Validation of CERES/SARB Data Product Using ARM Surface Flux Observations

D. A. Rutan
Analytical Services and Materials Inc.
Hampton, Virginia

T. P. Charlock
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Introduction

This paper uses surface observed broadband fluxes from Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP), ARM Tropical Western Pacific (TWP), and a number of other sites to validate model results from the Clouds and the Earth's Radiant Energy System (CERES) Surface and Radiation Budget (SARB) Clouds and Radiative Swath (CRS) data products during the months of January-December 2001. CERES instruments fly aboard the Terra and Aqua satellites measuring broadband radiation in three channels: total (0.3-∝ μm), shortwave (0.3-5.0 μm), and window (8-12.0 μm) at the top of the atmosphere (TOA). The CRS product supplies, along with CERES observed fluxes, model calculated fluxes at five atmospheric levels beneath every other CERES footprint. The radiation transfer model used is a modified version of the Fu and Liou radiation transfer model and is described in more detail below. CERES observations supply a "truth" against which the model can be compared at the TOA and broadband surface flux observations provide the same at earth's surface. Results are encouraging in that all sky biases, including all sites, for downward longwave (LW) and shortwave (SW) flux are less than 2%. For clear-sky biases are less than 1%. The worst error occurs in SW insolation under overcast skies with biases approaching 10%. These biases and their associated RMS' vary geographically as will be shown below.

Surface Flux Observation (ARM, SURFRAD, CMDL, BSRN, NREL, LARC)

Surface observations used in this study include 40 sites worldwide. Listed in Table 1, they were selected due to adherence to Baseline Surface Radiation Network standards (Ohmura et al 1998.) Table 1 also shows pertinent web sites and references for each set of surface data. Most sites are in fact baseline surface radiation network (BSRN) sites though much of the data is generously supplied to SARB before it enters the BSRN archive. Upwelling and downwelling surface observations of irradiance are generally made from 10 m towers and reported as one-minute averages. For SW insolation we preferentially choose "total" insolation (direct radiation + diffuse) if available. If the total

Table 1. Surface Sites, Associated Web Pages, and Referencing Information

Project	Sponsor	# Sites	Web Link	Reference:
ARM SGP/TWP	DOE[(a)]	22	www.arm.gov	Acknowledgements
CMDL	NOAA[(b)]	6	www.cmdl.noaa.gov	Acknowledgements
SURFRAD	NOAA[(b)]	6	www.srrb.noaa.gov	Augustine et al. 2000
BSRN	WCRP[(c)]	4	www.ethz.ch	Ohmura et al. 1998
NREL	DOE[(d)]	1	rredc.nrel.gov/solar/new_data/Saudi_Arabia	Myers et al. 1999
NASA LARC	NASA[(e)]	1	www-svg.larc.nasa.gov	Jin et al. 2002

(a) Atmospheric Radiation Measurement Program, Department of Energy
(b) Climate Monitoring Diagnostics Laboratory, National Oceanic and Atmospheric Administration
(c) Baseline Surface Radiation Network, World Climate Research Programme
(d) National Renewable Energy Laboratory, Department of Energy
(e) NASA Langley Research Center, National Aeronautics and Space Administration

observation is un-available a global (unshaded PSP) observation is used. For SARB validation these data are averaged to 30-minute time steps along with other surface meteorological variables available at each site. These 30-minute average data files (one file per month per site) along with on-line plotting capabilities are made available via the CERES/ARM Validation Experiment (CAVE) web site: http://www-cave.larc.nasa.gov/cave.

Radiation Transfer Model

The radiation transfer model used in SARB is a modified version of the Fu and Liou (1993) code. It is a delta-two stream (2 for SW, 2/4 for LW) radiation transfer code with fifteen spectral bands from 0.175 to 4.0 μm in SW and twelve LW spectral bands between 2850 and 0 cm^{-1}. Cloud properties are given by MODIS imager pixels collocated within larger CERES footprints. Aerosol optical depths are input from MODIS (MOD08D3) product. The Collins/Rasch Model of Atmospheric Transport and CHemistry (MATCH) model defines aerosol constituents (Collins et al 2001) and scale heights. Aerosol optical depths from MATCH are used where the MODIS product is un-available (often over desert regions) or cloud fraction is greater than 75% (often over Polar Regions). Actual aerosol properties (single scatter albedo, scattering coefficient etc…) are given by matching seven aerosol types from the MATCH model to aerosol properties given by Hess et al. (1998) and Tegen and Lacis (1996). Pressure, temperature, and water vapor profiles are specified from GEOS-4.0 and ozone from NCEP's, Stratospheric Monitoring Group Ozone Blended Analysis product from SBUV and TOVS (TIROS [television and infrared observation satellite] operational vertical sounder). Surface albedo over ocean is available from a lookup table based on the Coupled Ocean/Atmosphere Radiation Transfer (COART) model of Jin (2002). Over clear-sky land, surface albedo is derived from a TOA to surface parameter-ization. Clear-sky surface albedos are pre-processed for a month saving the minimum value in an equal angle, 10-minute resolution grid. This "history" map is used to supply broadband albedo under cloudy footprints. If no clear-sky is available a climatological value is used. Albedo spectral shapes come from a scene type (IGBP) based lookup table. The radiation transfer model is run eight times for each footprint. These runs include a pristine (no clouds or aerosols), clear (no clouds), cloudy pristine (include clouds, no aerosols) and an all-sky run. These four conditions are run twice, one untuned, and one tuned run. For the all sky run, CERES fluxes are assumed a "truth" against which the model can be compared. Hence, the model is run with its initial inputs (untuned) and TOA model flux is compared with CERES observations. Certain input parameters, depending on atmospheric conditions, are then modified using a Lagrange Multipliers minimization technique. Each possible tunable parameter is assigned a "sigma", an estimate of quality of that particular variable, which constrains the adjustment process not allowing any one variable to "move" too much. Similar error estimates are assigned to TOA fluxes so that exact matches of model and observed TOA fluxes are not required. For example under clear skies, for SW flux, aerosol optical depth, and surface albedo can be "tuned" to better match observed TOA flux. Only a single iteration is computed. Constraining the model to CERES observations at TOA leaves surface fluxes to change depending on what is required for a better match at the top.

Model/Data Comparison

As stated above, downwelling and upwelling surface observations of LW and SW irradiances are averaged to half hour means and collected for each month at each site. As CERES sweeps past a surface site contained in the CAVE database, the centroid of each footprint is located with respect to the surface site. Within a given half hour only the footprint that comes closest to a surface site (no greater than 10 km away) is retained for comparison with surface observations. To account for differences in solar zenith angle within the half hour flux averages, the surface flux observation is adjusted by the ratio of the surface 30 minute average solar zenith angle and footprint solar zenith angle at the satellite observation time. Clear skies are determined within the CERES footprint by collocation of satellite imager pixels within the larger CERES footprint. A secondary check for cloud fraction is specified by the Short Wave Flux (SWF) cloud fraction as given by the Long and Ackerman (2000) cloud fraction algorithm. Tables that include SWF cloud fraction are found at the CAVE website. Results are subset by "all sky"- all footprints, "clear-sky"- CERES cloud fraction equal to 0, and "overcast" – CERES cloud fraction equal to 1.0. CAVE sites are grouped by geographic region as shown in Table 2.

Table 2. Sites Contained in Each Geographic Region

Region	Central USA	Polar	Island	North America	Coastal
Sites	20 ARM/SGP sites	South Pole, G. Von Neumeyer, Syowa, Barrow, Alaska	Manus, Nauru, Kwajalein, Bermuda, Samoa	6 SURFRAD sites	Tatano, JP, COVE

Table 3 gives a comprehensive summary of downward LW and SW surface flux bias and RMS for each geographic region and for all sites combines. The sense is model minus observation hence negative LW implies to cool an atmosphere and positive SW implies the model is too transmissive. Recall these numbers are for instantaneous comparisons, not daily averages, so that though the LW does represent day and night footprints a daily average bias for SW would be halved from the numbers shown. Figure 1 shows a comparison of model and observed downwelling LW and SW fluxes at 20 ARM/SGP sites for all of 2001. Black, red, and blue indicate overcast, partly cloudy, and clear-sky footprints, respectively. This is an example of plots available at all surface sites in the CAVE database at http://www-cave.larc.nasa.gov/cave/.

Table 3. Surface SW and LW Bias CERES/SARB Tuned Model Results Minus Surface Observations

Downward Surface Flux (Tuned Model-Obs) Bias (RMS) (W/m^2)				
	All Sky		**Clear-Sky**	
	Longwave	**Shortwave**	**Longwave**	**Shortwave**
ARM/SGP	-9(17)	6(74)	-10(15)	3(18)
Island Sites	-4(15)	39(146)	-10(15)	3(18)
Polar Sites	0(29)	0(68)	-8(16)	-10(21)
SURFRAD	-7(20)	10(90)	-8(17)	-2(22)
Coastal	3(18)	24(90)	4(13)	-4(36)
All Available	-6(21)	9(86)	-9(16)	-2(27)

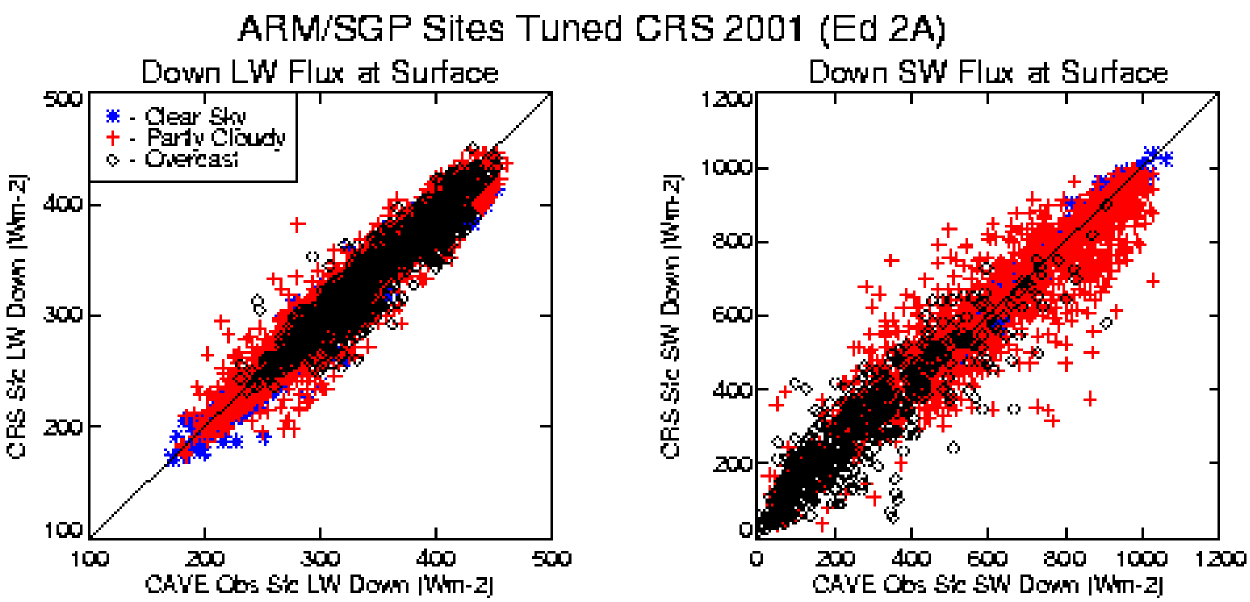

Figure 1. Comparison of model and surface observed downwelling LW and SW radiation at 20 ARM/SGP sites during 2001.

More detailed tables of statistics for each site along with aerosol and cloud forcing are also given with each plot. A summary of TOA and surface bias statistics for the subset of comparisons in Figure 1 is given in Table 4. Flux comparisons at TOA are shown in gray, surface fluxes in white. For each cloud condition both untuned and tuned results are shown. Recall that the model is constrained by the TOA comparison. This is evident by the reduction in bias and RMS under all cloud conditions at TOA from the untuned column to the tuned. Surface fluxes are left to react to changes in model inputs that made by the tuning algorithm. In general, this does not affect surface flux comparisons significantly. One exception is surface SW insolation under overcast skies (bottom right of each table). One finds an initial TOA SW error of 12W/m^2 and RMS of 26 W/m^2. The tuning algorithm assumes clouds are too

Table 4. Biases and RMS' for TOA and Surface Comparisons at 20 ARM/SGP Sites for all of 2001. Biases indicate model minus observations for both constrained and unconstrained model runs, subset by cloud condition.

ARM/SGP Sites		TOA and Surface Model-Observed Bias (RMS) (W/m^2)					
		All Sky		**Clear-Sky**		**Overcast**	
		Untuned	**Tuned**	**Untuned**	**Tuned**	**Untuned**	**Tuned**
LW	TOA Up	2(8)	1(4)	0(4)	0(2)	2(10)	1(3)
	Sfc Dn	-9(17)	-9(17)	-10(15)	-10(15)	-10(19)	-11(20)
	Sfc Up	-3(23)	-4(21)	2(16)	0(16)	2(18)	2(18)
SW	TOA Up	-3(22)	0(7)	1(3)	0(0)	12(26)	1(9)
	Sfc Dn	7(73)	6(74)	3(18)	3(18)	4(78)	23(82)
	Sfc Up	-17(31)	-15(31)	-17(24)	-18(24)	-10(32)	-6(33)

reflective, subsequently reducing either cloud amount or cloud optical depth or both. TOA error is reduced to 1 W/m^2 bias and 9 W/m^2 RMS. However, reducing either cloud amount or optical will increase flux observed at the surface hence increasing the relative difference. This is seen in Table 4 where a positive bias of 4 W/m^2 increases to 23 W/m^2. Tables 5 through 8 show the same statistics as Table 4 but for different subsets of surface sites based on geographical location. In each case the story is basically the same though biases change slightly depending on underlying surface condition.

Successes are found in these results in TOA upward fluxes, the effect of the tuning algorithm to reduce RMS at TOA, and clear-sky surface insolation results. Also in LW up at the surface, which is a proxy for surface skin temperature, biases are small. One exception is at the COVE site where footprints often overlap water and land. At this site, the input skin temperature is often more representative of land than water, the value observed at COVE. Besides overcast SW insolation another primary problem seen in the tables is a mismatch of upward surface flux. This is due to a spatial mismatch in surface albedos. The CERES footprint is approximately 20 km in a nadir viewing position and this spatial extent increases with increasing viewing zenith angle. Since most sites have downlooking radiometers at 10 m the albedos can only match if the few square meters viewed by the downlooking radiometer approximates that of the surrounding 20 to 100 square kilometers. Two places where there are good matches of albedo are the Polar sites, where snow dominates and subsequently a 10 m observation can match a much larger area, and in the Coastal table. Since there is no downlooking instrument at Tatano, all SW up observations are coming from the Chesapeake Lighthouse or COVE site. There, the downlooking radiometer is mounted directly over the water indicating that the COART derived ocean surface albedo is matching well with surface observations. This is shown in detail by Jin et al. (2002).

Table 5. Same as Table 4 but for 6 SURFRAD Sites

SURFRAD Sites		TOA and Surface Model-Observed Bias (RMS) (W/m^2)					
		All Sky		Clear-Sky		Overcast	
		Untuned	Tuned	Untuned	Tuned	Untuned	Tuned
LW	TOA Up	1(9)	1(5)	-1(5)	-1(3)	1(10)	1(4)
	Sfc Dn	-7(19)	-7(20)	-8(17)	-8(17)	-10(19)	-11(20)
	Sfc Up	-8(7)	-7(25)	-5(17)	-4(16)	1(20)	1(20)
SW	TOA Up	-1(24)	0(8)	1(4)	0(1)	10(34)	-1(11)
	Sfc Dn	11(88)	10(90)	-2(22)	-2(22)	25(107)	40(110)
	Sfc Up	-18(47)	-18(47)	-28(25)	-27(38)	-6(53)	-5(50)

Table 6. Same as Table 4 but for 4 Polar Sites

Polar Sites		TOA and Surface Model-Observed Bias (RMS) (W/m^2)					
		All Sky		Clear-Sky		Overcast	
		Untuned	Tuned	Untuned	Tuned	Untuned	Tuned
LW	TOA Up	3(10)	2(6)	1(3)	0(2)	4(12)	1(6)
	Sfc Dn	0(29)	0(29)	-8(16)	-8(16)	4(32)	5(32)
	Sfc Up	-1(15)	-2(15)	0(15)	-3(12)	-4(14)	-4(14)
SW	TOA Up	2(30)	0(17)	4(5)	1(2)	-12(39)	-7(28)
	Sfc Dn	2(62)	0(68)	-9(21)	-10(21)	9(90)	26(97)
	Sfc Up	-9(55)	-11(55)	-6(27)	-7(28)	-17(72)	-17(71)

Table 7. Same as Table 4 but for 5 Island Sites

Island Sites		TOA and Surface Model-Observed Bias (RMS) (W/m^2)					
		All Sky		Clear-Sky		Overcast	
		Untuned	Tuned	Untuned	Tuned	Untuned	Tuned
LW	TOA Up	-2(9)	0(4)	-4(6)	-2(3)	-4(10)	0(4)
	Sfc Dn	-3(15)	-4(15)	-1(9)	-10(15)	-5(16)	-5(16)
	Sfc Up	--------	--------	--------	--------	--------	--------
SW	TOA Up	14(28)	4(11)	1(22)	3(12)	23(33)	3(10)
	Sfc Dn	27(142)	39(146)	0(64)	3(18)	17(117)	40(126)
	Sfc Up	--------	--------	--------	--------	--------	--------

Table 8. Same as Table 4 but for 2 Coastal Sites

Coastal Sites		TOA and Surface Model-Observed Bias (RMS) (W/m^2)					
		All Sky		Clear-Sky		Overcast	
		Untuned	Tuned	Untuned	Tuned	Untuned	Tuned
LW	TOA Up	1(9)	2(6)	0(7)	0(4)	-1(9)	1(4)
	Sfc Dn	3(17)	3(18)	3(11)	4(13)	0(14)	-2(14)
	Sfc Up	30(35)	27(33)	25(28)	12(14)	31(38)	31(38)
SW	TOA Up	-24(45)	12(27)	2(16)	2(13)	26(35)	1(11)
	Sfc Dn	12(86)	24(90)	-2(35)	-4(36)	20(93)	51(104)
	Sfc Up	47(62)	49(64)	-2(38)	-2(38)	29(39)	35(44)

Acknowledgements

ARM data is made available through the U.S. Department of Energy as part of the Atmospheric Radiation Measurement Program. CMDL data is made available through the NOAA/CMDL Solar and Thermal Radiation (STAR) group. SURFRAD data is made available through NOAA's Air Resources Laboratory/Surface Radiation Research Branch. COVE data is made available through NASA Langley Research Center's, Atmospheric Sciences Competency, CERES Surface and Airborne Radiometry Calibration group. CERES data is made available from NASA Langley's Atmospheric Sciences Data Center at http://eosweb.larc.nasa.gov/.

Corresponding Author

David A. Rutan (d.a.rutan@larc.nasa.gov), (757) 827-4629

References

Augustine, J. A., J. J. DeLuisi, and C. N. Long, 2000: SURFRAD-A National Surface Radiation Budget Network for Atmospheric Research. *Bull. of Amer. Met. Soc*., **81**, No. 10, 2341–2358.

Collins, W. D., P. J. Rasch, B. E. Eaton, B. V. Khattatov, J.-F. Lamarque, and C. S. Zender, 2001: Simulating aerosols using a chemical transport model with assimilation of satellite aerosol retrievals Methodology for INDOEX. *J. Geophs. Rev*., **106**, 7313–7336.

Fu, Q., and K.N. Liou, 1993: Parameterization of the radiative properties of cirrus clouds. *J. Atmos. Sci*., **50**, 2008–2025.

Hess, M. P., P. Koepke, and I. Schult, 1998: Optical properties of aerosol and clouds: The software package OPAC. *Bull. Amer. Meteor. Soc*., **79**, 831–844.

Jin, Z., T. P. Charlock, and K. Rutledge, 2002: Analysis of broadband solar radiation over the ocean surface at COVE. *J. Atmos. Ocean Tech.*, **19**, 1585–1601.

Myers, D. R., S. Wilcox, M. Anderberg, S. H. Alawaji, N. M. Al Abbadi, and M. Y. bin Mahfoodh, 1999: *Saudi Arabian Solar Radiation Network of Data for Validating Satellite Remote-Sensing Systems*. Earth Obs. Sys. IV SPIE, Vol 3750, July 18-20, Denver, Colorado.

Ohmura A., E. Dutton, B. Forgan, C. Frohlich, H. Gilgen, H. Hegne, A., Heimo, G., Konig-Langlo, B. McArthur, G. Muller, R. Philipona, C. Whitlock, K. Dehne, and M. Wild, 1998: Baseline Surface Radiation Network (BSRN/WCRP): New precision radiometry for climate change research. *Bull. Amer. Meteor. Soc.*, **79**, No. 10, 2115–2136.

Rutan, D. A., F.G. Rose, N. Smith, and T. P. Charlock, 2001: Validation data set for CERES Surface and Atmospheric Radiation Budget (SARB). *WCRP GEWEX Newsletter*, **11**, No. 1, 11–12.

Tegen, I., and A. A. Lacis, 1996: Modeling of particle size distribution and its influence on the radiative properties of mineral dust aerosol. *J. Geophys. Res.*, **101**, 19,237–19,244.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment. *Bull. Amer. Meteor. Soc.*, **77**, 853–868.