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The newly released 5-year Terra-based monthly CERES radiative flux and cloud product

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1 INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES) project has recently released a multi-year global energy budget data set that represents a major advancement over currently available data. The Earth Radiation Budget Experiment (ERBE) project produced a 5-year global 2.5° gridded monthly mean radiation flux data set during the late 1980's that has become the reference database for General Circulation Models (GCM). The CERES project has provided a continuation of the ERBE record with the CERES ERBE-like product using data from the TRMM, Terra and Aqua spacecraft. The ERBE-like product is released within two months after the fact, and employs the same ERBE Angular Directional Models (ADM), spatial and temporal averaging techniques. The ERBE-like dataset is most appropriate for users who would like to combine or compare the historical ERBE record and CERES dataset.

The CERES experiment was designed not only to monitor changes in the earth's radiant energy and cloud systems, but also to provide these data with sufficient simultaneity and accuracy to examine critical cloud/climate feedback mechanisms that may play a major cloud role in determining future changes in the climate system (Wielicki et al. 1996). The newly released 3-year Terra-based CERES monthly regional top of atmosphere (TOA) and surface radiation budget average (SRBAVG) data product is the resultant climate-accurate global 1° gridded data set of consistent radiative surface and TOA fluxes, cloud and aerosol properties. Every aspect of the CERES algorithm has been carefully examined to ensure that the error in the TOA radiative fluxes is a factor of 2 or 3 less than ERBE. The CERES instruments have an instantaneous broadband calibration radiance stability of 0.2% per year (Priestley et al. 2006), and the accuracy of the longwave (LW 5-100µm) and shortwave (SW 0.2-5µm) radiances is better than 0.5% and 1% respectively. Improved scene identification based on Moderate Resolution Imaging Spectrometer (MODIS) cloud retrievals is used with scene-dependent anisotropic models to invert the radiances into fluxes. The radiative fluxes and cloud retrieval parameters are gridded into 1°x1° regions and temporally averaged, to account for changes in meteorology between CERES measurements, to derive monthly mean fluxes and cloud properties.

CERES employs two approaches to temporally interpolate between CERES measurements. The first method (**SRBAVG-nonGEO product**) interpolates the CERES observations using the assumption of constant meteorological conditions similar to the process used to average CERES ERBE-like data. These fluxes represent an improvement to ERBE-like fluxes due to improvements to input fluxes, scene identification, and directional models of albedo. The second interpolation method (**SRBAVG-GEO product**) uses 3-hourly radiance and cloud property data from geostationary (GEO) imagers to more accurately model variability between CERES observations. This technique represents a major advancement in the reduction of temporal sampling errors (Young et al. 1998).

The major breakthrough in this new release is the ability to eliminate GEO SW calibration trends using SW regional GEO-CERES normalization in the merged CERES and GEO product. The GEO derived broadband fluxes must maintain the CERES instrument calibration and the GEO TOA fluxes and cloud properties need to be consistent with those of CERES in order to eliminate temporal sampling error between CERES measurements. This paper will describe the procedure to derive GEO based broadband fluxes, highlight the SW regional GEO-CERES normalization technique, note the regional GEO diurnal sampling improvements, present and compare the differences between the CERES level-3 (monthly averaged) ERBE-like, SRBAVG-nonGEO and SRBAVG-GEO products, and with other global broadband flux datasets. The accompanying SRBAVG validation paper (Keyes et al. 2006) employs a full suite of GEO derived broadband flux validation activities designed to ensure the GEO fluxes are within climate quality standards.

Currently (May 2006) there are 3 years (March 2000 to February 2003) of Terra based SRBAVG Edition 2D products, which contain the GEO SW fluxes, released to the public. It is anticipated that 5 years (March 2000 to December 2005) of Terra SRBAVG products will be released to the public by the end of 2006. An extensive Data Quality Summary (DQS) (http://eosweb.larc.nasa.gov/PRODOCS/ceres/SRBAVG/Quality_Summaries/CER_SRBAVG_Terra_Edition2D.html) was prepared to inform users of the accuracy

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of the CERES SRBAVG data product as determined by the CERES Science Team. All the CERES products can be obtained at the Langley DAAC (http://eosweb.larc.nasa.gov/PRODOCS/ceres/table_ceres.php)

2 GEOSTATIONARY DERIVED BROADBAND FLUXES

To prepare GEO imager data for temporal interpolation, 3-hourly 8-km GEO visible (0.65µm) and IR (11.0µm) radiances from METEOSAT-7, METEOSAT-5, GMS-5, GOES-10 and GOES-8 are calibrated against MODIS using the same method described in Minnis et al. 2002a and 2002b. The GEO satellites do not have onboard visible calibration. Coincident, within 15 minutes, MODIS and GEO visible ray-matched radiances are regressed over oceans, to mitigate GEO spectral response differences. The visible gain change is then the trend of the monthly regressions over time. The MODIS calibrated GEO radiances can be compared at the GEO overlap regions for consistency and to ensure no discontinuity at GEO boundaries. The GEO IR radiances, which have been calibrated using onboard blackbodies, are very similar to MODIS and only a slight adjustment is necessary to account for the spectral differences.

GEO derived cloud properties are necessary for ADM scene selection to invert radiances into fluxes. The two-channel VIS and IR GEO cloud retrieval algorithm, which is a subset of the multiple-channel CERES-MODIS cloud algorithm, computes cloud amount, temperature, height, phase, and optical depth. At night the GEO retrievals are based only on the IR channel. The cloud height correction, dependent on cloud optical depth to infer an IR emissivity, cannot be used at night. The GEO optical depths are less than those retrieved from MODIS due to the effects of decreased spatial resolution. The SRBAVG cloud properties are given for both the nonGEO (MODIS only) and GEO (MODIS & GEO) products. The GEO retrieved cloud properties should be consistent with those from MODIS and are dependent on the accuracy of the GEO calibration. Any trend in the GEO calibration will be manifested over time in the cloud retrievals. Cloud properties are monitored over time to validate the visible calibration.

The GEO IR radiances are converted to narrowband fluxes using a simple limb-darkening model. An empirical narrowband to broadband relationship, which includes a water vapor term, is applied to compute the LW flux. A two-step process is used to convert GEO narrowband VIS radiances into broadband SW radiances. First, the GEO radiances are converted to MODIS equivalent radiances using a theoretical model, based on DISORT scattering and correlated-K absorption (Kato et al 1999). Secondly, a narrowband to broadband model developed from coincident MODIS and CERES radiances is applied. Both models employ the same scene identification as the CERES ADM, which are based on solar and viewing geometry, cloud amount, phase optical depth, and geo-type. The GEO SW radiances are converted to fluxes using the CERES-TRMM ADM (Loeb et al. 2003).

The GEO SW and LW flux estimates have a residual error of 10-15% in the SW and 3-5% in the LW depending on GEO satellite. The GEO time series of broadband fluxes are normalized to CERES observations to ensure that there are no systematic biases as a function of region, solar and viewing geometry, thus maintaining the CERES instrument calibration. After the addition of CERES fluxes into the GEO flux time series, the GEO flux time series is then temporally interpolated using the same SRBAVG-nonGEO (CERES only) algorithms to compute the SRBAVG-GEO (CERES & GEO) product monthly mean fluxes. The temporal interpolation algorithms are given in detail in Young et al 1998. A twilight correction is added to the monthly mean SW fluxes to account for solar insolation greater than 90° (Kato and Loeb 2003). The maximum correction is 1.8 Wm^{-2} over the poles, however the global mean SW correction is 0.2 Wm^{-2}. For the LW fluxes, regional instantaneous normalization is used at coincident CERES and GEO temporally interpolated observations within a local hour segment. In the SW this method leads to significant angular and cloud amount dependencies.

3 SW REGIONAL GEO-CERES NORMALIZATION

A major break through in the SW GEO-CERES normalization was achieved by employing a 5°x5° regional monthly normalization, which resolved the inadequacies of instantaneous matching. Regressions of coincident GEO and CERES SW fluxes are matched within 90-minutes, to ensure matching of all 3-hourly GEO fluxes. The regressions are performed using 5° by 5° regions to increase sampling. The regressions are bound by GEO-satellite, and geo-type and are devoid of glint. Regions with insufficient sampling use matches from all regions inside a 5° GEO zone. These regressions provide slopes and offsets to account for GEO VIS calibration inadequacies and regional narrowband to broadband variability.

Any narrowband to broadband GEO derived fluxes need to be examined for functionality and GEO viewing artifacts. Since the regressions were performed regionally, the regional SW normalization removes the regional functionality in the narrowband to broadband algorithm. The biases as a function of solar zenith, view angle, and cloud amount biases are within 3% for each GEO satellite, indicating that the GEO fluxes are free from GEO artifacts that could be interpreted as changes in the climate system.

The 5°x5° SW regional monthly normalization is not limited to days with CERES measurements and can be applied to all days of GEO data. Instantaneous normalization adjusted all GEO measurements for the day by the same factor derived at the CERES measurement time. However, regional normalization of every GEO measurement is adjusted independently according to changing meteorology throughout the day. GEO clear-sky fluxes are replaced with CERES (nonGEO product) fluxes, since land spectral differences are difficult to resolve with GEO radiances and diurnal variation in the clear-sky is minimal. Also snow-covered regions use the nonGEO product fluxes, because GEO cloud properties over snow are suspect and bright surfaces have little diurnal variation.

4 COMPARISON OF CERES TOA FLUX PRODUCTS

The CERES SRBAVG product contains the regional monthly and monthly hourly TOA SW, albedo, LW, Window (WN 8-12μm) and net (0.2-100μm) fluxes for both all-sky and clear-sky conditions. The **SRBAVG-nonGEO** product fluxes are computed using only CERES observations, assuming constant meteorology between CERES measurements. The CERES fluxes and 3-hourly GEO fluxes are termed the **SRBAVG-GEO** product. The SRBAVG product also provides the corresponding cloud properties separated into 4 layers based on height. The SRBAVG-GEO product also provides surface downwelling and net SW, LW, and WN parameterized fluxes. An associated daily SRBAVG product is expected by the end of the year. Also the cloud property retrievals will be stratified by cloud height and optical depth similar to the ISCCP-D2 dataset to be released simultaneously with the daily product. The **CERES-ES-4** is the CERES ERBE-like product. The CERES project anticipates a flux product that combines TOA flux observations and radiative transfer calculations to provide flux estimates consistent with cloud properties for 5layers in the atmospheric column (Rose et al. 2006).

The SRBAVG-GEO product is the most robust CERES TOA monthly mean flux product. The product takes into account regional diurnal flux cycles that cannot be resolved by the Terra 10:30LT sun-synchronous orbit by incorporating 3-hourly GEO fluxes between 60°N and 60°S. Regions pole-ward replicate the nonGEO fluxes. Examples of strong systematic regional diurnal signatures include sub-tropical maritime stratus, land afternoon convection, and clear-sky daytime land heating. Random ocean convection should have little effect between nonGEO and GEO fluxes given enough daily observations. To evaluate the impact of improved diurnal sampling on the monthly flux product, the difference of the nonGEO and GEO monthly 14:30 LT hourly flux means are shown in Fig. 1. The GEO – nonGEO 14:30LT SW difference can be as great as 120 Wm^{-2} over South American stratus and -80 Wm^{-2} over southern hemisphere convective land regions. The corresponding LW difference is -10 Wm^{-2} over stratus and 20 Wm^{-2} over convective land. The monthly mean SW differences are 30 Wm^{-2} and -20 Wm^{-2}, respectively, and the LW differences are within 5 Wm^{-2}. However, globally these two competing events seem to offset each other. For December 2002, the nonGEO and GEO global means are within 1%. The positive land LW nonGEO – GEO difference is probably the land thermal heating peak slightly offset from noon.

1a)

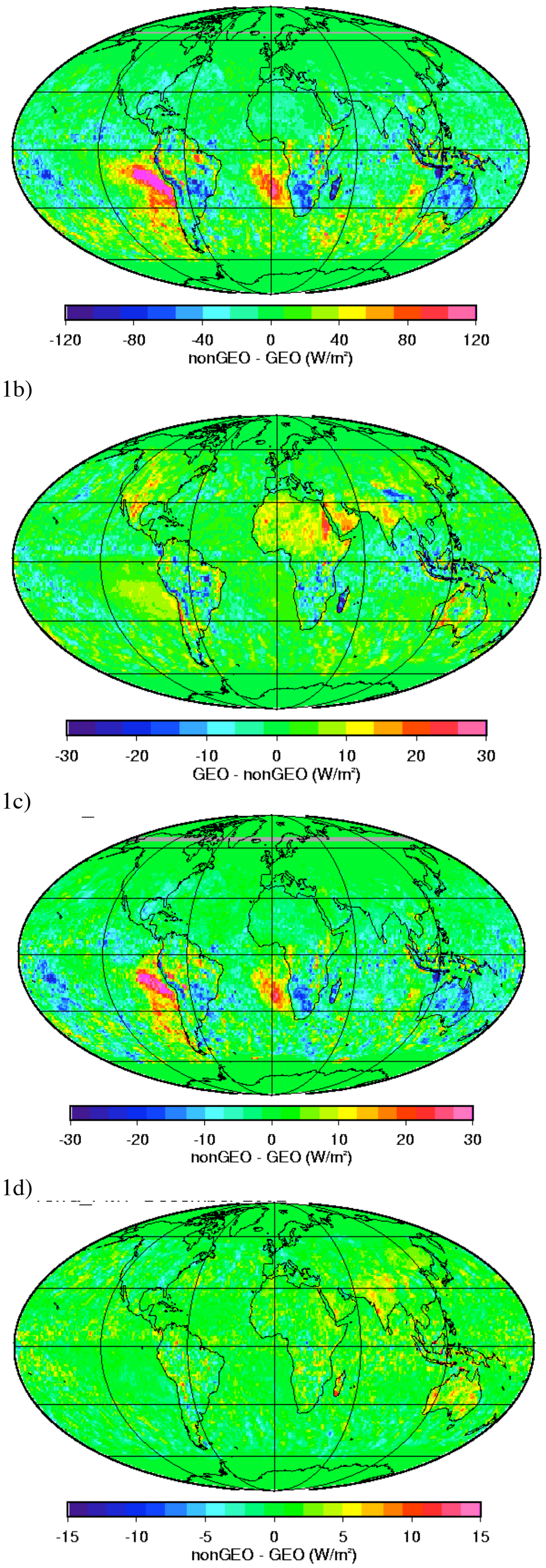


Fig. 1. The nonGEO – GEO flux monthly hourly difference at 14:30 LT for SW a) and LW b) and monthly mean for SW c) and LW d) for December 2002.

The 3-year global mean flux means for CERES Edition 2D products are given in Table 1. The difference in the ERBE-like and nonGEO fluxes represents the differences in the ERBE and CERES directional models and scene identification. The CERES ADMs tend to decrease the LW and SW fluxes. The nonGEO and GEO differences signify the difference in diurnal sampling. The GEO improved diurnal product increases the SW flux and decreases the LW flux. The net flux shows an apparent net imbalance of 6.4 Wm^{-2} in the GEO product. The net imbalance is similar to the ERBE 1986-1988 mean global net flux of 4.9 Wm^{-2}. The CERES Science Team has performed an exhaustive error analysis (Wielicki et al 2006) of the CERES fluxes and conclude that an error of <1 Wm^{-2} is possible in the global mean monthly flux. Analyzing our current knowledge of uncertainty in the Earth's climate system, the range of the net flux is predicted to be between 1.3-6.1 Wm^{-2}. This takes into the account the combined mainly positive systematic error in ocean heat storage, solar insolation and TOA SW reflected. More information on the net flux error analysis and suggested method to achieve net flux equilibrium is given in the SRBAVG DQS under Global Net Error Budget (http://eosweb.larc.nasa.gov/PRODOCS/ceres/SRBAVG/Quality_Summaries/CER_SRBAVG_Terra_Edition2D.html)

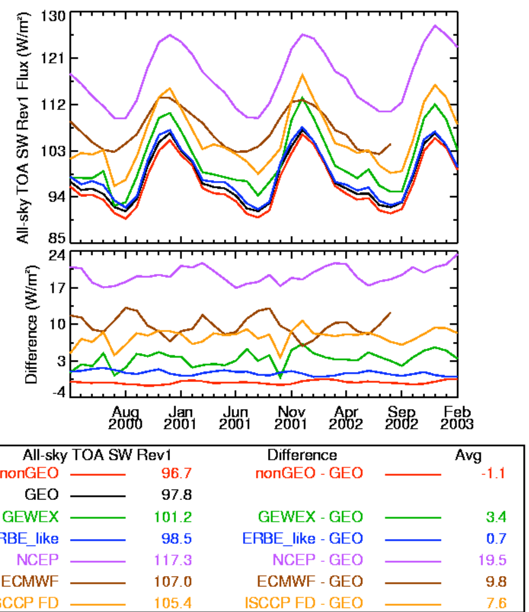
Table 1. Comparison of 3-year CERES ERBE-like, nonGEO and GEO TOA fluxes between Mar. 2000 and Feb. 2003.

Wm^{-2}	ES-4 ERBE-like	SRBAVG non-GEO	SRBAVG GEO
$OLR_{ALL-SKY}$	239.0	237.7	237.1
$SW_{ALL-SKY}$	98.5	96.7	97.8
$NET_{ALL-SKY}$	3.8	6.9	6.4

5 COMPARISON OF CERES AND OTHER GLOBAL TOA FLUX DATASETS

How do the SRBAVG global mean fluxes relate to other global flux datasets? To answer this question, the monthly mean global CERES SRBAVG-GEO all-sky SW fluxes are compared with SRBAVG-nonGEO, CERES ERBE-like, SRB-GEWEX (http://gewex-srb.larc.nasa.gov/), ISCCP-FD (http://isccp.giss.nasa.gov/), NCEP-reanalysis (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html), and ECMWF-ERA40 (http://data.ecmwf.int/data/d/era40_moda/) fluxes. The datasets are ordered from generally observed to modeled fluxes. The monthly mean fluxes are plotted along a 3-year timeline and shown in Figure 4. The dataset differences with respect to SRBAVG-GEO is shown in the middle panel and the 3-year global means in the bottom panel along with the legend. The corresponding LW fluxes are shown in figure 4b. Generally all datasets have the same seasonal cycle. The difference panel shows no apparent trends between datasets over time, indicating calibration stability in the CERES product. The ISCCP-FD had an algorithm change beginning in 2002 to compute LW fluxes. However the CERES 3-year mean fluxes are somewhat less than the average of the other datasets in the SW. The CERES LW flux is within the envelope of the other datasets. The object of these comparisons is to inform the user of the differences and not to explain or critique the differences. No intentional dataset preference is implied by this comparison. Further comparisons are shown in Mickowitz et al 2006.

2a)



2b)

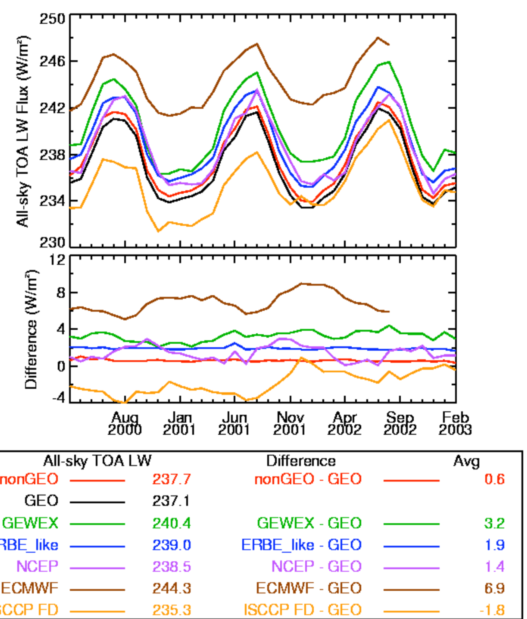


Fig. 2. Comparison of several monthly mean global 3-year flux datasets described in the text for all-sky TOA SW a) and LW b) between Mar. 2000 and Feb. 2003.

6 CONCLUSIONS AND FUTURE WORK

It has been shown that the addition of GEO fluxes into the CERES flux data stream, available in the CERES-SRBAVG-GEO product, has improved diurnal sampling between Terra CERES measurements. Although the global monthly mean SRBAVG nonGEO and GEO flux difference is <1%, the regional monthly and monthly mean differences can be as high as 20 Wm^{-2} and 100 Wm^{-2}, respectively. These GEO fluxes have been rigorously derived and thoroughly validated and meet the requirements for a climate quality dataset. The CERES SRBAVG-GEO product provides the most robust TOA fluxes. It is expected to have 5 years of Terra SRBAVG products in the archive by the end of 2006.

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