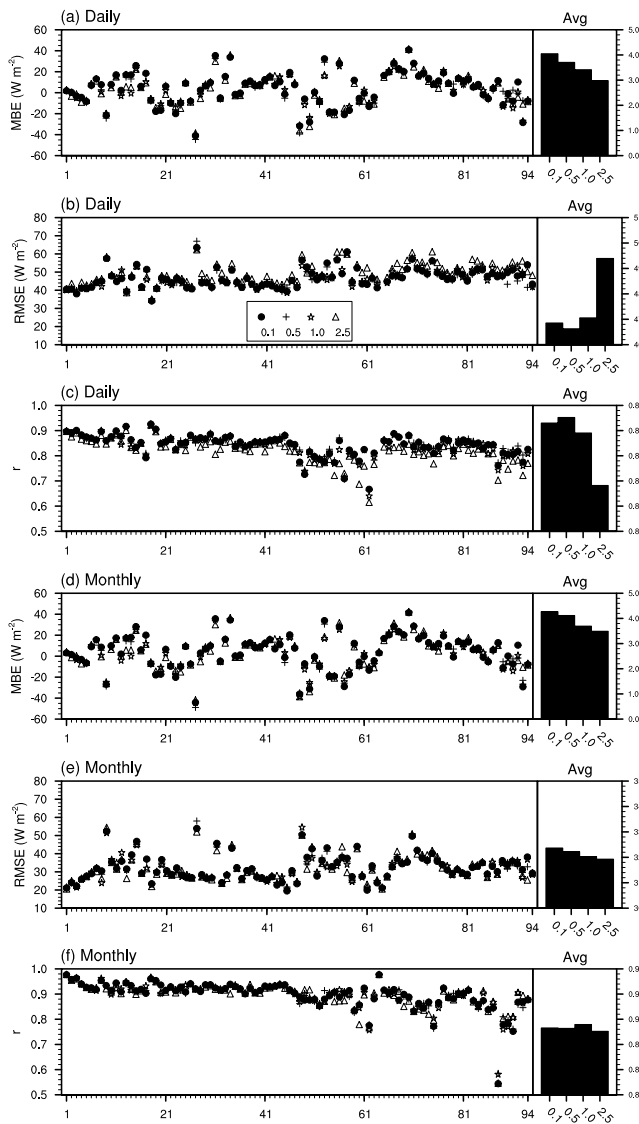


Figure 6. MBE, RMSE, and r over each of the 94 sites (see Figure 2) and their average values (Avg) for (a)–(c) daily and (d) – (f) monthly DSSR from the FY-2C product at different spatial resolutions, compared with collocated station observations July 2006 to June 2009. The x -axis on the left-hand side represents 94 sites; x -axis on the right-hand side represents spatial resolutions (0.1° , 0.5° , 1.0° , and 2.5°).

Table 2. The RMSE (Wm^{-2}) and Correlation Coefficients (r) Between FY-2C Satellite-Simulated “Point Measurements” at 0.1° Resolution (Used as the Reference) and Areal Mean Values Averaged Over Larger Grids of Varying Size From 0.25° to 2.5° for Daily and Monthly Mean DSSR

Spatial Resolutions	Daily		Monthly	
	RMSE	r	RMSE	r
0.25°	4.89	0.9964	2.02	0.9992
0.5°	7.64	0.9917	2.99	0.9986
1.0°	9.71	0.9877	4.36	0.9976
2.5°	15.11	0.9691	6.39	0.9943

The difference between the point DSSR and the larger grid box mean DSSR is a measure of the error due to the mismatch in the averaging spatial scales between the two types of DSSR values.

that the mean biases are lower in Northeast China (NEC) and West China (WC) than in North China (NC) and South China (SC). The lowest RMSE of the four products for the four regions was found in NEC. The FY-2C product is in good agreement with OBS, with mean biases of only 4.7 Wm^{-2} in NEC, -0.1 Wm^{-2} in WC, and no more than 6 Wm^{-2} in both NC and SC. The FLASHFlux product shows noticeable positive biases over all the regions, with a minimum bias of 14 Wm^{-2} in NEC, which is greater than the maximum bias for FY-2C. However, FLASHFlux gives the lowest RMSE of the four products, except in NC. Compared with OBS, the ERA-Interim reanalysis overestimates DSSR by about $10\text{--}35 \text{ Wm}^{-2}$, and the NCEP-DOE reanalysis overestimates DSSR by an even greater amount of about $30\text{--}60 \text{ Wm}^{-2}$. The RMSEs over the four subregions for ERA-Interim are around $30\text{--}42 \text{ Wm}^{-2}$ and for NCEP-DOE are $44\text{--}65 \text{ Wm}^{-2}$.

[21] Figure 7 shows the Taylor diagram [Taylor, 2001] comparing all available monthly DSSR from OBS and collocated grid values from two satellite products and two reanalysis datasets over the four regions for the period from July 2006 to June 2009. All the satellite and reanalysis products show the best agreement with OBS in NEC (black dots in Figure 7), with the correlation $r > 0.96$ and the normalized standard deviations (NSD) between 0.75 and 1.25, except for FY-2C ($r=0.93$) and NCEP-DOE ($\text{NSD}=1.3$). Relatively weak correlation between the four DSSR products and OBS is seen over NC and SC. The main reason is likely due to stronger seasonal variations in NEC (which increase the correlation with OBS) and larger effects of cloudiness, water vapor, and aerosols over NC and SC (see Section 5 for more discussions). Despite lower biases with OBS (Table 3), the FY-2C product has lower correlations and higher cRMSE than FLASHFlux. Figure 7 also shows that the FLASHFlux DSSR correlates best with OBS despite higher biases than FY-2C (Table 3). Unlike the NCEP-DOE reanalysis, the ERA-Interim DSSR matches OBS relatively well, comparable to the performance of the two satellite products.

4. Spatial and Seasonal Variations of DSSR

[22] Since ground observations are available only at a limited number of sites, and thus, they are insufficient for studying DSSR spatial variations; here, we use the satellite and reanalysis products to examine the spatial

Table 3. (a) MBE and (b) RMSE in Wm^{-2} and in % of the Mean (in Parentheses) of the DSSR From the Satellite or Reanalysis Products Compared With Ground Observations Over Four Subregions in China

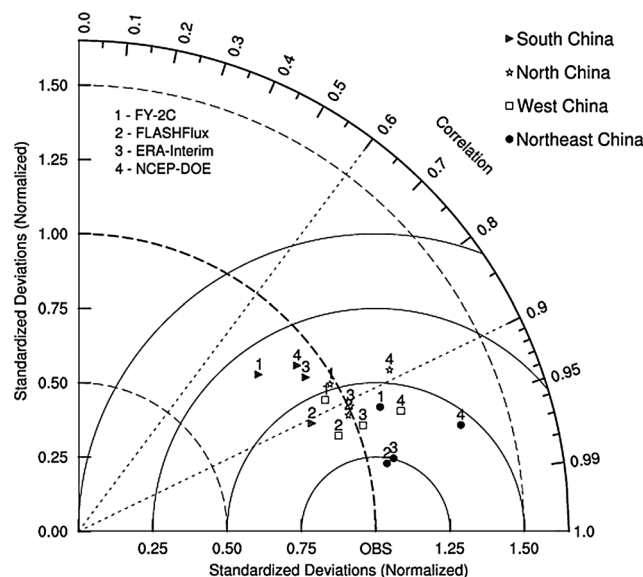
(a) MBE				
Products	Northeast China	West China	North China	South China
FY-2C	4.7 (3%)	-0.1 (0.05%)	5.2 (3.1%)	6.0 (4%)
FLASHFlux	14.0 (9%)	14.2 (7.5%)	20.6 (12%)	24.7 (16.5%)
ERA-Interim	13.1 (8.4%)	25.9 (13.7%)	24.7 (14.4%)	30.2 (20.2%)
NCEP-DOE	41.2 (26.5%)	31.5 (16.7%)	55.2 (32.1%)	47.8 (31.9%)
(b) RMSE				
Products	Northeast China	West China	North China	South China
FY-2C	26.6 (17.1%)	31.8 (16.8%)	30.7 (17.9%)	33.4 (22.3%)
FLASHFlux	20.2 (13.0%)	29.6 (15.7%)	32.2 (18.7%)	32.5 (21.7%)
ERA-Interim	30.4 (19.6%)	37.5 (19.8%)	36.2 (21.1%)	41.5 (27.7%)
NCEP-DOE	50.2 (32.3%)	44.3 (23.4%)	64.6 (37.6%)	56.9 (37.9%)

patterns of DSSR. Figure 8 shows the spatial distributions of the mean DSSR averaged from July 2006 to June 2009 (left column) over the Asia Pacific domain from the satellite products and reanalysis datasets, together with four factors (right column) that affect DSSR. These include the total cloud cover (CC) and aerosol optical thickness (AOT) from the MODIS observations (<http://modis.gsfc.nasa.gov>), and the precipitable water (PW) and incident solar radiation at the top of the atmosphere (ISR-TOA) from the ERA-Interim reanalysis. It can be seen that all four products show similar broad patterns, with high DSSR ($180\text{--}280 \text{ Wm}^{-2}$) over western China, South Asia, and the North Pacific Ocean and low DSSR ($120\text{--}200 \text{ Wm}^{-2}$) over southeastern and northeastern China. The reduction of DSSR by the extensive cloud cover (more than 70%; Figure 8e) over southern and central China is captured by all four products, especially over the Sichuan Basin

where the CC is more than 80% and DSSR is less than 160 Wm^{-2} (180 Wm^{-2} for NCEP-DOE). On the other hand, the high DSSR values over the Tibetan Plateau are associated with low cloud amount (50%), AOT (0.2), and PW (5 mm). Compared with FY-2C and FLASHFlux (and OBS, see Table 3), the reanalysis datasets clearly overestimate DSSR, especially over the Tibetan Plateau where the DSSR values from ERA-Interim and NCEP-DOE are 40 Wm^{-2} higher than the satellite products. The FY-2C DSSR shows considerably lower DSSR (and thus smaller MBE, Table 3) and less spatial variation than the other products.

[23] Figure 9 shows the multi-year seasonal patterns of the four DSSR products from July 2006 to June 2009, and Figure 10 shows the corresponding multi-year seasonal maps of the four factors affecting DSSR. Similar to the annual mean, the FY-2C DSSR shows lower values and smaller spatial and seasonal variations than the other products. In contrast to the regular, large seasonal variations in ISR-TOA (Figure 10), the DSSR maps (Figure 9) show complex regional variations mainly due to the damping effects of clouds, water vapor, and aerosols. For example, DSSR over South Asia is less than 170 Wm^{-2} in June to August (JJA) due primarily to large cloud amount during the monsoon season (Figure 10e). This DSSR minimum occurs in Southeast China in March to May (MAM) as cloud amount peaks there (Figure 10a). The annual cycle of the ISR-TOA dominates DSSR's seasonal variations over northern China and central Asia.

[24] The FY-2C DSSR varies from 210 to 270 Wm^{-2} over most of the East Asia domain ($15^{\circ}\text{--}55^{\circ}\text{N}$, $70^{\circ}\text{--}140^{\circ}\text{E}$) during MAM, except in southeastern China where large amounts of clouds ($>70\%$; Figure 10a) and precipitable water ($>25 \text{ mm}$; Figure 10c) reduce DSSR to less than 190 Wm^{-2} . In JJA, DSSR over most of China is not notably different from MAM, but it decreases to 170 Wm^{-2} over South Asia (Figure 9e) due to increased cloudiness ($\sim 90\%$; Figure 10e) and precipitable water (60 mm ; Figure 10g) in these regions. In September to November (SON) (Figure 9i), DSSR decreases to around $90\text{--}150 \text{ Wm}^{-2}$ over most of East Asia except for the Tibetan Plateau, where fewer clouds ($\sim 40\%$; Figure 10i) and little precipitable water (5 mm ; Figure 10k) allows more incident solar radiation to reach the surface. During the boreal winter (DJF, Figure 9m), DSSR decreases to around $50\text{--}110 \text{ Wm}^{-2}$

**Figure 7.** Taylor diagram summarizing the comparison results of satellite and reanalysis DSSR products compared with ground observations (OBS) over the four subregions.

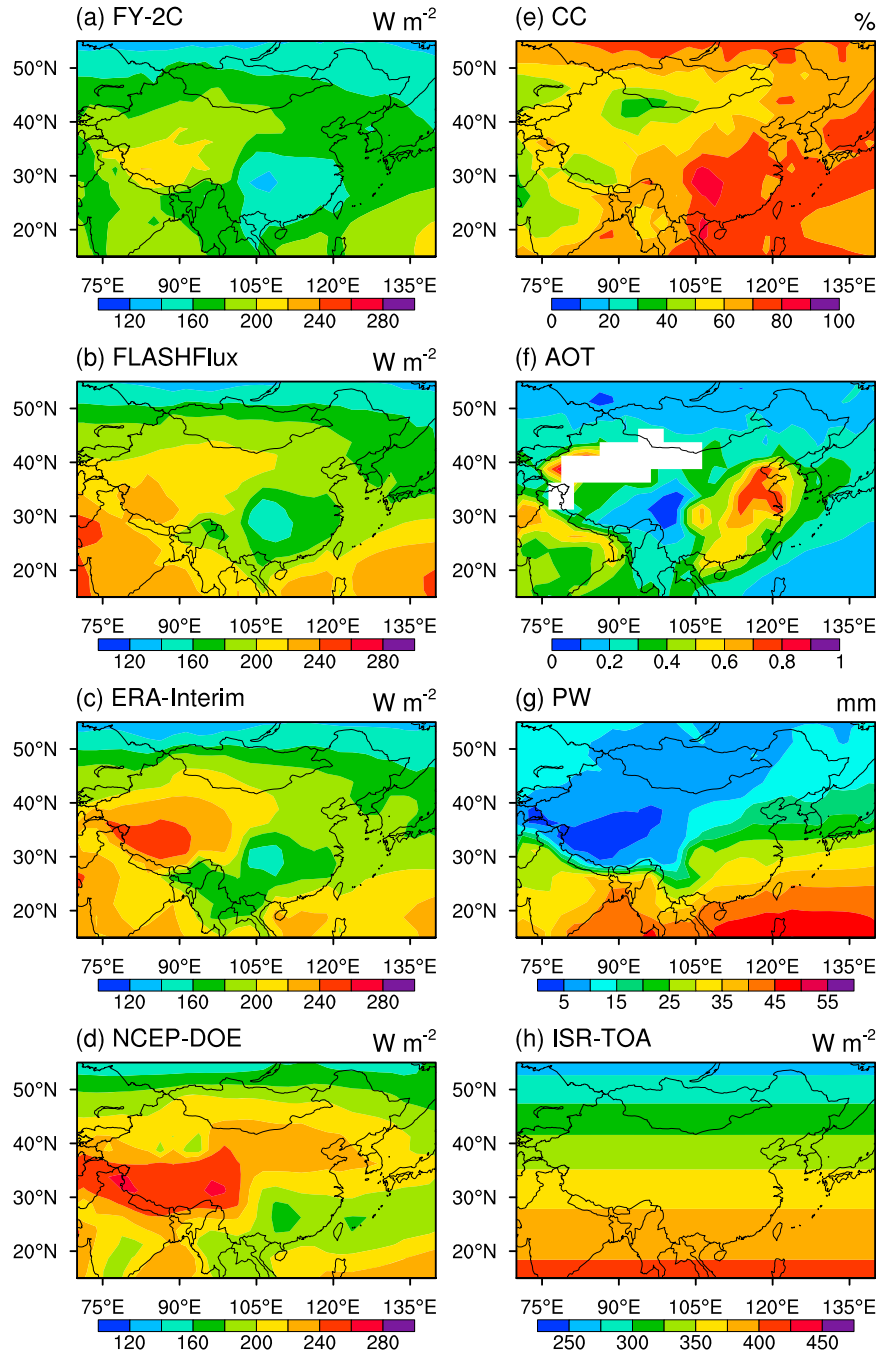


Figure 8. Three-year (July 2006–June 2009) mean DSSR (Wm^{-2}) from (a) FY-2C, (b) FLASHFlux, (c) ERA-Interim, and (d) NCEP-DOE, compared with (e) total cloud cover (CC), (f) aerosol optical thickness (AOT), (g) total precipitable water (PW), and (h) incident solar radiation at the top of atmosphere (ISR-TOA) (Wm^{-2}). CC and AOT are from MODIS, and PW and ISR-TOA are from ERA-Interim.

north of about 40°N and over the Sichuan Basin in central China (due to high cloud amount there, ~80%; Figure 10 m), while the Tibetan high DSSR center largely disappears. These seasonal variations are also seen in FLASHFlux and the two reanalysis datasets, except for some regional mean biases (e.g., over western China and South Asia).

[25] To calculate the spatial correlation between the DSSR and each of ISR-TOA, CC, PW, and AOT, the intercorrelation of the four factors needs to be removed. This can be reached through the following steps: 1) to calculate the spatial correlation coefficient r using equation (3) between DSSR and ISR-TOA and remove the variations associated with ISR-TOA through linear

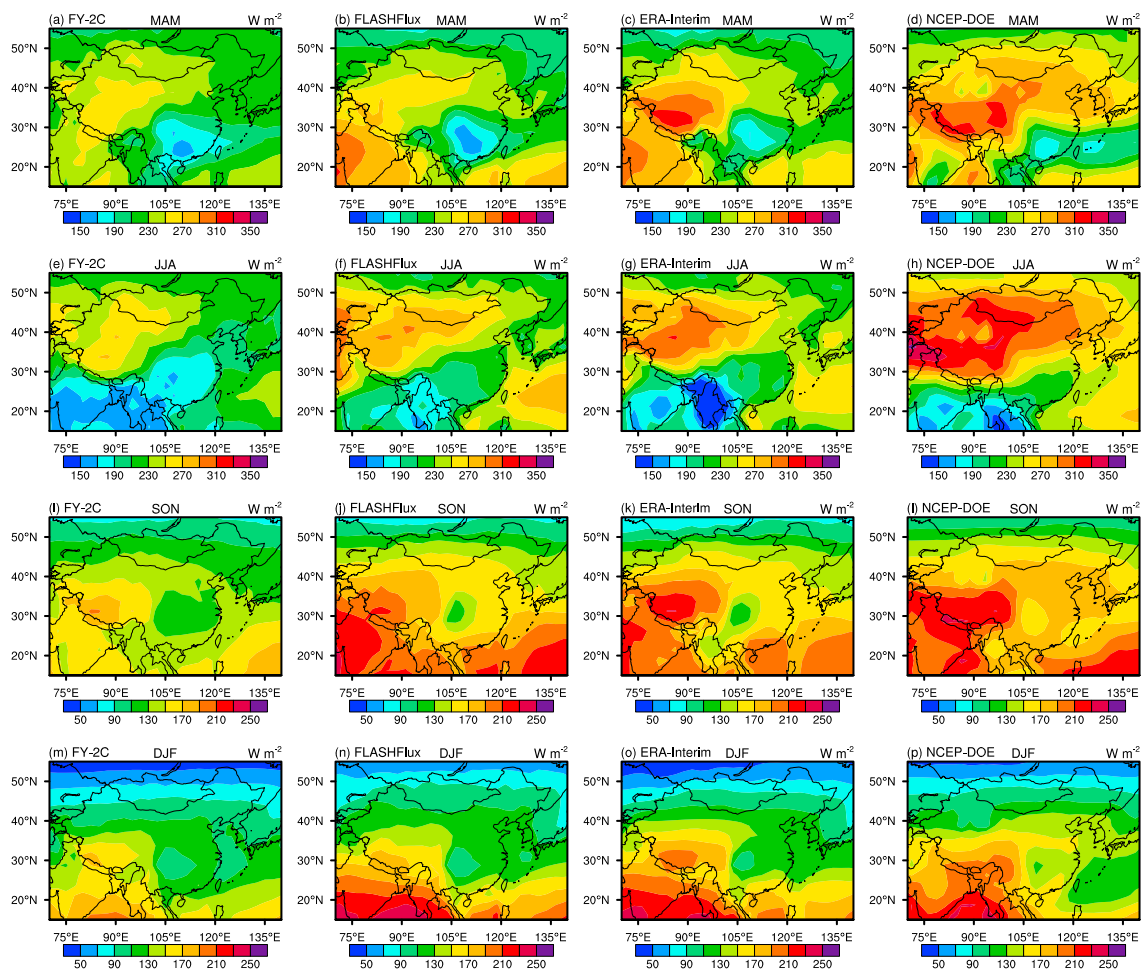


Figure 9. Three-year (July 2006 to June 2009) mean seasonal DSSR patterns from the satellite (FY-2C, FLASHFlux) and reanalysis (ERA-Interim, NCEP-DOE) products, (a–d) March to May (MAM), (e–h) June to August (JJA), (i–l) September to November (SON), and (m–p) December to February (DJF). Units are W m^{-2} .

regression; 2) to compute the partial correlation between the remaining DSSR variations and CC and remove the CC-induced variations; 3) to use same methodology on PW and AOT. The squared r or pr values from these correlations are used to quantify the spatial variations explained by each factor. Figure 11 shows the squared spatial correlation coefficients between the DSSR and four factors for the four seasons, with the gridded data values weighted by the square root of the grid-box area in the calculation. The incident solar radiation at TOA has a large influence ($r^2 > 0.62$) on DSSR's spatial variations over East Asia in SON and DJF, while the DSSR spatial variations in MAM and JJA are mostly affected by clouds ($pr^2 = 0.4$ to 0.7 except for NCEP-DOE in MAM). The low partial correlations of DSSR with AOT and PW suggest that AOT and PW have smaller influences on DSSR than ISR-TOA and CC do. Figure 11 shows that the four products exhibit considerable differences in the spatial correlations with the four factors, although the seasonal differences in the correlation are

similar among the four products, except for FY-2C (with AOT, Figure 11d).

5. Discussion

[26] As shown above, the four DSSR products show similar spatial patterns and seasonal variations but differ in magnitude with varying mean biases. Here, we discuss the causes of the discrepancies among the four DSSR products, especially for the two satellite products, which were produced using different radiative transfer models and different sources of input data. As discussed in Section 4, clouds have the largest impact on DSSR, followed by smaller influences from PW and aerosols.

[27] To further discuss the impacts, the temporal correlation coefficient between the DSSR and each of CC, PW, and AOT over four subregions in China is shown in Table 4, which is derived by removing the influence of the ISR-TOA and the intercorrelations among the three

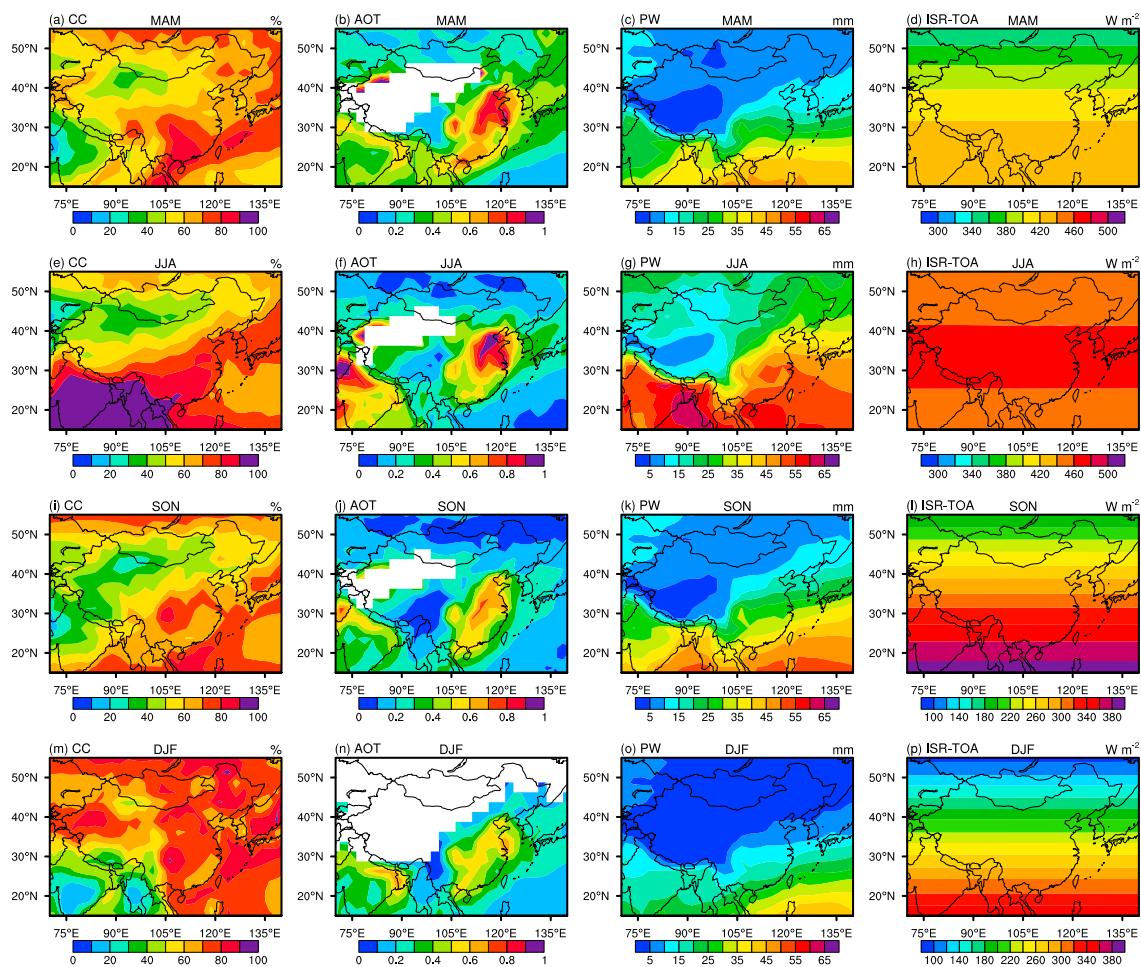


Figure 10. Three-year (July 2006 to June 2009) mean seasonal CC, AOT, PW, and ISR-TOA, for (a–d) spring (MAM), (e–h) summer (JJA), (i–l) autumn (SON), and (m–p) winter (DJF).

factors (CC, PW, and AOT) using the procedures described in the last section. Each factor's squared partial correlation coefficient is converted into a percentage (the weight in Table 4) to reflect the relative importance of each factor in the DSSR retrieval. It can be seen that cloud cover clearly has the highest partial correlation coefficient and thus the largest influence on DSSR over NEC and SC. AOT shows the highest weight among the three factors over North China, where high aerosol loading is observed (Figures 8 and 10). It suggests that aerosols play a key role in the satellite- and reanalysis-derived DSSR over NC. Although the AOT also has large weight for four DSSR products over WC, these values are unrealistic because the AOT data are not available over most of this region (Figure 8f). In addition, the three impact factors contribute more to DSSR's temporal variations for both satellite products over NC and SC than over NEC and WC, which suggests that cloudiness, water vapor, and aerosols have larger effects on satellite DSSR retrievals in NC and SC than in other regions. Compared with FLASHFlux, FY-2C shows lower correlations with CC, which is likely due to the

insufficient representation of clouds' influence on DSSR in the FY-2C's retrieval algorithm. It should be noted that the sum of pr^2 in Table 4 may be over 1.0 (e.g., for FLASHFlux over NC and NCEP-DOE over NEC and NC) because the squared partial correlations for the three cases (CC, AOT, and PW) represent the fraction of the variance in the original (for CC) and remaining DSSR data (for AOT and PW). (If the fraction of the variance explained is always for the original DSSR, then the sum should be 1.0.)

[28] The parameterization scheme for clouds from *Pinker and Laszlo* [1992] was used in the FY-2C retrieval algorithm. The single scattering albedo and asymmetry factors were considered to be a function of the cloud optical thickness, solar zenith angle, and wavelength, which were obtained from the look-up tables in *Yuan* [2005] (see Tables 2.1 and 2.2). Cloud optical thickness was retrieved in the FY-2C retrieval algorithm using the DISORT model, in which the atmospheric and surface parameters were taken from climatological monthly ISCCP C2 data averaged over 1983–1990 (see section 2.1). The unrealistic input data (instead of real-time states) could introduce errors in the

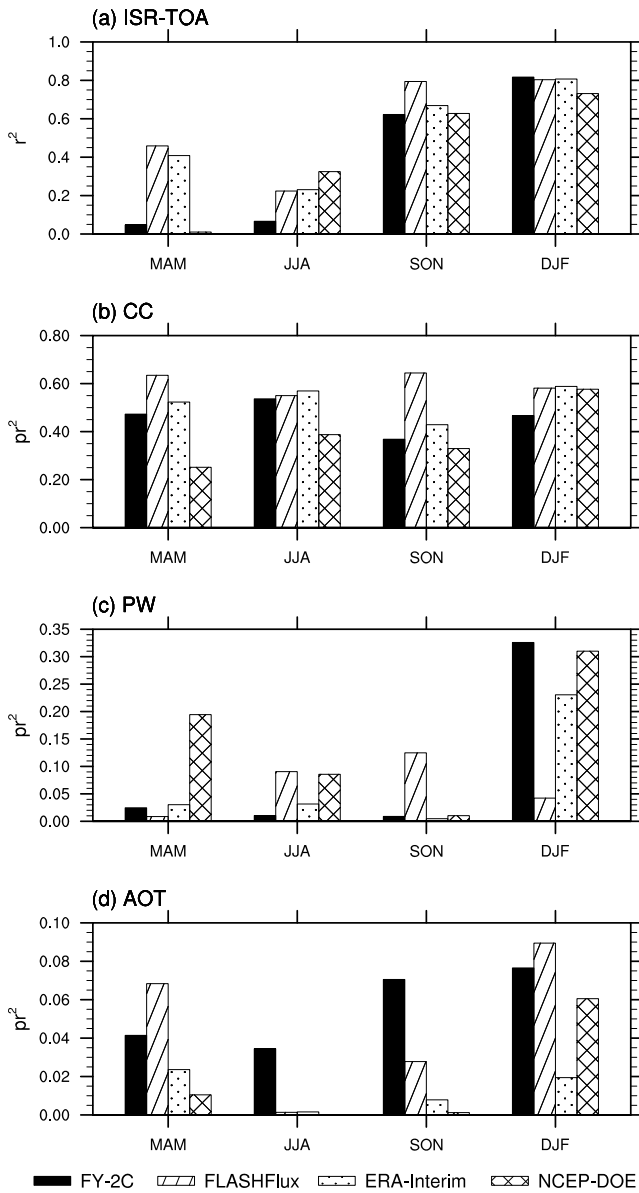


Figure 11. Squared spatial correlation coefficients between DSSR products from FY-2C, FLASHFlux, ERA-Interim and NCEP-DOE, and four impact factors: (a) ISR-TOA, (b) CC, (c) PW, and (d) AOT, for the four seasons. The y axis for (a) is the squared correlation coefficient between DSSR and ISR-TOA and for (b) – (d) is the squared partial correlation coefficient (pr^2).

temporal variations in the FY-2C data. These errors may contribute to the lower correlation of the FY-2C data with OBS than the FLASHFlux DSSR products (Figures 4 and 5). The temporal correlation with OBS for daily FY-2C DSSR is lower ($r=0.82$, Figure 3a) than for monthly data ($r=0.90$, Figure 4a). On the other hand, cloud information in FLASHFlux algorithm was taken from MODIS observations, which may contribute to FLASHFlux's higher correlations with OBS.

[29] In addition, the attenuation factor α_{Aer} of AOT for FY-2C was calculated from PW (in cm) using the method from Darnell *et al.* [1988], where $\alpha_{Aer} = 0.03 + 0.013 \text{ PW}$. For FLASHFlux, a more precise algorithm with the absorption and backscattering of aerosols described by Gupta *et al.*, [2001] (equation 29) for the attenuation factor was used, $\alpha_{Aer} = \tau_{Aer}(1 - \omega_0) + \frac{1}{2}\tau_{Aer}\omega_0(1 - g)$, where τ_{Aer} , ω_0 , and g are the broadband aerosol optical depth, single scattering albedo, and asymmetry parameter, respectively. However, the three parameters (τ_{Aer} , ω_0 , and g) were assumed to be constant and could introduce some effects on the DSSR retrievals, such as low correlation with OBS over NC (Figure 4).

[30] The parameterization scheme associated with water vapor absorption from Lacis and Hansen [1974] was employed in the FY-2C DSSR retrieval algorithm. Li [1995] pointed out that Lacis and Hansen's parameterization caused significant errors in water vapor absorption, which may lead to large systematic biases ($5\text{--}40 \text{ Wm}^{-2}$) for DSSR. FLASHFlux used a different scheme, from Gupta *et al.* [2001], for water vapor absorption. The comparisons between these two schemes by Gupta *et al.* [2001] suggested that there were large discrepancies in water vapor absorptivity for column-integrated precipitable water under 10 mm (see Figure B1 in Appendix B of Gupta *et al.* [2001]). In addition, satellite-retrieved DSSR is sensitive to differences in the “precipitable water” input parameter and may induce large discrepancies in DSSR [Li, 1995]. As mentioned above, the precipitable water data for FY-2C were derived from the climatological monthly ISCCP C2 dataset. FLASHFlux, on the other hand, used the data assimilation model products of the Goddard Earth Observing System, version-1 (GEOS-1) (Schubert *et al.* [1993]), produced by the Data Assimilation Office at the NASA Goddard Space Flight Center.

[31] However, in this study, we have not presented a quantitative evaluation of the causes of the discrepancies between two satellite products due to the effects of different input datasets or algorithms. Sensitivity experiments using the method proposed by Li [1995] will be carried out in the future by applying the same algorithm to two different input datasets (e.g., cloud optical depth, TOA reflectance, water vapor, and aerosol) or applying two different algorithms to the same data.

[32] It should be noted that the outliers (outside the ± 3 SD range of multi-year mean daily values for each $0.1^\circ \times 0.1^\circ$ grid) in the daily FY-2C DSSR data were removed in this study during our quality control. For example, the daily mean DSSR values from the original FY-2C product were found to be more than 800 Wm^{-2} on 19 and 20 April 2008 and less than 10 Wm^{-2} on 21 April 2008 over some areas of China. The removal of the outliers would have some effects on the evaluation for FY-2C product. The original FY-2C DSSR data show larger RMSEs (49.3 Wm^{-2} and 31.9 Wm^{-2} for daily and monthly data, respectively) and lower correlations of 0.82 (daily) and 0.90 (monthly) compared with the data with the removal of the outliers (Figures 3 and 4). The same quality control was

Table 4. The Squared Partial Correlation Coefficients (pr^2) Between DSSR and Each Impact Factor (CC, AOT, PW) Over Four Subregions in China

	FY-2C		FLASHFlux		ERA-Interim		NCEP-DOE	
	pr^2	Weight ^a	pr^2	Weight	pr^2	Weight	pr^2	Weight
NEC								
CC	0.209	46%	0.233	51%	0.484	51%	0.506	45%
PW	0.135	29%	0.126	27%	0.275	29%	0.409	36%
AOT	0.114	25%	0.100	22%	0.193	20%	0.214	19%
Total	0.458	100%	0.460	100%	0.952	100%	1.129	100%
WC								
CC	0.038	11%	0.141	27%	0.153	28%	0.233	38%
PW	0.018	5%	0.116	23%	0.099	18%	0.096	15%
AOT	0.275	83%	0.258	50%	0.289	53%	0.291	47%
Total	0.331	100%	0.515	100%	0.541	100%	0.620	100%
NC								
CC	0.229	35%	0.394	37%	0.337	34%	0.439	33%
PW	0.138	21%	0.261	25%	0.251	25%	0.381	29%
AOT	0.294	44%	0.410	38%	0.404	41%	0.492	38%
Total	0.661	100%	1.065	100%	0.992	100%	1.312	100%
SC								
CC	0.332	60%	0.383	59%	0.336	54%	0.254	68%
PW	0.215	39%	0.174	27%	0.276	45%	0.105	28%
AOT	0.003	1%	0.092	14%	0.006	1%	0.014	4%
Total	0.550	100%	0.649	100%	0.618	100%	0.373	100%

^aWeight = $pr_i^2 / \sum_{i=1}^3 pr_i^2$, $i = 1, 2, 3$ for CC, PW, and AOT.

also applied to other three products by removing their outliers; however, for these data sets, there were only small differences between these cases with and without the removal of the outliers (not shown).

6. Summary and Conclusions

[33] We have analyzed downward surface solar radiation (DSSR) data from two satellite products (FY-2C and FLASHFlux) and two reanalyses (ERA-Interim and NCEP-DOE) over East Asia (15°–55°N, 70°–140°E). The DSSR derived from the FY-2C satellite was analyzed for the first time in this study. Ground-based measurements from a BSRN site (Xianghe) and 94 stations from the CMA were used to evaluate the DSSR products, which were then used to quantify the DSSR spatial and seasonal variations over East Asia during July 2006 to June 2009.

[34] Results show that the FY-2C DSSR generally compares well with surface in situ observations, with small mean biases of 3.0 Wm^{−2} on a daily basis and 3.5 Wm^{−2} on a monthly basis. Moderate RMSEs of 49.3 Wm^{−2} (daily) and 31.9 Wm^{−2} (monthly), with correlations of 0.82 (daily) and 0.90 (monthly) between FY-2C and OBS were observed. Among the four DSSR products, FLASHFlux DSSR showed the lowest RMSEs of 43.2 Wm^{−2} (daily) and 30.5 Wm^{−2} (monthly) and the best correlation with OBS with $r = 0.90$ (daily) and $r = 0.93$ (monthly) but produced larger biases than FY-2C, with MBE = 19.9 Wm^{−2} (daily) and 19.5 Wm^{−2} (monthly). The DSSR from the two reanalyses showed larger biases than the two satellite products, with RMSEs of 53.1 Wm^{−2} (daily) and 37.1 Wm^{−2} (monthly) for ERA-Interim and 71.4 Wm^{−2} (daily) and 56.5 Wm^{−2} (monthly) for NCEP-DOE.

[35] The satellite and reanalysis products compare with surface observations better ($r > 0.9$) over Northeast and West China than North and South China. This result is

consistent with that reported by Xia *et al.* [2006], likely due to stronger seasonal variations in Northeast China (which increase the correlation with OBS) and larger effects of cloudiness, water vapor, and aerosols on DSSR in North and South China. Comparisons between surface observed and FY-2C daily and monthly DSSR at different spatial resolutions (0.1°, 0.5°, 1.0°, and 2.5°) show that estimates of monthly DSSR are insensitive to spatial resolution but comparisons of daily data may be affected by the scale mismatch. This is further confirmed by a comparison between the FY-2C satellite-simulated “point measurements” (0.1° × 0.1°) of DSSR and areal mean values of DSSR averaged over larger grids of varying size from 0.25° to 2.5°. The comparison showed that the scale mismatch increases the errors in daily DSSR comparisons, while monthly mean DSSR values are insensitive to the averaging scales.

[36] The four datasets all show similar broad spatial patterns of DSSR over East Asia, with high DSSR (180–280 Wm^{−2}) over the Tibetan Plateau due to low cloud amount (50%) and little precipitable water (5 mm) there and low DSSR (120–200 Wm^{−2}) over southeastern and northeastern China. However, there are considerable differences in magnitude among the two satellite and two reanalysis products: ERA-Interim and NCEP-DOE clearly overestimate DSSR compared to OBS, FY-2C, and FLASHFlux, especially over the Tibetan Plateau (by about 40 Wm^{−2}).

[37] Strong seasonal variations of DSSR are seen over East Asia in all four products. During MAM, high DSSR is seen over western China and South Asia, while DSSR is low over southern China. In JJA, DSSR patterns are similar to those of MAM, except in South Asia where JJA DSSR is lower than in MAM due to increased cloudiness (~90%) and precipitable water (60 mm) in JJA. In SON, DSSR increases over the Tibetan Plateau, where fewer clouds (~40%) and little precipitable water (5 mm) allow more solar radiation

to reach the surface. During DJF, DSSR decreases to around 50–110 Wm^{-2} north of about 40°N and over the Sichuan Basin in central China due to high cloud amount, while the Tibetan high DSSR center largely disappears in DJF.

[38] DSSR data from the FY-2C satellite have much higher temporal and spatial resolution and show closer agreement with in situ observations than either the NCEP-DOE or ERA-Interim reanalysis data; however, the correlation between FY-2C DSSR with OBS is slightly inferior to FLASHFlux. This is likely due to deficiencies in the treatment of clouds, aerosols and water vapor, and unrealistic input data (of atmospheric and surface properties). Future improvements in these areas are desirable. In addition, more observations from other Fengyun-2 series of geostationary meteorological satellites (i.e., FY-2D and FY-2E) should be included to improve the retrieved DSSR product in the future.

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