CERES TRMM-PFM-VIRS Edition2B SSF
TOA Fluxes - Accuracy and Validation

CERES shortwave (SW), longwave (LW) and window (WN) channel radiative fluxes are derived from empirical Angular Distribution Models (ADMs) that convert a measured radiance in a given Sun-Earth-satellite viewing configuration to a top-of-atmosphere (TOA) radiative flux. In the Earth Radiation Budget Experiment (ERBE) - as well as the CERES ERBE-Like product - a set of 12 ADMs were used. These models relied on scene identification from the Maximum Likelihood Estimation technique (Wielicki and Green, 1989). Since ADMs are highly sensitive to the physical properties of the observed scene, the strategy for the CERES SSF product is to construct new ADMs that take advantage of improved scene identification from high-resolution, multi-spectral imager measurements. In SSF Edition2B, a set of SW, LW and WN ADMs stratified by imager-derived cloud properties are used to estimate TOA fluxes. The cloud properties used to develop these ADMs are those appearing on the TRMM SSF Edition2B product.

The main strength of the Edition2_TRMM ADMs lies in the improved scene identification from VIRS. This allows for a better discrimination between cloud and clear fields of view, which is of paramount importance for aerosol and cloud forcing studies. Also, since cloud properties based on VIRS radiances are available over each CERES footprint, this means that ADM scene types can be defined according to parameters that have the greatest influence on the anisotropy of the scene. These improvements translate to a reduction in flux errors. A description of the ADM scene types is provided in the Validation of CERES/TRMM SSF Edition2 Angular Distribution Models (PDF). Briefly, the Edition2_TRMM ADMs are divided into broad classes of clear and cloud scenes over ocean, land, desert and snow. Each of these is further stratified by several parameters that influence anisotropy. Unlike ERBE scene types, the Edition2_TRMM ADM SW and LW classification schemes are independent of one another. For example, SW cloud ADMs are stratified by cloud phase, cloud fraction and cloud optical depth, whereas LW cloud ADMs use retrievals of IR emissivity, precipitable water, and surface-cloud temperature difference. Other important differences include the manner in which land and desert are categorized in the SW. As shown in the above PDF document, land is separated into a moderate-to-high tree/shrub coverage class (i.e. mainly forests) and a low-to-moderate tree/shrub coverage class (i.e. mainly grasslands), whereas desert is stratified by "dark" desert and "bright" desert. Since the sampling over snow from TRMM is insufficient to develop ADMs, snow ADMs are based on a theoretical model (for Terra we will develop empirical snow ADMs).

Table 1 illustrates the difference in scene identification between SSF and ERBE-Like. Scene type frequencies of occurrence for ERBE definitions of clear, partly cloudy, mostly cloudy and overcast from the ERBE Maximum Likelihood Estimation (MLE) Technique (Wielicki and Green, 1989) are compared with those based on the CERES cloud mask. The CERES cloud mask uses high-resolution imager pixel radiances within CERES footprints to derive an estimate of cloud cover (f) over the footprint. The following relationship between f and ERBE-Like scene type is assumed: 0% <= f < 5%= "Clear"; 5% <= f < 50%= "Partly Cloudy"; 50% <= f < 95%= "Mostly Cloudy"; f >= 95%= "Overcast". As shown in Table 1, the ERBE-Like classification differs markedly from SSF, particularly for overcast conditions. For ERBE-Like, only the coldest and brightest scenes are classified as overcast, wheras SSF overcast scenes can also include extensive thin cirrus, which likely would be classified as either partly or mostly cloudy by ERBE-Like. One reason for the much higher frequency of clear scenes in the ERBE-Like result is likely due to the anomalous conditions associated with the 1998 El Nino event. Because ERBE uses a *priori* thresholds derived in "normal" conditions to determine scene type, a strong deviation from these conditions can have a strong influence on scene type determination. Another reason is the factor of 4 reduction in footprint size between CERES/TRMM and ERBE (Loeb et al., 2001). Because CERES SSF uses high-resolution, multispectral imager data to determine cloud cover, scene identification from SSF Edition2B is less sensitive to these kinds of problems.

Table 1. Scene type frequency of occurrence for clear, partly cloudy, mostly cloudy and overcast scenes over ocean as determined by the MLE technique and the CERES cloud mask for daytime and nighttime conditions (January, 1998).

Scene Type	Scene Type Frequency of Occurrence (%)			
	Daytime		Nighttime	
	MLE	Imager	MLE	Imager
Clear	36	26	25	29
Partly Cloudy	28	18	46	17
Mostly Cloudy	23	15	20	17
Overcast	13	41	9	37

In the Validation of CERES/TRMM SSF Edition2 Angular Distribution Models (PDF), a detailed analysis of flux errors based on SSF Edition2B TRMM and ERBE ADMs (from the CERES ES-8 product) is provided. Results from that study can be summarized as follows:

SHORTWAVE FLUXES

A new clear ocean SW ADM that accounts for variations in aerosol optical depth and wind speed is introduced. Fluxes based on the new SSF Edition2_TRMM ADMs are larger than those from SSF Edition1 (which ignore aerosol optical depth and wind speed variations) at low aerosol optical depths, and smaller when aerosol optical depth is high. Using alongtrack measurements, instantaneous fluxes based on

Edition2_TRMM ADMs show a relative dispersion of only 2% compared to 9% for ERBE-Like. The direct radiative effect of aerosols based on SSF Edition2B fluxes show excellent correlation with VIRS aerosol optical depth retrievals (Loeb and Kato, 2001). Uncertainties due to cloud contamination using scene identification from the SSF is significantly reduced compared to ERBE-Like scene identification. We recommend that users interested in studying aerosol radiative effects with this dataset familiarize themselves with all of the "Clear Footprint Area" (SSF-66 to SSF-80) parameters described in the Collection Guide. Note that in some cases an aerosol optical depth based on the VIRS imager can be reported for CERES footprints that are cloud contaminated. Aerosol A Supplement 1 (SSF-75) provides the PSF-weighted area fraction in percent over the CERES FOV associated with the mean aerosol optical depth at 0.63 µm.

All-sky albedos based on Edition2_TRMM ADMs show a much smaller dependence on viewing geoemtry compared to ERBE and CERES ERBE-Like ADMs. For ERBE and CERES ERBE-Like, a relative increase in albedo of 10% is observed between nadir and a viewing zenith angle of 70° (Suttles et al., 1992). This dependence is largely removed in SSF Edition2_TRMM: on average, the mean albedo over the tropics is consistent to within 2% from all viewing zenith angles used in determining TOA fluxes.

The ADM contribution to the error in gridded time-averaged SW fluxes is estimated by comparing ADM-derived fluxes with fluxes inferred by directly integrating regionally averaged radiances over all upwelling directions and scaling the differences by weighting factors that account for the relative effect of different viewing zenith angles on gridded time-averaged fluxes. The results in Table 2 show that the ADM contribution depends strongly on what viewing zenith angle range is considered in determining the regional mean fluxes. For ERBE-Like, the bias in the tropical mean SW flux is -2.8 W m^{-2} if the viewing zenith angle range is restricted to < 50°, and 0.35 W m^{-2} if viewing zenith angles out to 70° are considered. For SSF Edition 2, the bias is negligible in both cases. The standard deviation in the regional flux bias meets the CERES goal of 1 W m^{-2} if viewing zenith angles out to 70° are used. For $\theta < 50°$, the SSF Edition2B regional flux error is 1.4 W m^{-2}. Since the SSF product retains only footprints with at least some imager coverage, and since the VIRS imager can only scan to a maximum viewing zenith angle of approximately 48°, results for the $\theta < 50°$ range are representative of ADM flux errors when CERES/TRMM scans in the crosstrack scan mode, whereas the $\theta < 70°$ range is more representative of ADM flux errors when CERES/TRMM scans in RAP and alongtrack scan modes.

Table 2. Estimated ADM contribution (W m^{-2}) to the error in gridded time-averaged SW fluxes for ERBE and SSF Edition2_TRMM ADMs over the Tropics. Δ is the bias error and σ_Δ is the standard deviation in the bias estimated from 20°x20° regional means. Separate results are shown for two different ranges in viewing zenith angle (θ). The last row shows the "CERES Goal" set by Wielicki et al. (1995).

W m^{-2}	**ERBE-like**		**SSF Edition2B**	
θ Range	Δ	σ_Δ	Δ	σ_Δ
$\theta < 50°$	-2.8	1.5	-0.07	1.4
$\theta < 70°$	0.35	0.74	-0.15	0.52
CERES Goal	0	1	0	1

All-sky SW flux errors from both ERBE-Like and SSF Edition2B show little dependence on latitude when the $\theta < 70°$ viewing zenith angle range is used. Restricting the range to $\theta < 50°$ results in flux biases of up to -5 W m^{-2} for ERBE-Like, and -2 W m^{-2} for SSF Edition2B. In both cases, biases are most pronounced at latitudes near 10°N. When fluxes near 10°N are further stratified by solar zenith angle, the largest biases are observed for solar zenith angles between 10° and 40° (see p. 37 in Validation of CERES/TRMM SSF Edition2 Angular Distribution Models (PDF)). This increased bias may be associated with convective clouds in the Intertropical Convergence Zone (ITCZ).

In general, SSF Edition2B all-sky flux errors are larger over the land than ocean. For $\theta < 70°$, flux biases generally remain < 1 W m^{-2} over most oceanic regions. Over much of the Saharan desert and Amazon forest, flux biases up to -1.5 W m^{-2} are common (see p. 42 in Validation of CERES/TRMM SSF Edition2 Angular Distribution Models (PDF)).

When SSF Edition2B and ERBE-Like near-nadir TOA SW fluxes from overcast scenes identified by the imager are compared as a function of cloud optical depth, SSF Edition2B fluxes are larger than ERBE-Like fluxes at small cloud optical depths and smaller at large cloud optical depths. Differences between the two can be as large as ±75 W m^{-2} for solar zenith angles near 43°. The cause for these large differences is because ERBE-Like ADMs do not account for changes in anisotropy with changes cloud optical depth. Therefore, the ERBE ADMs overestimate the true cloud anisotropic factor for very thin clouds and underestimated it for very thick clouds. Albedo estimates for deep convective clouds (DCC) based on CERES SSF Edition2_TRMM ADMs are consistent with those of Hu et al. (2001) to within 0.5%. Hu et al, (2001) independently built ADMs from CERES specifically for DCC using different identification criteria and methodology.

Preliminary estimates of errors in instantaneous TOA flux are obtained from 9 days when CERES scans in the alongtrack mode. Instantaneous albedos from all available viewing conditions over a region (e.g. 30 km diameter) are used to determine a dispersion parameter, defined as the ratio of the standard deviation in albedo over the region to the mean. For clear scenes, the footprint collocation uses latitudes and longitudes referenced at the surface. For overcast scenes, the reference altitude is at the effective cloud height, as provided by the CERES cloud algorithm. The average dispersion for a particular scene type is then multiplied by a typical albedo value for that scene type and a TOA flux uncertainty is estimated. For clear scenes over ocean, forest and grasslands, TOA flux uncertainties remain below 10 W m^{-2}. In overcast conditions over ocean, the errors reach 20 W m^{-2}. A limitation of the method is that separating ADM error from footprint-to-footprint spatial variability is highly uncertain. If the scenes are inhomogeneous, the variable footprint size will increase spatial variability since different footprints will sample different cloud or clear sky properties.

LONGWAVE FLUXES

The all-sky mean LW flux over the tropics based on SSF Edition2_TRMM ADMs shows a much smaller dependence on viewing geoemtry compared to ERBE and CERES ERBE-Like ADMs. For ERBE and CERES ERBE-Like, a decrease in LW flux of 9 W m^{-2} from nadir to a viewing zenith angle of 70° is observed. By comparison, the tropical mean LW flux from SSF Edition2_TRMM ADMs decreases by approximately 1.5 W m^{-2} between nadir and 50°, and remains constant between 50° and 70°.

The daytime ADM contribution to the error in gridded time-averaged LW fluxes is estimated by comparing ADM-derived fluxes with fluxes inferred by directly integrating regionally averaged radiances over all upwelling directions and scaling the differences by weighting factors that account for the relative effect of different viewing zenith angles on gridded time-averaged fluxes. The results in Table 3 show that the ADM contribution depends strongly on what viewing zenith angle range is considered in determining the regional mean fluxes. For ERBE-Like, the bias in the tropical mean LW flux is 4.4 W m^{-2} if the viewing zenith angle range is restricted to < 50°, and 1.2 W m^{-2} if viewing zenith angles out to 70° are considered. For SSF Edition 2, the bias is 0.87 W m^{-2} and 0.29 W m^{-2}, respectively. The standard deviation in the SSF Edition2B regional flux bias is 0.4 W m^{-2} for viewing zenith angles out to 70°, which satisfies the CERES goal of 0.5 W m^{-2}. For < 50°, the SSF Edition2B regional flux error is 1.37 W m^{-2}.

Table 3. Estimated daytime ADM contribution (W m^{-2}) to the error in gridded time-averaged LW fluxes for ERBE and SSF Edition2_TRMM ADMs over the Tropics. Δ is the bias error and σ_Δ is the standard deviation in the bias estimated from 10°x10° regional means. Separate results are shown for two different ranges in viewing zenith angle (θ). The last row shows the "CERES Goal" set by Wielicki et al. (1995).

W m^{-2}	**ERBE-like**		**SSF Edition2B**	
θ Range	Δ	σ_Δ	Δ	σ_Δ
$\theta < 50°$	4.35	1.50	0.87	1.37
$\theta < 70°$	1.22	0.60	0.29	0.40
CERES Goal	0	0.53	0	0.5

The nighttime SSF Edition2_TRMM ADM contribution to the error in gridded time-averaged LW fluxes is provided in Table 4. Bias errors are typically 0.5 W m^{-2} for both January-March and June-August, and show little dependence on the viewing zenith angle range considered. The standard deviation in the bias is also approximately 0.5 W m^{-2} for $\theta < 70°$, but ranges from 1.5 - 2.0 W m^{-2} for $\theta < 50°$. The reason for the 0.5 W m^{-2} bias in the tropical mean is unclear. One possibility may be due to an overestimation of infrared cloud emissivities for thin clouds at night. VIRS retrievals of cloud emissivity are based solely on infrared window channels, which cannot penetrate very deeply into the cloud. As a result, even thin clouds can appear thicker and more emissive than they actually are. An overestimation of cloud emissivity would lead to ADMs that are too isotropic, which in turn can cause a bias in the overall mean flux.

Table 4: Estimated nighttime ADM contribution (W m^{-2}) to the total error budget in gridded time-averaged LW fluxes for SSF Edition2_TRMM ADMs over the Tropics. Δ is the bias error and σ_Δ is the standard deviation in the bias estimated from 10°x10° regional means. Separate results are shown for two different ranges in viewing zenith angle (θ). The last row shows the "CERES Goal" set by Wielicki et al. (1995).

W m^{-2}	**January - March**		**June - August**	
θ Range	Δ	σ_Δ	Δ	σ_Δ
$\theta < 50°$	0.66	1.5	0.46	2.0
$\theta < 70°$	0.45	0.46	0.52	0.36
CERES Goal	0	0.5	0	0.5

SSF Edition2B daytime regional LW flux biases over 10°x10° regions are typically < 1 W m^{-2} over ocean for both $\theta < 50°$ and $\theta < 70°$. Because of the large viewing zenith angle dependence in mean LW fluxes, the ERBE-Like biases show a marked reduction for $\theta < 70°$ compared to $\theta < 50°$. Flux biases tend to be larger over land, except for the SSF Edition2B $\theta < 70°$ case.

The 0.5 W m^{-2} nighttime bias in SSF Edition2B LW fluxes shows no dependence on latitude for the $\theta < 70°$ case. For the $\theta < 50°$ case, biases are slightly larger near 10°N.

When SSF Edition2B and ERBE-Like near-nadir TOA LW fluxes from overcast scenes identified by the imager are compared as a function of cloud emissivity, SSF Edition2B fluxes are smaller than ERBE-Like fluxes at small cloud emissivities, but are comparable at cloud emissivities near 1.0. Differences between the two can be as large as 25 W m^{-2}. The reason for these large differences is because ERBE-Like ADMs do not account for changes in anisotropy with changes cloud emissivity. Since near-nadir anisotropic factors increase with decreasing cloud emissivity, ERBE-Like TOA fluxes are too large for clouds with low emissivity. The reason why differences become smaller when cloud emissivity approaches 1.0 is because these clouds correspond more closely with the ERBE-Like definition of "overcast" clouds, which tend to be cold and bright.

SSF Edition2B LW flux errors as a function of precipitable water are a factor of 3-4 smaller than ERBE-Like.

WINDOW FLUXES

The daytime SSF Edition2_TRMM ADM contribution to the error in gridded time-averaged WN fluxes is provided in Table 5. Bias errors are typically 0.3-0.5 W m^{-2} for $\theta < 50°$ and 0.03-0.07 W m^{-2} for $\theta < 70°$. The standard deviation in the bias is typically 0.3 W m^{-2} for $\theta < 70°$, and ranges from 0.8 - 0.9 W m^{-2} for $\theta < 50°$.

Table 5: Estimated daytime ADM contribution (W m^{-2}) to the error in gridded time-averaged WN fluxes for SSF Edition2_TRMM ADMs over the Tropics. Δ is the bias error and σ_Δ is the standard deviation in the bias estimated from 10°x10° regional means. Separate results are shown for two different ranges in viewing zenith angle (θ).

W m^{-2}	**January - March**		**June - August**	
θ Range	Δ	σ_Δ	Δ	σ_Δ
$\theta < 50°$	0.48	0.79	0.33	0.87
$\theta < 70°$	0.07	0.27	0.03	0.32

The nighttime SSF Edition2_TRMM ADM contribution to the error in gridded time-averaged WN fluxes is provided in Table 6. The trends for the WN channel are similar to those in the LW channel except that the magnitudes are smaller. In particular, a bias error of 0.25 W m^{-2} persists even when the $\theta < 70°$ angle range is used.

Table 6: Estimated nighttime ADM contribution (W m^{-2}) to theerror in gridded time-averaged WN fluxes for SSF Edition2_TRMM ADMs over the Tropics. Δ is the bias error and σ_Δ is the standard deviation in the bias estimated from 10°x10° regional means. Separate results are shown for two different ranges in viewing zenith angle (θ).

W m^{-2}	**January - March**		**June - August**	
θ Range	Δ	σ_Δ	Δ	σ_Δ
$\theta < 50°$	0.34	0.66	0.25	0.86
$\theta < 70°$	0.23	0.22	0.25	0.18

TOA FLUX REFERENCE ALTITUDE

Because CERES fluxes are estimated over a non-flat Earth, the flux exiting the earth-atmosphere system is a function of reference altitude. As the reference altitude changes, the flux increases/decreases as the inverse square of the distance from the reference altitude to the center of the earth. For example, a flux defined at a reference altitude of 30 km is approximately 2% larger than at 100-km reference altitude. Moving the reference down to the surface causes an increase in flux of approximately 1% compared to that with reference altitude 30 km.

To estimate the Earth's radiation budget at the top of the atmosphere (TOA) from satellite-measured radiances, it is necessary to account for the finite geometry of the Earth and recognize that the Earth is a solid body surrounded by a semi-transparent atmosphere of indeterminate thickness that reflects, absorbs and transmits solar radiation differently at different heights. As a result, in order to account for all of the reflected solar and emitted thermal radiation from the planet by direct integration of satellite-measured radiances, the measurement viewing geometry must be defined at a reference level well above the Earth's surface (e.g. 100 km). This ensures that all radiation contributions, including radiation escaping the planet along slant paths above the Earth's tangent point, are accounted for. As shown in CERES TOA Radiative Flux Reference Level (PDF), CERES SSF Edition2B ADMs account for off-Earth view radiance contributions by using a reference altitude of 100 km when constructing the ADMs. The ADM reference altitude is then adjusted to the surface reference level using the inverse-square law.

Since TOA flux represents a flow of radiant energy per unit area, and varies with distance from the Earth according to the inverse-square law, a reference level is also needed to define TOA flux. Is there an optimal reference level that can be used for radiation budget studies? CERES TOA Radiative Flux Reference Level (PDF) presents an argument for using a 20-km reference level as the optimal level for radiation budget studies. It shows that at the 20-km reference level corresponds to the effective radiative "top-of-atmosphere" for the planet since there is no need to explicitly account for the transmitted solar radiation through the atmosphere in the Earth radiation budget calculation. Although the actual flux reference level likely depends on scene type due to differences in effective transmission of solar radiation with cloud height, the difference in flux caused by neglecting the scene type dependence is less than 0.1%.

On ERBE, the ADMs were constructed using a surface reference level (thereby ignoring off-Earth view radiance contributions), but were then applied using a 30-km reference level. Consequently, the viewing zenith used to estimate TOA flux is inconsistent with how models were constructed. It turns out that the viewing zenith angle is systematically too low when the ADMs are applied (CERES TOA Radiative Flux Reference Level (PDF), Slide 21). When all effects are included (i.e. ADM errors, reference level differences etc.), and ERBE fluxes are compared with fluxes determined by direct integration of the measured radiances defined at a 20-km reference level, ERBE ADMs overestimate the tropical average SW TOA flux by 0.4 W m^{-2}, and overestimate the tropical average LW TOA flux by 1.2 W m^{-2}.

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