Derivation of Improved Surface and Top of the Atmosphere Broadband Shortwave and Longwave Fluxes over Atmospheric Radiation Measurement Program Domains

M.M. Khaiyer, D.R. Doelling, P.K. Chan, M.L. Nordeen, R. Palikonda, Y. Yi, and D.N. Phan
Analytical Services and Materials, Inc.
Hampton, Virginia

P. Minnis
National Aeronautics and Space Agency/Langley Research Center
Hampton, Virginia

Introduction

Global coverage of broadband (BB), shortwave (SW), and longwave (LW) fluxes at the top of the atmosphere (TOA) and surface is imperative for climate studies. These parameters can be estimated from narrowband (NB) Geostationary Operational Environmental Satellite (GOES) data, but their accuracy is highly dependent on the validity of the narrowband-to-broadband (NB-BB) conversion formulas that are used to convert the NB fluxes to BB values. The formula coefficients have historically been derived by regressing matched polar-orbiting satellite BB fluxes or radiances with their NB counterparts from GOES (e.g., Minnis et al. 1984). More recently, the coefficients have been based on matched Earth Radiation Budget Experiment (ERBE) and GOES-6 data (Minnis and Smith 1998). The Clouds and the Earth's Radiant Energy Budget (CERES, see Wielicki et al. 1998) project has recently developed much improved Angular Distribution Models (ADM; Loeb et al. 2003) and has higher resolution data compared to ERBE. A limited set of coefficients was derived from matched GOES-8 and CERES data taken on the Tropical Rainfall Measuring Mission (TRMM) satellite (Chakrapani et al. 2003; Doelling et al. 2003). Those two satellites were also used to derive NB-BB coefficients over the Southern Great Plains (SGP) site for the period April 2000-March 2003 and for Darwin in the Tropical Western Pacific (TWP) using CERES-GOES9 fits for June 2004 - May 2005 (Khaiyer et al. 2006).

The NB-BB coefficients derived from CERES and the GOES suite should yield more accurate BB fluxes than from ERBE, but are limited spatially and seasonally. With CERES data taken from *Terra* and *Aqua*, it is now possible to derive more reliable NB-BBcoefficients for any given area. Better TOA fluxes should translate to improved surface radiation fluxes derived using various algorithms. As part of an ongoing effort to provide accurate BB flux estimates for the Atmospheric Radiation Measurement (ARM) Program, this paper takes the CERES-GOESx NB-BB fits (Khaiyer et al. 2006) a step further and documents the derivation of new seasonal NB-BB coefficients for the ARM Climate Research Facility (ACRF) SGP domain and for the Darwin domain.

Data and Methodology

GOES-8 data from April 2000 through March 2003 are used for the SGP, while GOES-9 data taken from June 2004 through May 2005 are analyzed for the Darwin domain. The latter covers 0°N – 17°S, 125°E – 136°E, while the former covers 32°N – 42° and 91°W – 105°W. All GOES data were calibrated against Terra Moderate Resolution Imaging Spectroradiometer data as in Minnis et al. (2002). Rapid Update Cycle model analyses provide vertical profiles of temperature and humidity for the SGP analyses. Meteorological Ozone and Aerosol atmospheric profiles from CERES were used for Darwin processing.

The BB fluxes from the Terra CERES FM-1 or FM-2 scanner are matched with the GOES data as follows. The CERES SW and LW fluxes are from the 20-km Single Scanner Footprint TOA/Surface Fluxes and Clouds product (SSF; Geier et al. 1999). The SSF footprint data are averaged into a 1° gridded product, the Monthly Gridded Surface Fluxes and Clouds. The CERES FM-1 or 2 Surface Fluxes and Clouds fluxes (cross-track mode only) are matched to GOES NB fluxes averaged over a 1° grid within +15 minutes at viewing zenith angles less than 65° for CERES and 70° for GOES.

The application of the new ADMs requires determination of the cloud properties for a given scene. The Visible Infrared Solar Split-Window Technique (VISST; Minnis et al. 1995) uses 0.65, 3.9, 11 and 12-µm radiances to derive cloud properties from GOES-8, 9, 10, and 12 data at a nominal pixel resolution of 4 km (Minnis et al. 1998; Phan et al. 2004). ADMs, selected according to the cloud conditions, are used to estimate VIS (0.65-µm) albedos and infrared (10.7-µm) fluxes from the NB radiances. VISST processing is done for the expanded TWP locale from 10°N – 10°S and 120°E to 180°; the SGP domain processing covers 32°N – 42°N, 91°W – 105°W. Validation is performed using GOES-10 and 12 data over the SGP.

The NB-BB coefficients are determined by regressing the GOES NB data against their CERES counterparts using the following equations:

$$A_{bb} = a_0 + a_1 A_{nb} + a_2 A_{nb}^2 + a_3 \ln(1/\mu_o), \quad (1)$$

where A_{bb} = SW BB albedo, A_{nb} = VIS albedo, μ_o = cos(SZA), and

$$OLR_{bb} = b_0 + b_1 L_{nb} + b_2 L_{nb}^2 + b_3 L_{nb} \ln(RH), \quad (2)$$

where OLR_{bb} = LW BB flux, L_{nb} = infrared flux, and RH = column-weighted relative humidity.

An earlier study (Khaiyer et al. 2006) derived SGP and Darwin NB-BBfits for the entire periods outlined in this section. That study identified several future work items that are carried out here. These include the derivation of seasonal NB-BB fits for both the SGP and TWP. For the SGP site, April 2000 -March 2003 GOES8 data will be used to create fits for winter (December – February), spring (March – May), summer (June – August), and autumn (September – November). Additionally, available GOES10 and GOES12 data from March 2005 - November 2005 are used to create spring, summer and autumn fits over the SGP. Finally, fits to GOES9 data from June 2004 - May 2005 are split into dry (May – October) and wet (November – April) seasons over the Darwin site.

Results

Figure 1 shows a scatterplot of the GOES NB albedos and fluxes derived over the SGP domain versus Terra CERES BB fluxes for the spring months (March – May) between April 2000 and March 2003. The average CERES BB albedo for 26,470 cases was 0.293 compared to the average GOES NB albedo of 0.320 (Figure 1a). The regression curves, also plotted, have a very slight dependence on μ_o. The SW albedo increases with μo for a given VIS albedo. Overall, the root mean square (RMS) error in the fit is 6.2%. For 39,005 samples, the mean CERES BB LW flux is 241.3 Wm^{-2} (Figure 1b). It corresponds to an average GOES infrared flux of 42.3 Wm^{-2}. The RMS error in the fit is 3.7%. The regression coefficients (Ax) listed at plots' lower right and in Table 1 can be used to convert NB fluxes to BB, using (1) for SW and (2) for LW. Similar fits were performed for the other seasons: Summer, autumn, and winter; results for these seasons are summarized in Table 1. Seasonal dependence and the Terra local crossing time of 10:30 a.m. combine to limit the SZA availability in any given seasonal NB-BB fit (not shown). Autumn and winter SZA's range between about 40° – 70°, whereas spring and summer 10° – 30°.

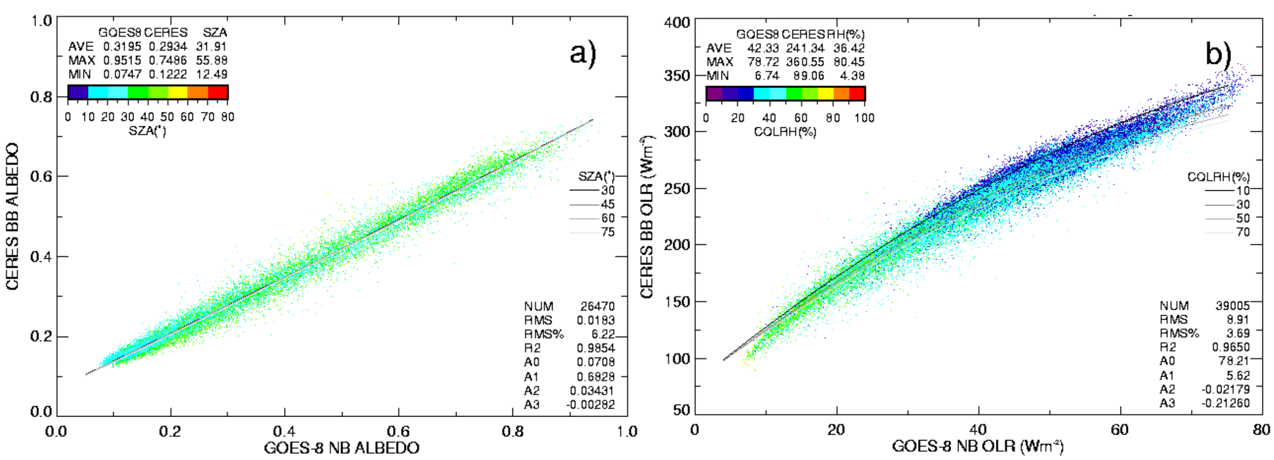

Figure 1. Scatterplot of NB and BB fluxes for spring months during April 2000 - March 2003 over the SGP domain using GOES NB and Terra CERES BB (a) SW albedos and (b) LW fluxes. Colors indicate (a) μo or (b) relative humidity.

Table 1. Summary of coefficients (A0-A3), averages of GOES (GOES AVG) and CERES (CERES AVG), number of cases (NCASE), and RMS % error (RMS) for the SGP winter (WI), spring (SP), summer (SU), and autumn (AU) longwave (LW) and shortwave (SW) NB-BB fits.

	A0	A1	A2	A3	GOES AVG	CERES AVG	N CASE	RMS
WI LW	63.89	7.48	-0.04593	-0.36355	33.8	219.9	38381	3.0%
SP LW	78.21	5.62	-0.02179	-0.21260	42.3	241.3	39005	3.7%
SU LW	72.90	6.23	-0.02381	-0.30839	48.8	262.7	40730	3.4%
AU LW	81.25	6.0	-0.02450	-0.29643	43.5	247.2	38160	3.0%
WI SW	0.0248	0.8171	-0.08309	0.03756	0.390	0.350	18108	7.1%
SP SW	0.0708	0.6828	0.03431	-0.00282	0.320	0.293	26470	6.2%
SU SW	0.0712	0.6521	0.06425	0.04277	0.230	0.230	22283	7.1%
AU SW	0.0629	0.6567	0.07111	0.03109	0.296	0.280	24682	6.8%

Similar correlations were performed for Darwin to obtain domain-specific NB-BB regression coefficients. Unlike the SGP, the Darwin domain includes both ocean and land. Thus, separate fits were made not only for dry and wet seasons, but also to account for the spectral differences inherent in these two scene types. The SW albedo is typically larger for clear land than for ocean at the same VIS albedo, because the ocean albedo is spectrally flat compared to the land albedo, which increases with wavelength from 0.65-µm into the near infrared. Thus, land-scene dependent fits are needed. Although LW flux land-ocean spectral differences are not as large, some significant differences can occur due to surface emissivity and relative humidity differences. Over the Darwin site, column-weighted relative humidity varies greatly between the ocean and the dry Australian continent. Additionally, the seasons were broken down into the wet season, characterized by monsoonal activity, and dry season.

Figure 2 depicts the fits for the Darwin ocean dry season cases. For 6,400 BB albedo matches (Figure 2a), the average CERES (GOES) values are 0.134 (0.111). The regression fit shows a slightly larger μ_o-dependence than in Figure 1a; however, the range of observed µo is relatively small in this tropical locale. The RMS error in the multiple regression results is 10.1%.

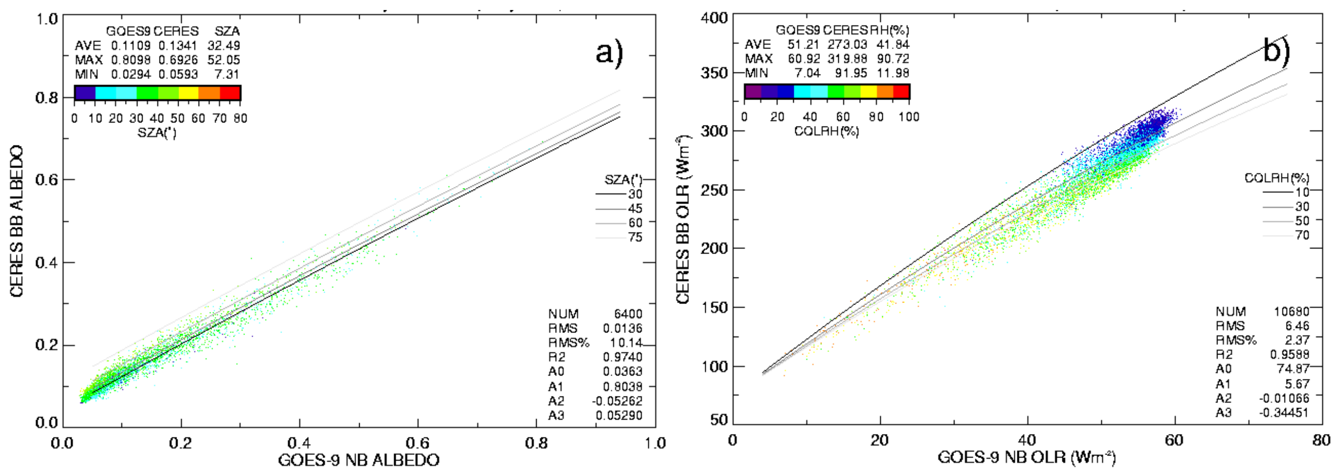

Figure 2. Same as Figure 1, except for the Darwin domain June 2004 - May 2005 over ocean only, for dry season data.

The mean CERES (GOES) outgoing LW radiation (OLR) for 10,680 cases is 273.0 Wm^{-2} (51.2 Wm^{-2}). Less curvature is apparent in the regression lines compared to the SGP primarily because of a lack of very dry cases over the water. The RMS% error is 2.4%. The fits for wet season ocean (OW) and land (LW), and dry season land (LD) are summarized in Table 2.

Table 2. As in Table 1, but for the Darwin dry (D), wet (W), ocean (O), and land (L) NB-BB fits.

	A0	**A1**	**A2**	**A3**	**GOS AVG**	**CER AVG**	**N CASE**	**RMS**
OD LW	74.87	5.67	-0.01066	-0.34451	51.2	273.0	10680	2.4%
OW LW	76.39	5.15	-0.00462	-0.31159	43.8	236.7	9261	3.4%
LD LW	43.57	7.98	-0.04151	-0.35540	57.2	297.0	3867	2.4%
LW LW	62.96	6.18	-0.02130	-0.30311	46.8	245.9	3307	3.9%
OD SW	0.0363	0.8038	-0.05262	0.05290	0.111	0.134	6400	10.1%
OW SW	0.0374	0.8183	-0.04710	0.06359	0.177	0.188	5456	12.3%
LD SW	0.0417	0.8261	-0.08938	0.02754	0.144	0.165	2277	5.1%
LW SW	0.0489	0.7588	0.01365	0.04465	0.198	0.205	1873	7.5%

To illustrate one case of using NB-BB fits to calculate TOA BB SW and LW fluxes from satellite, Figure 3 shows the GOES-8 imagery and results for the SGP at 1715 Universal Time Coordinates July 1, 2002. This case is coincident with a Terra overpass. Cirrus from a convective storm is present in the center of the domain, exhibiting high SW albedos (maxima, 70-80%) and low OLR values (minima, 100 – 125 Wm^{-2}).

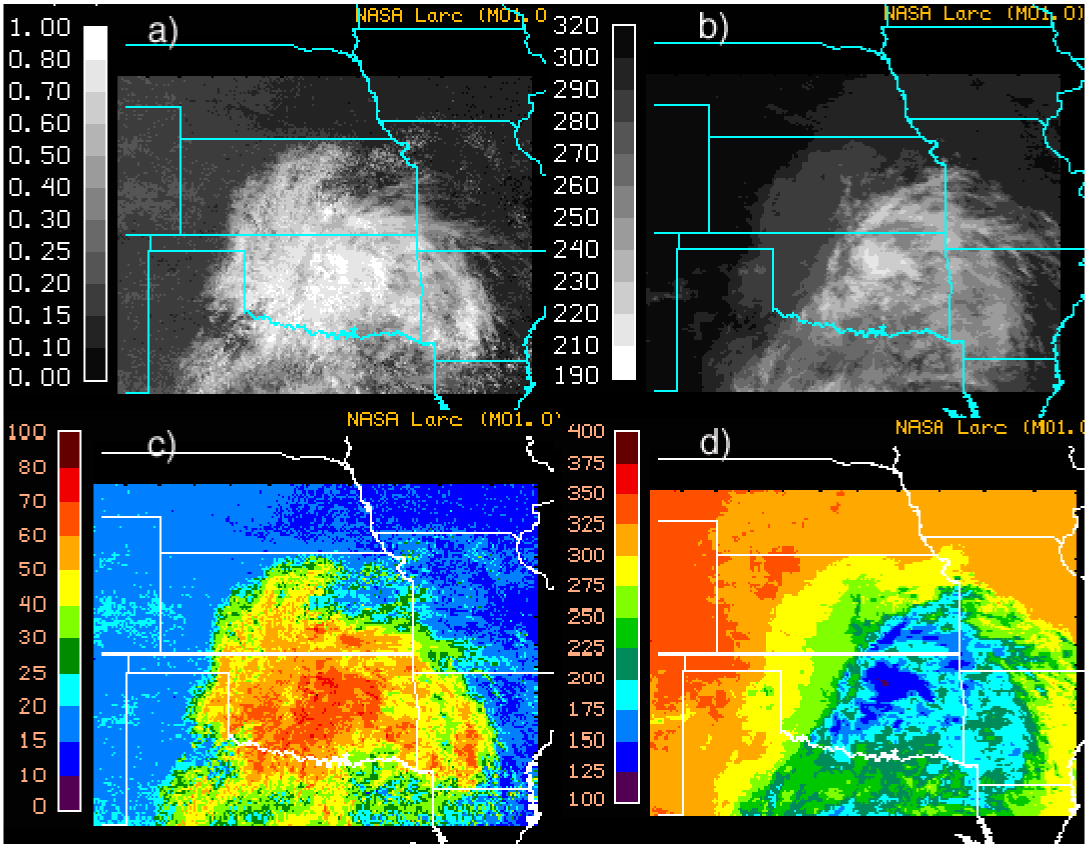

Figure 3. GOES-8 derived parameters over the SGP domain for 1715 Universal Time Coordinates July 1, 2025 (a) 0.65-µm reflectance, (b) infrared brightness temperature, (c) BB SW albedo, and (d) BB longwave flux.

The surface fluxes estimated from satellites are affected by several factors, one of which is the accuracy of NB-BB coefficients for deriving TOA flux. However, before assessing the impact of the new coefficients, other inputs that affect estimates must be examined. VISST cloud properties are used as input to the National Aeronautics and Space Agency (NASA) Langley Parameterized Longwave Algorithm (LPLA; Gupta et al. 1992) that derives upwelling longwave surface flux (UPLW). Skin temperature is the most important parameter for deriving the surface upwelling longwave flux, so methods deriving it from satellite must be accurate. Figure 4 shows an example of the LPLA algorithm applied to the GOES-12 data over Boulder, Colorado during January 2004 and plotted against surface measurements from the Surface Radiation Budget Network (SURFRAD). In the past, a simple empirical conversion from air temperature to skin temperature, based on SGP data, was employed in derivations of UPLW flux from VISST using LPLA (Figure 4a). The comparisons of clear-sky UPLW in Figrue 4a yield an RMS error of 13.1% and a bias of -37.6 Wm^{-2}. However, using atmosphere-corrected clear-sky GOES-8 satellite 10.7-µm to obtain skin temperatures (Figure 4b), the RMS error decreased to 3.6% with a bias of -10.1 Wm^{-2}. The remaining bias may be due to discrepancies in the LW and infrared surface emissivities.

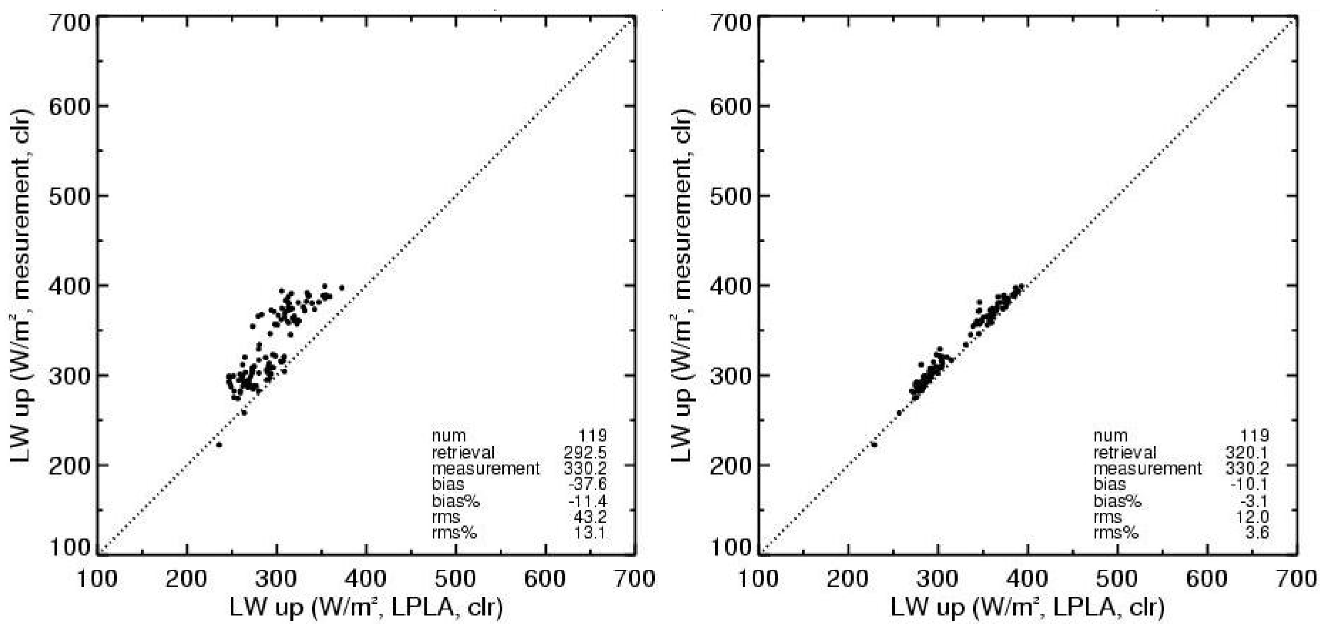

Figure 4. Comparison of clear-sky LPLA and SURFRAD UPLW over Boulder, January 2004, for (a) old air-to-skin temperature conversion method and (b) correlated-k skin temperature method.

Discussion

To gauge the effects of these new fits on the data, comparisons can be made of the VISST-derived BB fluxes to CERES, using both the old and new sets of NB-BB coefficients. Figure 5 compares the GOES-8 SGP TOA BB fluxes with their CERES counterparts. By applying the seasonal NB-BB fits and a third-order correction for residuals at the lower and higher ends of the scale, both longwave averages are identical at 243.1 Wm^{-2}, with an RMS error of 3.3%. Applying seasonal NB-BB fits, rather than one NB-BB fit for the entire 3 year period, decreases the RMS error slightly, from 3.4% to 3.3% (not shown). For the SW fluxes, the averages for CERES and GOES are identical at 284.5 Wm^{-2}, so that the bias is zero. The RMS error is 6.7%. Again, using the seasonal fits instead of whole-period fits reduces the RMS error; the decrease in this case is 0.2%, from 6.9% to 6.7% (not shown).

Figure 6 shows how the Darwin GOES-9 TOA BB fluxes compare to CERES. With the addition of correction based on a linear fit to the residuals for ocean data, the CERES (GOES) average longwave flux is 260.8 Wm^{-2} (260.7 Wm^{-2}), with an RMS error of 2.9%. The RMS error decreased 0.1% from the use of the June 04 – May 05 entire period fit. For the SW fluxes, the averages for CERES and GOES are both 192.5 Wm^{-2}; the RMS error is 10.8%, very close to that of the fit done for the whole period.

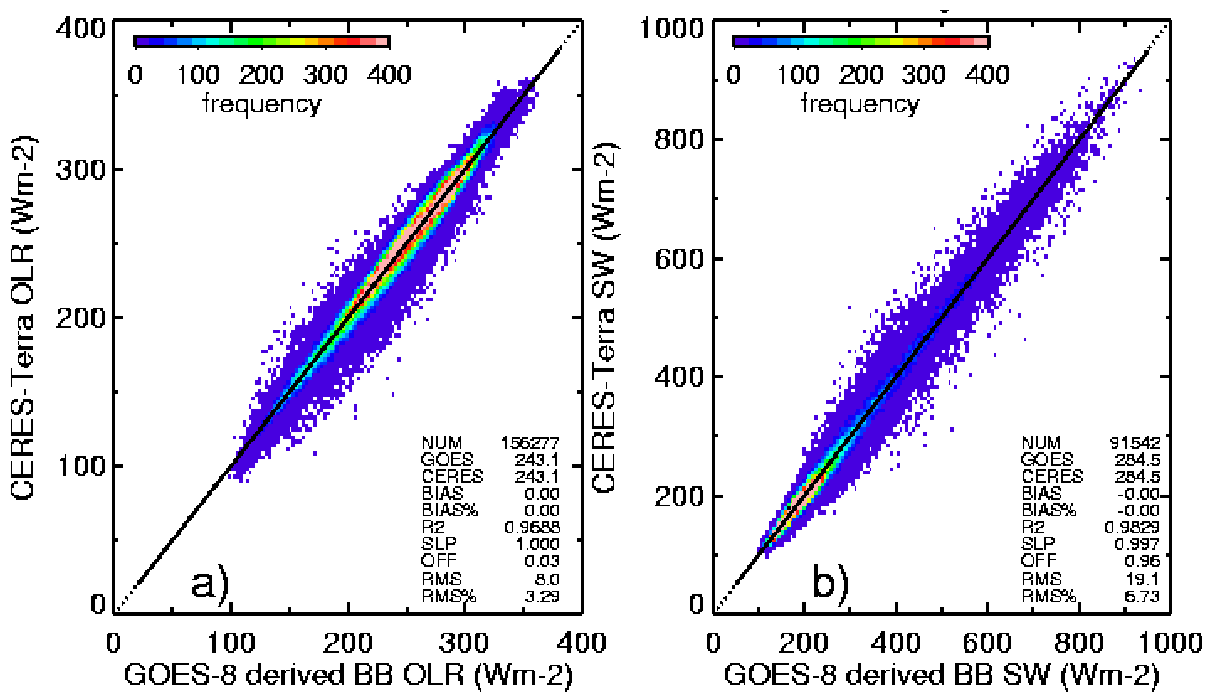

Figure 5. Comparison of Terra CERES and GOES-8 BB fluxes over the SGP for April 2000 – March 2003.

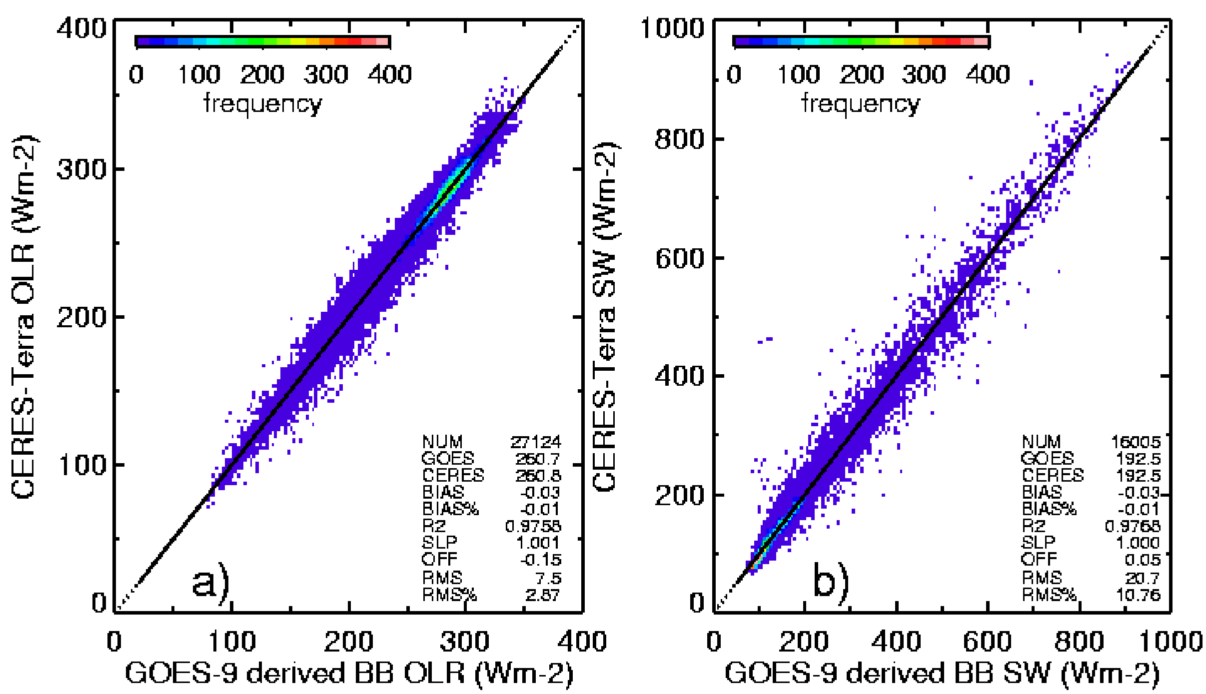

Figure 6. Same as Figure 5, except for Darwin, during June 2004 - May 2005.

Historically, the SGP was represented by only GOES-8 NB-BB fits. However, with the current use of GOES-10 and 12 satellites to view the region, new seasonal NB-BB fits using these satellites should be derived as well. Figure 7 shows the comparison of GOES-12 BB (a) LW and (b) SW fluxes derived from the new fits, versus CERES Terra. With an additional linear correction, the LW comparison yields a bias of 0, with average values of 254.3 Wm^{-2}. The RMS error was 3.3%. These values represent a significant improvement over the GOES-12 values derived using the old GOES8-CERES TRMM fit, which yielded a bias of 3.9% and an RMS error of 3.5%. The new SW fluxes also yield a bias of 0%, with an RMS error of 6.8%; this is an improvement compared to the old SW fluxes, with a bias of 5.3% and RMS error of 7.1%. GOES-10 values showed similar improvement. The old and new values are summarized in Table 3.

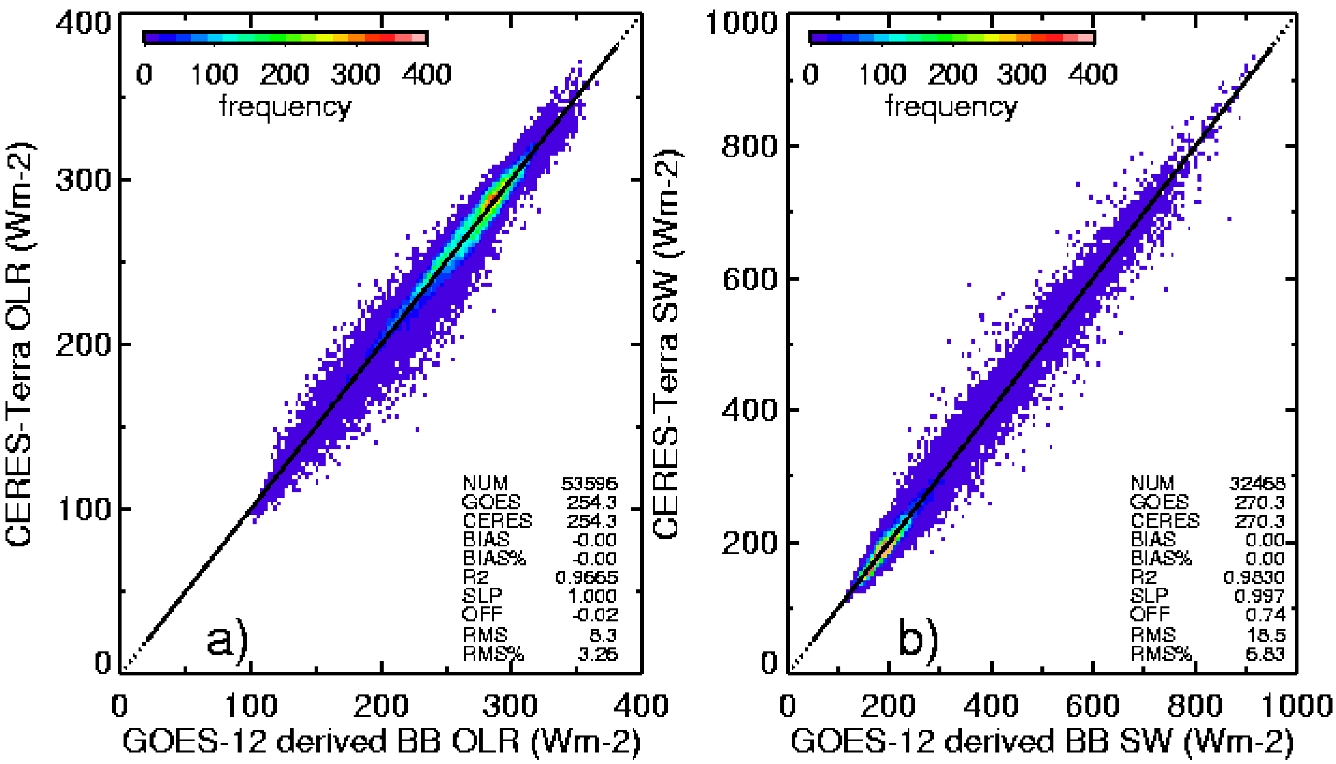

Figure 7. Comparison of Terra CERES and GOES-8 BB fluxes over the SGP GOES-12, during March – November 2005.

Table 3. Summary of biases and RMS errors for the SGP and Darwin, old and new NB-BB fits. Asterisk indicates the "new" values are for the GOES8 NB-BB coefficients, as validation.

	Dates	**Old Bias**	**Old RMS**	**New Bias**	**New RMS**
G8 OLR	4/00-3/03	1.4%	3.6%	0.0%	3.3%
G9 OLR	6/04-5/05	2.4%	3.9%	0.0%	2.9%
G10 OLR*	3/05-11/05	2.1%	3.1%	0.2%	3.0%
G10 OLR	3/05-11/05	2.1%	3.1%	0.0%	2.9%
G12 OLR*	3/05-11/05	3.9%	3.5%	1.8%	3.3%
G12 OLR	3/05-11/05	3.9%	3.5%	0.0%	3.3%
G8 SW	4/00-3/03	5.3%	6.9%	0.0%	6.7%
G9 SW	6/04-5/05	-9.5%	13.4%	0.0%	10.8%
G10 SW*	3/05-11/05	2.5%	7.2%	-2.1%	7.2%
G10 SW	3/05-11/05	2.5%	7.2%	0.0%	7.1%
G12 SW*	3/05-11/05	5.3%	7.1%	0.4%	6.9%
G12 SW	3/05-11/05	5.3%	7.1%	0.0%	6.8%

The zero biases for these cases is expected since the same cases that created the new NB-BB fit are used in the validation. To see if the NB-BB fit shows improvement, independent validation is required. GOES-10 and -12 also provide imager data over the SGP for other periods than the GOES-8 satellite. SW fluxes from March – November 2005 for the GOES-12 satellite are compared in Figure 8 using the (a) CERES-TRMM NB-BB fits ("OLD N-B") versus the new seasonal (b) CERES-Terra fits ("NEW N-B"). The old fits had a bias of 14.4 Wm^{-2} and an RMS error of 7.1%, whereas the new NB-BB fit yields a bias of only 1.1 Wm^{-2} and an RMS error of 6.9%. The GOES-10 SW results (not shown) improved the bias, while the RMS error stayed unchanged. The "before" bias was 6.6 Wm^{-2} with an RMS error of 7.2%, which changed to an "after" bias of –5.5 Wm^{-2}. Even so, the LW results for both GOES-10 and 12 improved using the new NB-BB fits with the residual correction (not shown). The GOES-10 bias of 5.3 Wm^{-2} (RMS 3.1%) using the old fit improved to 0.4 Wm^{-2} (RMS, 3.0%) using the new fit. GOES-12 had a "before" bias of 9.8 Wm^{-2} and an RMS error of 3.5%, but an "after" bias of 4.6 Wm^{-2} and an RMS error of 3.3%. The biases and RMS errors using old and new NB-BB fits are summarized in Table 3.

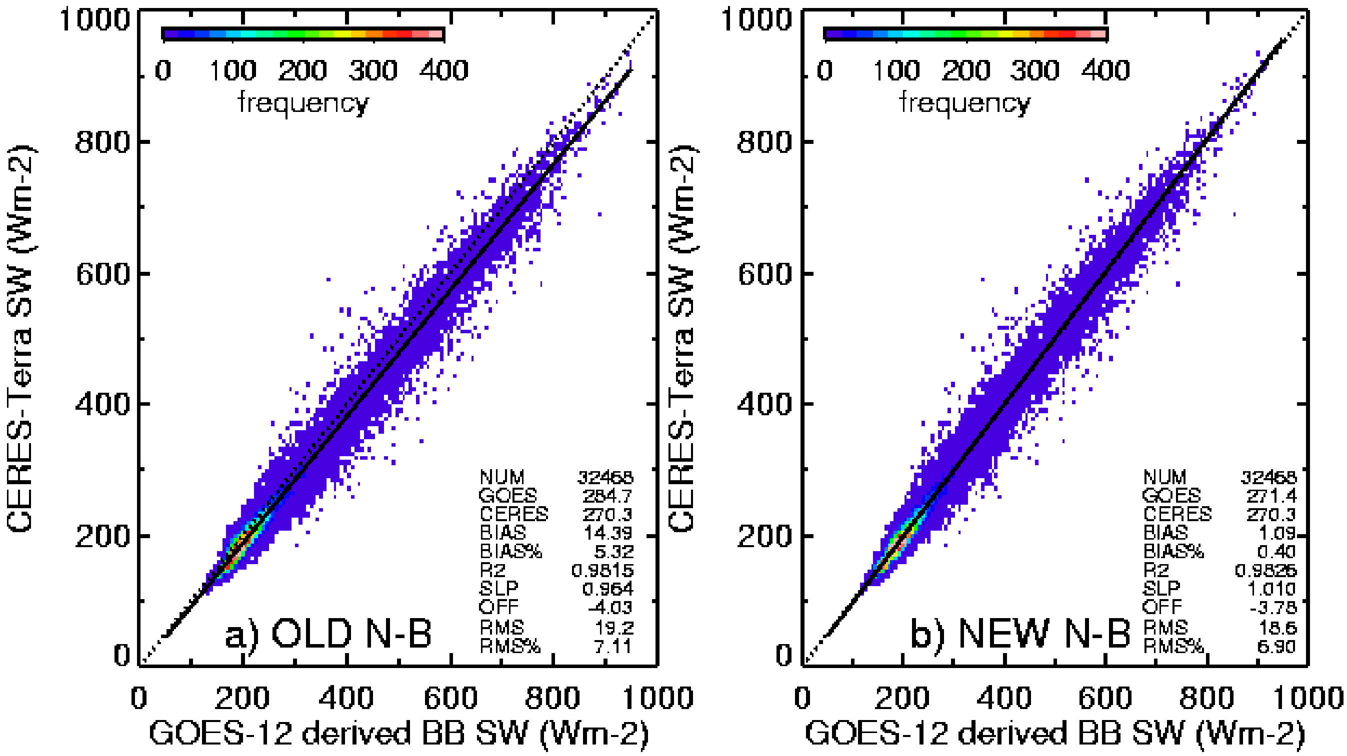

Figure 8. Validation of GOES-12 SW fluxes over the SGP domain using Terra CERES data from February - May 2005 for (a) old GOES-8-TRMM NB-BB fit and (b) new GOES-8-Terra NB-BB fit.

Summary and Future Work

The NB-BB fits were recomputed using the most up-to-date satellite information available, separated by season. GOES-8, -10, and -12 and Terra were used to derive new NB-BB coefficients for the SGP domain, and GOES-9 and Terra were employed for the TWP Darwin domain. SGP fits are for land-only, but separate fits for land and ocean were developed for Darwin. Both domains showed improvement in longwave and SW fluxes when the new coefficients were used, as expected. Additionally, slight improvement was found when using the seasonal NB-BB fits versus NB-BB fits derived using all the data in the given period.

The new SGP NB-BB coefficients were tested on GOES-10 and GOES-12 as an independent validation. Using the new GOES-8/Terra coefficients improved or left unchanged GOES-10 and 12 improved SW and longwave flux biases and RMS errors. The exercise was useful as a validation of the GOES8-Terra coefficients, but independent NB-BB fits for GOES-10/12 and Terra will be used when data from those satellites are employed.

Correlated-k distribution corrected skin temperatures input to LPLA were shown to improve agreement when compared to SURFRAD data. Surface fluxes could also be improved using the new NB-BB fits, but this is left to future work.

Future work includes performing outside validation for the GOES-9 – Terra NB-BB fits. Also, as more GOES-10 and 12 data are processed with the VISST, more data will be used to augment the seasonal NB-BB fits for those satellites, including a fit for winter. Finally, the impact of the improved TOA fluxes from these fits on derived surface fluxes will be assessed.

Acknowledgments

This research was supported by the U.S. Department of Energy ITF No. 3407 from the Pacific Northwest National Laboratory and NASA through the CERES Project. Some of the atmospheric profiles were generated by the CERES Meteorological, Ozone, and Aerosols group and obtained from the NASA Langley Atmospheric Sciences Data Center.

References

Chakrapani, V, DR Doelling, MM Khaiyer, and P Minnis. 2003. "New visible to broadband shortwave conversions for deriving albedoes from GOES-8 Over the ARM-SGP." In *Proceedings of the Thirteenth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting*, March 31-April 4, Broomfield, Colorado.

Doelling, DR, MM Khaiyer, and P Minnis. 2003. "Improved ARM-SGP TOA OLR Fluxes from GOES-8 IR radiances based on CERES data." In *Proceeding of the Thirteenth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting*, March 31-April 4, Broomfield, Colorado.

Geier, EB, RN Green, DP Kratz, P Minnis, WF Miller, SK Nolan, and CB Franklin. 2001. Single satellite footprint TOA/surface fluxes and clouds (SSF) collection document. http://asd-www.larc.nasa.gov/ceres/ASDceres.html

Gupta, SK, WL Darnell, and AC Wilber. 1992. "A parameterization for longwave surface radiation from satellite data: recent improvements." *Journal of Applied Meteorology* 31:1361-1367.

Khaiyer, MM, P Minnis, DR Doelling, PK Chan, ML Nordeen, R Palikonda, and Y Yi. 2006. "Derivation of improved surface and TOA broadband fluxes using CERES-derived narrowband-to-broadband coefficients." In *Proceedings of the American Meteorological Society Twelfth Conference Cloud Physical and Atmospheric Radiation*, Madison, Wisconsin, 10-14 July 2006, CD-ROM, P3.5.

Loeb, NG, N Manalo-Smith, S Kato, WF Miller, S Gupta, P Minnis, and BA Wielicki. 2003. "Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earths Radiant Energy System instrument on the Tropical Rainfall Measuring Mission satellite. Part I: Methodology." *Journal of Applied Meteorology* 42:240-265.

Minnis, P, and EF Harrison. 1984. "Diurnal variability of regional cloud and clear-sky radiative parameters derived from GOES data. Part I: Analysis method." *Journal of Climate and Applied Meteorology* 23:993-1011

Minnis, P, and WL Smith, Jr. 1998. "Cloud and radiative fields derived from GOES-8 during SUCCESS and the ARM-UAV Spring 1996 Flight Series." *Geophysical Research Letters*, 25:1113-1116.

Minnis, P, DP Kratz, JA Coakley, Jr., MD King, D Garber, P Heck, S Mayor, DF Young, and R Arduini. 1995. Cloud Optical Property Retrieval (Subsystem 4.3). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document. Volume III: Cloud Analyses and Radiance Inversions (Subsystem 4)," NASA RP 1376 Vol. 3, edited by CERES Science Team, pp. 135-176.

Minnis, P, DP Garber, DF Young, RF Arduini, and Y Takano. 1998. "Parameterization of reflectance and effective emittance for satellite remote sensing of cloud properties." *Journal of Atmospheric Science* 55:3313-3339.

Nguyen, L, P Minnis, and DR Doelling. 2006. "Rapid calibration of operational and research meteorological satellite imagers. Part III: Application to geostationary satellite visible channels." Submitted to *Journal of Atmospheric and Oceanic Technology*.

Phan, D, DA Spangenberg, R Palikonda, MM Khaiyer, ML Nordeen, L Nguyen, and P Minnis. 2004. "Web-based satellite products database for meteorological and climate applications." In *Proceedings of the Thirteenth American Meteorology Society Conference Satellite Oceanography and Meteorology*, Norfolk, Virginia, September 20-24, CD-ROM, P8.2.

Wielicki, BA, BR Barkstrom, BA Baum, TP Charlock, RN Green, DP Kratz, RB Lee III, P Minnis, GL Smith, T Wong, DF Young, RD Cess, JA Coakley, Jr., DAH Crommelynck, L Donner, et al. 1998. "Clouds and the Earth's Radiant Energy System (CERES): Algorithm Overview." IEEE Transactions on Geoscience and Remote Sensing 36:1127-1.