Surface Radiation Budget from ARM Satellite Retrievals

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Introduction

Since the Atmospheric Radiation Measurement (ARM) Program measurements of the surface radiation budget (SRB) are confined to the various central and extended facility sites, extensive gaps exist in the domain typically used to characterize the radiation budget for modeling purposes. In order to bound the vertical radiation fields more completely, it is necessary to fill in the gaps in the SRB using satellite data. SRB products have been generated using various satellites, but they may or may not be available in a timely fashion or compatible in spatial or temporal coverage with the ARM satellite cloud and top of the atmosphere (TOA) radiation data. This paper describes the implementation of an initial set of algorithms to compute the surface fluxes using both abridged radiative transfer models (RTM) and simplified empirical techniques that are currently used in other programs. The RTM method uses the satellite-derived cloud products including temperature and humidity profiles along with cloud amount, optical depth, particle size, and altitude. The empirical methods also utilize the TOA broadband fluxes. The results are compared with surface radiation measurements at the ARM sites in the Southern Great Plains (SGP) domain to determine which techniques will be implemented as part of the standard ARM satellite data products. Although the SRB satellite products will never be as accurate as the surface measurements, they can provide reasonable estimates of the fluxes between the various surface sites. The results presented here are preliminary estimates derived using a raw implementation of the methods to the operational ARM products.

Data

Cloud products, TOA shortwave albedo (Asw), and outgoing longwave radiation (OLR) were derived Geostationary Operational Environmental Satellite (GOES-8) imager data using the visible infrared solar-infrared split-window technique (VISST) over a 10-km radius over the SGP Central Facility (SCF) from March 2000 to February 2001 (Minnis et al. 2001). The Asw and OLR are used as input into four different algorithms to calculate the surface fluxes and albedos at the SCF. In this study, days with recorded snow measurements have been removed from the dataset.

Aerosol optical depth (AOD) values from the Clouds and the Earth's Radiant Energy System (CERES)/ARM Validation Experiment (CAVE; see Rutan et al. 2001) are used to calculate aerosol correction parameters needed to calculate SW fluxes and surface albedo, Asfc. The CAVE surface pressures are also used in the algorithms.

Vertical profiles of pressure, temperature, and specific humidity are extracted or calculated from the European Centre for Medium-Range Weather Forecasts based Meteorology Ozone Aerosol (ECMWF-MOA; see Gupta et al. 1995) profiles and temporally interpolated to match the GOES-8 data. The column-weighted precipitable water and ozone are calculated using the ECMWF-MOA profiles.

Average fluxes are computed over a 10-min interval centered on the satellite Universal Time Coordinates (UTC) at the SCF using data from the Solar Infrared Radiation Station (SIRS) instruments located at the SCF to validate the satellite-inferred surface fluxes and albedos.

Algorithms

Using AOD, TOA clear-sky albedo from VISST, precipitable water, and the solar zenith angle (SZA), the Li-Leighton model (LLM) estimates surface absorbed broadband (BB) shortwave (SW) flux (Li et al. 1993). Surface albedo under clear-sky conditions is estimated using the Li and Garand (1994) method (LGM). Precipitable water is used to slightly modify surface SW net flux and surface albedo in the LGM.

The Langley Parameterized Shortwave Algorithm (LPSA) model is used to estimate surface SW downwelling flux and surface albedo under all-sky conditions. Using SZA, TOA clear and cloudy albedo from VISST, AOD, precipitable water, ozone, surface pressure, VISST cloud optical depth, and VISST cloud amount, the LPSA model computes surface insolation for all-sky conditions (Gupta et al. 2001). Surface albedos for partly cloudy and overcast conditions are calculated by weighting clear-sky albedos by the cloudiness transmissivity (Gupta et al. 2001).

The Inamdar and Ramanathan (1997) method (IRM) is used to estimate surface LW upwelling and downwelling fluxes under clear-sky conditions. Utilizing SZA, TOA outgoing longwave radiation (OLR), surface temperature, surface type, surface emissivity, and precipitable water, this method calculates the normalized window and non-window downward fluxes that are used to calculate the net and downward fluxes.

The Gupta method uses parameterizations to estimate surface LW upwelling and downwelling fluxes under clear and cloudy conditions from TOA fluxes (Gupta et al 1992). The parameterizations are based on surface temperature, surface and cloud emissivity, atmospheric profiles of temperature and humidity, cloud base pressure, and liquid or ice cloud amount and emissivity.

Results and Discussion

In comparing the data for this initial study, the instrument measurements and satellite-model calculations are compared and the best-fit correction line is calculated as a means of tuning this particular dataset.

This best-fit correction line is then applied to the satellite-model calculations to eliminate biases. Figure 1 compares the clear-sky surface SW net flux (SWnet) calculated using the Li-Leighton method and the SIRS SWnet. The raw retrieval (Figure 1a) underestimates the SIRS flux by 5.1 Wm^{-2} or 1% with a standard deviation of 24.5 Wm^{-2}. The RMS error for the corrected satellite-derived net flux (Figure 1b) is 23.9 Wm^{-2}. In Figure 2a, the LGM-derived surface albedo is unbiased at the 0.5% level although at large values, the LGM tends to overestimate Asfc. The best fit correction to the LGM in Figure 2b reduces the RMS error from 0.020 to 0.018, but the adjustment of the albedos to minimize the overestimate of the larger values tends to cause an overestimate of the low values. This results in an obvious imbalance in the scatter of points about the line of agreement. In both Figures 1b and 2b, the outlying points appear to be unrelated to SZA, Asw, or precipitable water. The outliers are probably the result of contamination of the observed scene by partly cloudy pixels that were classified as clear. In Figure 2a, the tendency to overestimate the high values of Asfc, which only occur at large SZAs, is most likely due to an error in the anisotropic reflectance correction model or to biases in the model used to convert the GOES-8 TOA narrowband albedo to Asw. Both corrections are less certain when SZA is large. On average, the corrected LGM and LLM instantaneously estimate Asfc and SWnet to within ±5 and 10%, respectively, of the SIRS values.

The raw clear-sky LPSA SW downwelling flux (SWd) underestimates the SIRS SWd by an average of 25.8 Wm^{-2} with a standard deviation of 29.8 Wm^{-2} (Figure 3a). After applying the best -fit correction (Figure 3b), the RMS error drops from 39.4 Wm^{-2} to 26.9 Wm^{-2}, or 4.4%. The raw values of LPSA Asfc in clear skies (Figure 4a) underestimates the SIRS values by 0.006, on average, with a standard

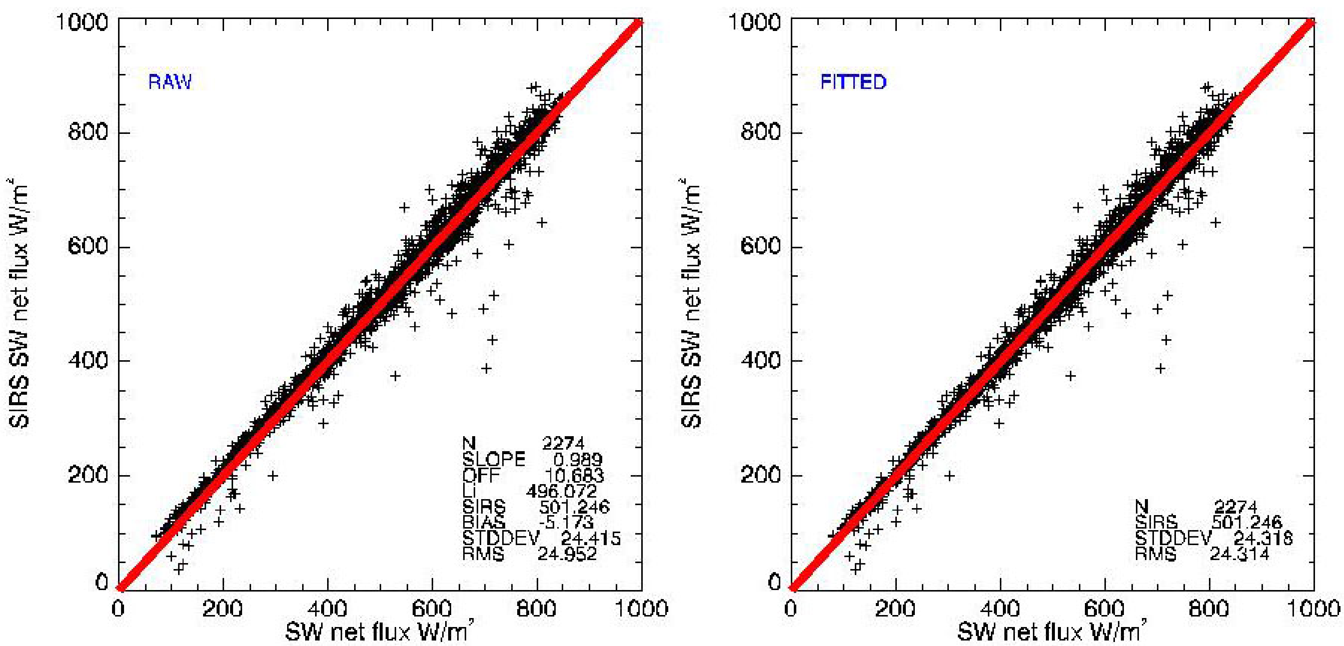

Figure 1. Clear-sky daytime surface SW net flux from the SIRS instrument and the Li-Leighton method.

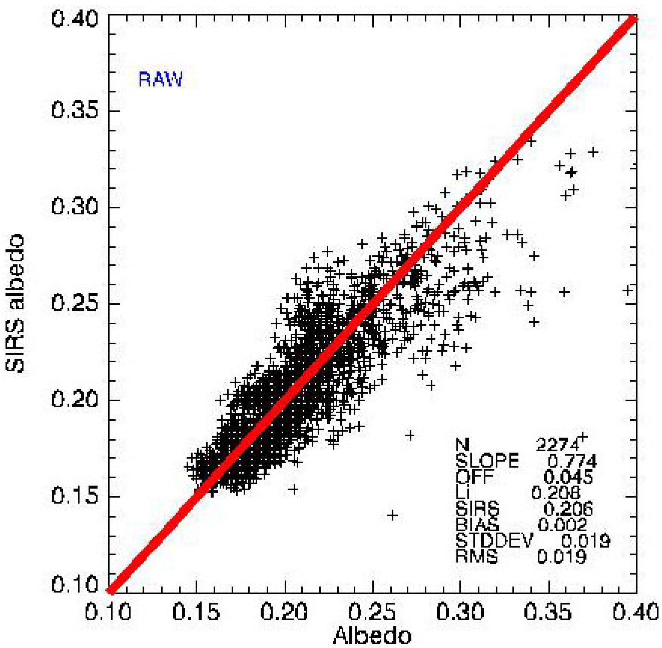

Figure 2. Clear-sky daytime surface albedo from the SIRS instrument and the Li-Leighton method.

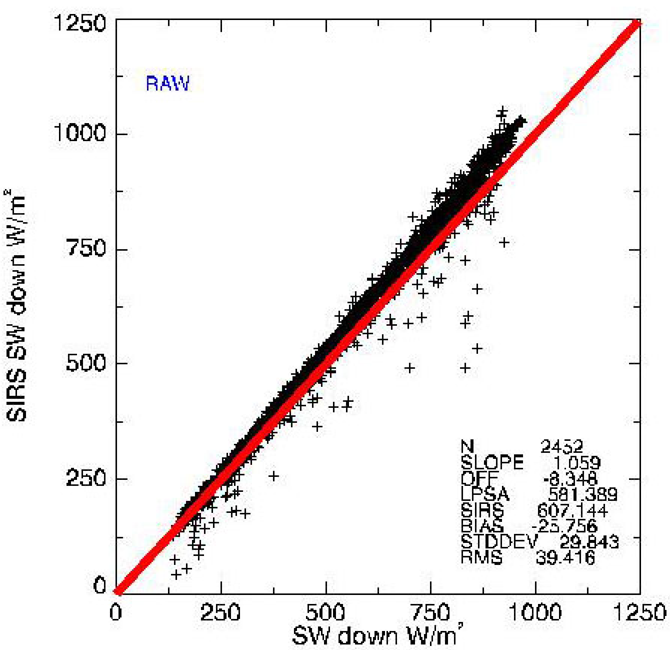

Figure 3. Clear-sky daytime SW downwelling flux from SIRS and LPSA method.

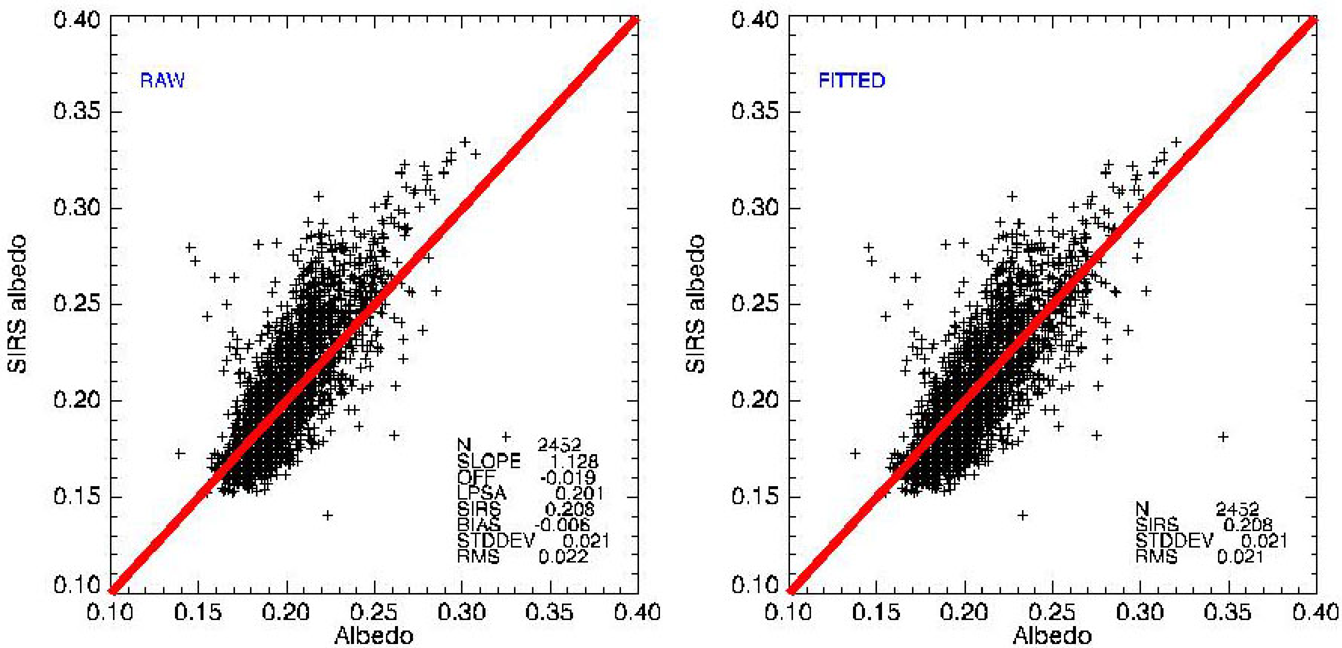

Figure 4. Clear-sky daytime albedo from SIRS and LPSA method.

deviation of 0.021. After correction (Figure 4b), the LPSA surface albedos have an RMS difference of 0.021 compared to the SIRS clear-sky values. When the SWd is combined with the retrieved Asfc, the values of SWnet from the LPSA should have an RMS of ~10%. Thus, LPSA, when tuned should produce results very similar in accuracy to those from the LLM in clear skies.

During overcast conditions, the raw LPSA method (Figure 5a) tends to underestimate SWd for relatively thin clouds, while overestimating it for all but the thickest clouds. The mean bias is -5.8 Wm^{-2}, but the 106 Wm^{-2} RMS error is 36% of the mean SIRS SWd. The best-fit correction (Figure 5b) only reduces the RMS difference to 32%. The uncertainty could derive from a number of sources including the TOA narrowband-broadband albedo conversion, the anisotropic corrections, field of view discrepancies between the satellite and surface, or basic random errors in the LPSA.

The results for the LPSA in cloudy conditions are summarized in Table 1 along with those discussed above. In partly cloudy conditions, the LPSA yields almost unbiased values of Asw, but the rms error is considerably larger than found for the clear conditions. The rms error in the downward SW flux is five times that for the clear scenes and the raw retrieval underestimates the SIRS value by 5%. The mean raw bias in SWd in overcast conditions is less than that in partly cloudy conditions, while the bias in Asfc is greater. After correction, SWd has an instantaneous uncertainty of 32%, which is greater than any of the other errors.

In Figure 6a, the downwelling LW fluxes at the surface (LWd) under daytime clear-sky conditions from the raw IRM are closely correlated with the corresponding SIRS data, but are 21.8 Wm^{-2} too large. Applying the best-fit corrections (Figure 6b) drops the RMS error from 26.4 Wm^{-2} to 13.3 Wm^{-2}, or 3.8%. The daytime clear-sky surface upwelling longwave fluxes (LWu) from the IRM (Figure 7a) are similarly correlated with the SIRS observations but are too low by 24.4 Wm^{-2}, or 5.3%. The RMS

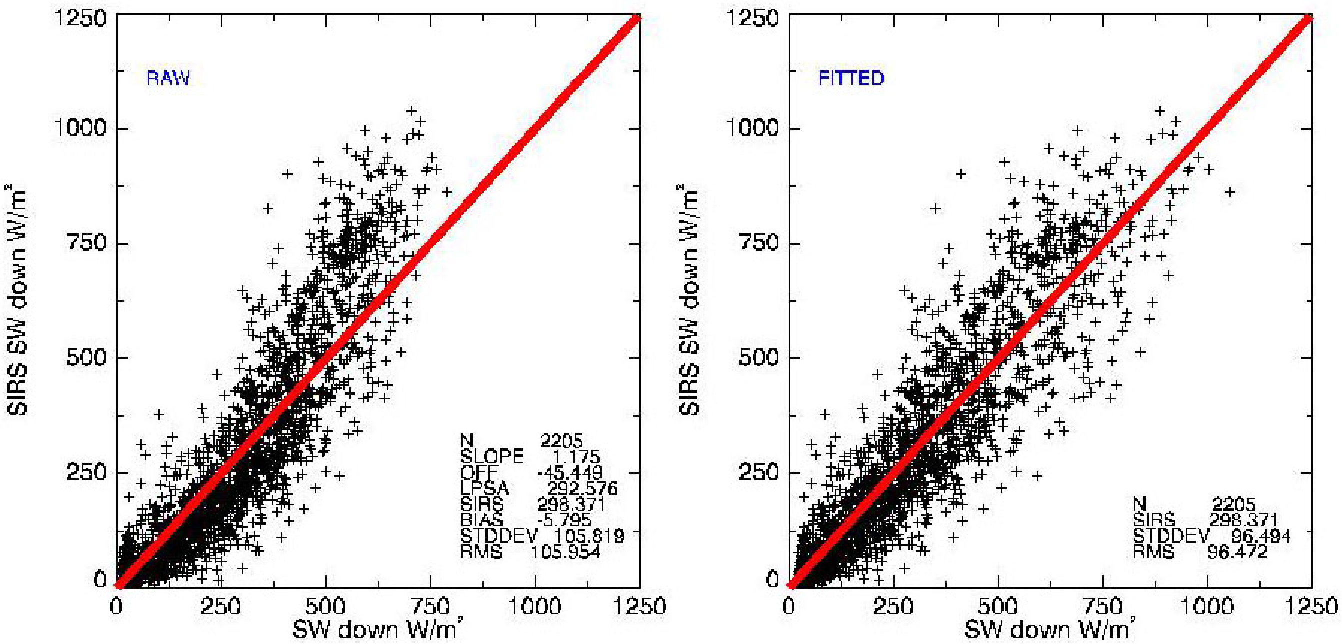

Figure 5. Daytime SW downwelling flux under cloudy conditions from SIRS and LPSA.

decreases from 31.2 to 20.7 Wm^{-2}, or 4.5%. The scatter in LWu is slightly greater than that for LWd, perhaps as a result of uncertainties in the surface emissivity. The fact that the raw LWd and LWu errors are of opposite signs and have similar magnitudes suggests that the model might be absorbing or emitting too much LW radiation. Thus, the tuning most likely, in effect, decreases the atmospheric absorption and emission to yield more radiation from the surface when OLR is large and less to the surface than found with the raw IRM.

The daytime clear-sky LW downwelling and upwelling fluxes calculated using the Gupta method are in generally good agreement with the corresponding SIRS values (Figures 8 and 9), especially for LWd. As seen in Table 1, the bias errors from the raw Gupta method are considerably smaller than their IRM counterparts. The RMS errors for LWd and LWu are 13.9 Wm^{-2} and 17.7 Wm^{-2}, respectively. When the corrections are applied, both the IRM and Gupta method yield comparable RMS errors. At night (Table 1), the raw Gupta method produces less biased results than the IRM, but the two methods are comparable when the corrections are applied. Interestingly, the sign of the bias in LWu switches from negative in the daytime to positive at night for both methods.

Under cloudy conditions (Table 1), the Gupta method is the only applicable model for LW fluxes. The downwelling fluxes are overestimated by an average of 9 Wm^{-2} during day and night together. This positive bias suggests that the cloud base estimate might be too low. The RMS error is nearly double that for the clear-sky cases. Surprisingly, the raw upwelling fluxes are less biased than their clear-sky counterparts and the RMS errors are similar to those in cloud-free skies.

Table 1. Summary of differences in surface fluxes derived from SIRS fluxes and GOES-8 radiation and cloud products before (raw) and after best-fit corrections.

Parameter and Method	Raw Bias (raw)	Raw RMS	Corrected RMS	Corrected RMS(%)
Daytime Clear skies				
Asfc (LGM)	0.001	0.020	0.018	8.6
Asfc (LPSA)	-0.006	.022	0.021	10.1
SWnet (LLM)	-5.1	24.5	23.9	4.9
SWd (LPSA)	-25.7	39.4	26.9	4.4
LWd (IRM)	21.8	26.4	13.3	3.8
LWd (Gupta)	-5.3	15.2	13.9	4.0
LWu (IRM)	-24.4	32.2	20.7	4.5
LWu (Gupta)	-13.8	22.5	17.7	3.8
Nighttime Clear skies				
LWd (IRM)	25.0	30.7	12.1	3.6
LWd (Gupta)	-3.7	13.9	12.2	3.6
LWu (IRM)	21.1	23.5	10.2	2.6
LWu (Gupta)	10.3	16.0	11.5	2.9
Daytime Partly Cloudy				
Asfc (LPSA)	0.001	0.034	0.034	16.5
SWd (LPSA)	-24.9	102.8	99.8	19.5
Daytime Overcast				
Asfc (LPSA)	0.012	0.036	0.034	18.5
SWd (LPSA)	-5.8	105.9	96.5	32.3
Daytime Cloudy				
LWd (Gupta)	13.0	25.5	21.9	6.0
LWu (Gupta)	-0.9	20.5	20.3	4.8
Nighttime Cloudy				
LWd (Gupta)	5.3	26.2	24.8	7.5
LWu (Gupta)	7.4	15.6	12.1	3.3

Discussion and Conclusions

The results of the initial comparisons indicate that, compared to the LPSA, LGM, and LLM yield a more unbiased estimate of surface albedo, net SW flux and, therefore, downwelling SW flux. Because the LPSA is the only method tested that estimates SW fluxes at the surface in cloudy conditions, it would not be possible use only the LLM and LGM as simplified methods. It might be possible to combine the techniques by using the LLM to estimate surface albedos, the LGM to estimate fluxes in clear scenes, and use the LLM albedo in the LPSA for cloudy conditions. This approach might reduce the errors in the cloudy conditions. The IRM and Gupta method produce comparable results in clear-sky conditions after the biases are removed. However, the smaller biases in the Gupta method suggest that it should be used alone, especially since it performs relatively accurately under cloudy conditions.

This preliminary assessment of a potential satellite-based ARM SRB product has only considered simple parameterizations using minimal computer time. The results have only been compared over one SGP site. Additional analyses must be performed before an operational method can be applied. The sources

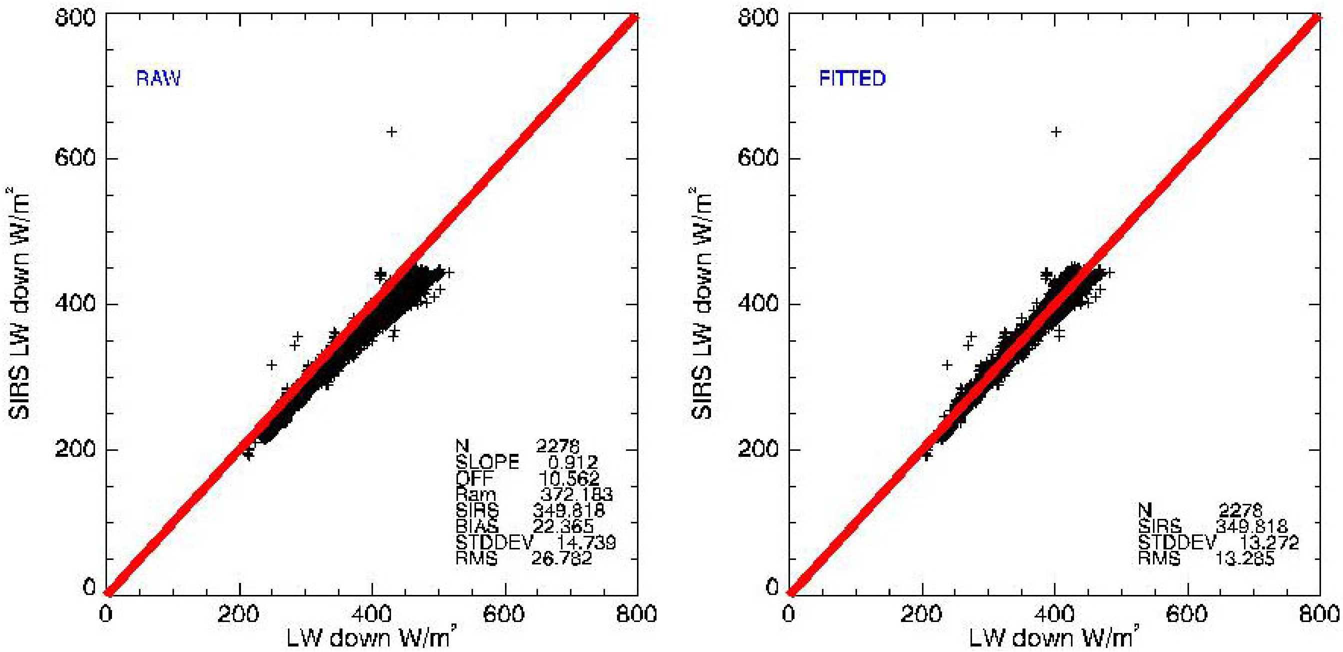

Figure 6. Clear-sky daytime LW downwelling flux from SIRS and Inamdar and Ramanathan method.

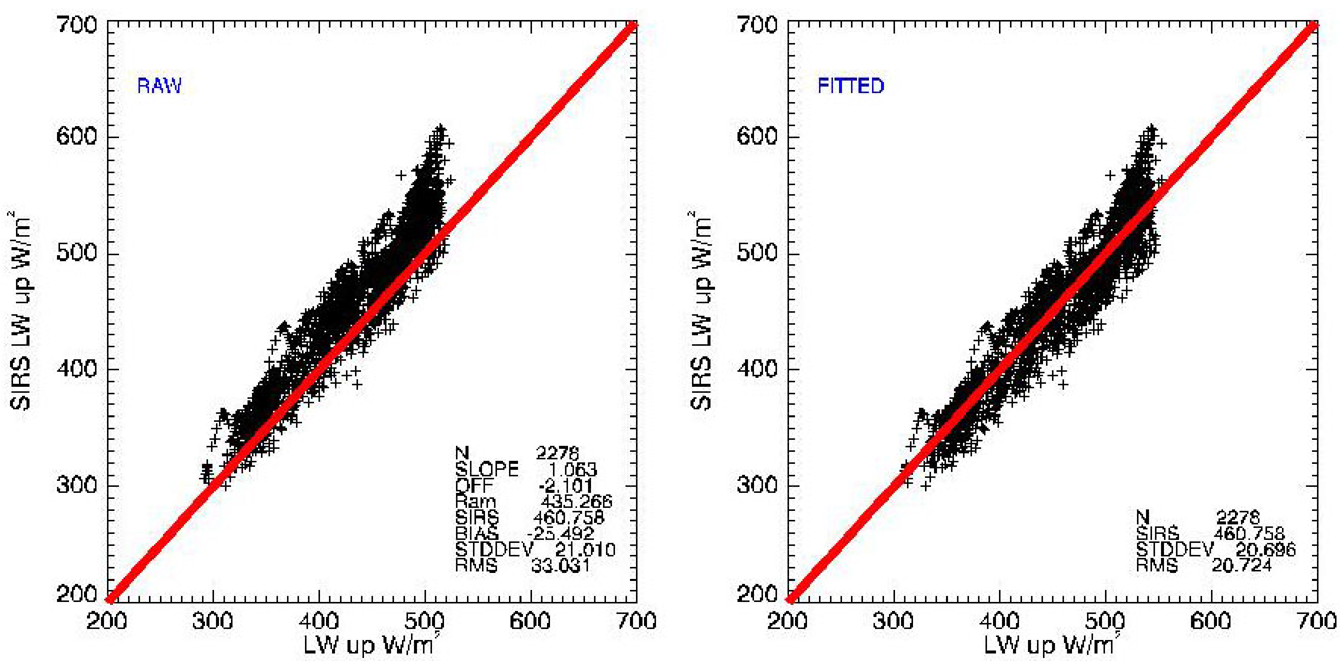

Figure 7. Clear-sky daytime LW upwelling flux from SIRS and Inamdar and Ramanathan method.

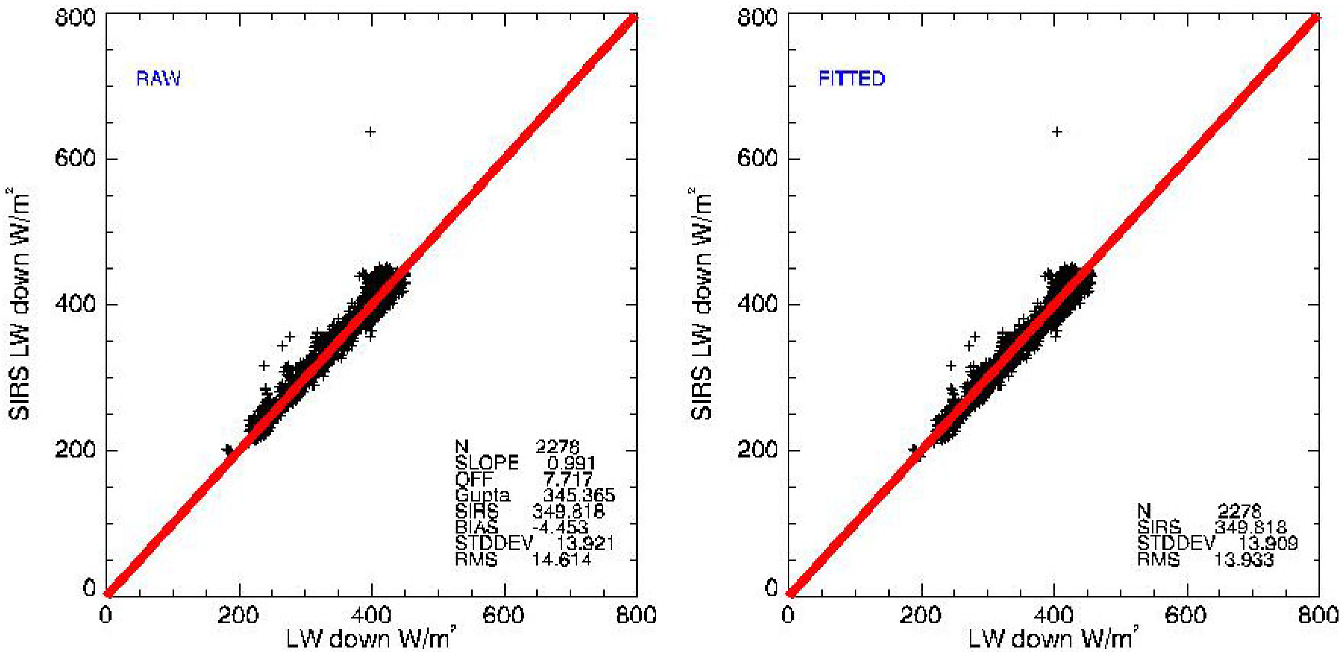

Figure 8. Clear-sky daytime LW downwelling flux from SIRS and Gupta method.

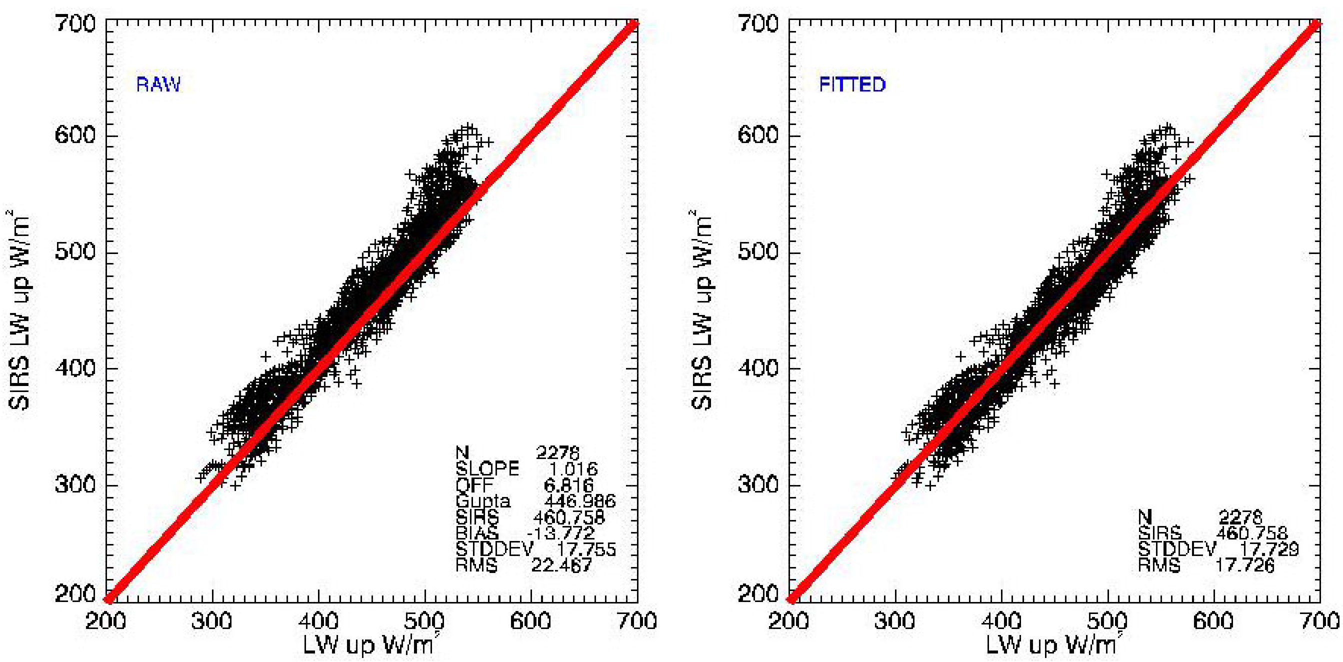

Figure 9. Clear-sky daytime LW downwelling flux from SIRS and Gupta method.

of the biases, especially those in LW fluxes have not been examined. These will be examined using different model and observed sounding data. Furthermore, the uncertainty estimates can be improved by comparing with radiometers at the other sites and with data taken more recently to ensure that any day-night biases in the LW fluxes have been removed. Improvements in the accuracy of the SW fluxes in cloudy conditions may require the use of a more complex radiative transfer model. The gain in accuracy versus the additional computational time must be assessed. The comparisons of the calculated results with actual surface data indicate that surface fluxes and albedos may be calculated from satellite data with acceptable accuracy and can fill in gaps in the SRB over ARM domain. If up- and down-welling SW and LW fluxes at the surface were added to the current ARM satellite cloud products, it would provide the ARM community with a more comprehensive satellite-based cloud and radiation package.

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