Final report for work under NRA-97-MTPE-03

Title of funded proposal: EOS/CERES Surface Radiation Validation at NOAA Climate Monitoring and Diagnostics Laboratory Field Sites

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1. Summary of Proposal

This proposal supplemented and expanded ongoing activities to acquire, process, and deliver high-quality surface radiation budget data from varied and remote sites that primarily contribute to the validation of CERES derived surface irradiances. The proposed work improvemened and extended the measurement capabilities of the NOAA Climate Monitoring and Diagnostics Laboratory's (CMDL's) solar and thermal surface radiation measurements. The CMDL maintains a presence at seven baseline climate monitoring observatories where surface radiation measurements were made for the past two decades. The proposal is for allowing the acquisition of new and greatly improved radiation equipment and instrumentation and to enhance data processing and analysis related to the evaluation and delivery of those data to EOS programs, especially CERES.

Included in the needed measurement improvements was further development of measurement methodologies that would facilitate progress in the establishment of highly desirable, widely recognized, measurement reference standards. This work was aided by the PI's close association with other related efforts at the forefront of the discipline. Measurements of broadband solar and thermal IR irradiance along with supporting observations of basic meteorological variables were made at all sites. Portions of the proposal that would have supplemented those measurements with aerosol optical depth, spectral albedo, digital sky imagery, and in some cases, lidar aerosol backscatter were abandoned when the funding for those aspects of the proposal was not approved. The PI was available to consult with CERES, and other EOS users, regarding the specifics and peculiarities of the acquired data and to assist in the interpretation and application of the data to the EOS programs. The proposal was funded for three years, 1998-2000, and was extended for two additional years at the reduced funding level of the third year. A no-cost extension was granted that allowed the use of a small amount of carry over funds until 30 Sept 2003.

2. Accomplishments

2.1 Data collection and delivery

As proposed, observations of surface solar and thermal IR irradiances were carried out continuously at all seven of the involved field sites from the beginning to well beyound the end of the funding period. These data were provided to the CERES program for all times for which the CERES sensors were operating and are available at http://snowdog.larc.nasa.gov/cave, and http://wwwcave.larc.nasa.gov/cave/cave2.0/CERES_ES8.html. To date, this includs nearly 308 station-months of data. The field sites described herein are: Barrow, Alaska; Boulder (BAO), Colorado; Prospect Hill, Bermuda; Mauna Loa, Hawaii; Kwajalein, Marshall Islands; Cape Matatula, American Samoa; and the South Pole, Antarctica. The CMDL irradiance data are 1-minute means and standard deviations for the 1 hz samples comprising the 1-minute average. All data are processed and supplied with this maximum temporal resolution. Prior to supplying the data to CAVE, the data were processed and reviewed to identify any obviously flawed data, which can occur for several reasons. Consistency checks on the expected relationship between various parameters are performed and only the data meeting CMDL criteria are carried forward. This conservative approach to data processing insures that only the best quality data are presented for further consideration and for comparisons to EOS data. All the original data are retained and are available for closer examination as desired. There is some redundancy in the observations of downwelling solar irradiance at the field sites that enables gaps created by either the failure of one instrument or by the removal of marginal quality data can be filled. For example, downwelling solar irradiance is measured as the product of the sum of diffuse and direct solar observations, and is also measured independently with an unshaded pyranometer. When either the diffuse or direct measurement is unavailable, usually because of failed solar tracking, the total measurement is substituted. These data processing and quality control procedures were developed specifically for the EOS validation applications and therefore any summaries of the data that involve averaging over time may vary from the other sources of data that originate within the CMDL program. *Gupta et al., [2003]* have suggested that averaging these one-minute data over a 60-minute interval centered on the satellite overpass is optimal for comparison to surface irradiances derived from the overpassing satellite. The CAVE site supplies data and analysis for 30-minute averages of the ground-based data, although there are some open questions about what is the best averaging time because the averaging time varies depending on cloud type and wind conditions. It is the intention of the CMDL group to supply surface irradiance data from the 7 CMDL sites for as long as CERES sensors are operational, even though the initial funding has expired and as long as there are no major failures in the CMDL observation system. A proposal to continue the work is pending NASA funding under NRA-03-OES-02.

2.2 EOS Validation activities

Both the CERES Surface and Atmospheric Radiation Budget (SARB) and Surface-Only (S-O) projects use the accumulated data as seen on the CERES web sites and in their related products. Much of the available CERES data are from the TRMM satellite, ending in 1998. As of the writing of this report, SARB data are just beginning to become available from Terra and some preliminary results are available for this report. Even though the S-O project is able to perform its retrievals more quickly as it has little of the computational overhead of the SARB project, the S-O product has been primarily compared only to the CMDL irradiance data for the TRMM era (*Gupta et al., 2003*).

Comparisons between the CMDL and CERES surface irradiance are performed by members of the CERES Science Team at LARC. They compare surface-based observations averaged over some time interval, typically from 30-min to 1 hr, to satellite overpasses at the mid-point of the averaging interval. This is a reasonable approach because the satellite observation averages over a few 100's of Km^2 area whereas the in situ surface measurement averages the portion of the atmosphere advected over the site during the time interval. The match is not exact between the portions of the atmosphere sampled by the two methods, but it is assumed that the randomness of the environment allows mean-bias comparisons between the two if a sufficient number of comparisons are made and there are no locally induced biases. Figure 1 shows such a comparison similar to that available from the CAVE web site. These figures show the SARB derived (Cloud Radiative Swath, CRS) values on the y-axis and the CMDL supplied observations (CAVE obs) on the x-axis. This and similar comparisons for the other CMDL sites have been prepared by Dave Rutan at LaRC and are summarized in Table 1.

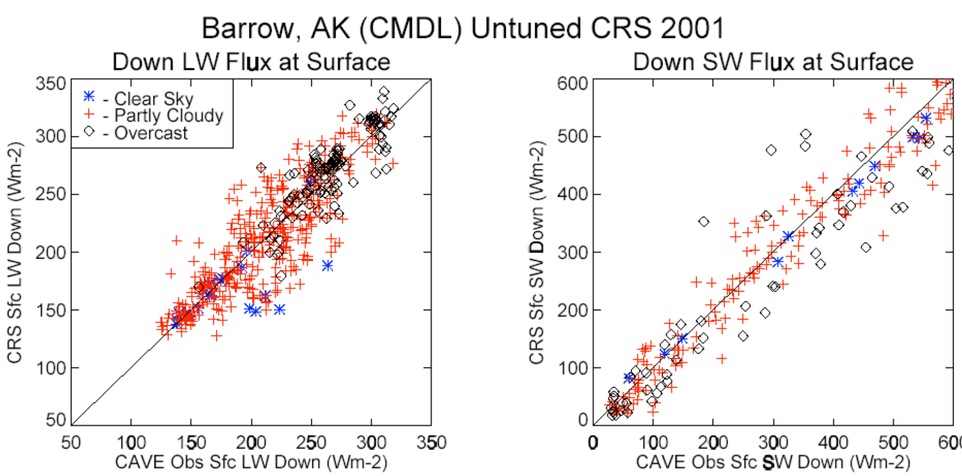

Figure 1. Scatter diagram for SARB/Terra (CRS) and CMDL (CAVE) longwave (left) and shortwave (right) irradiances for Jan. – May 2001 for Barrow Alaska.

An example of a scatter diagram comparison for a tropical site is shown in Figure 2. In Figure 2, a few outlying points in the upper left portion of the diagram suggest that the ground based observations were strongly impacted by clouds, but little or no cloud was used in the satellite retrieval. These cases are sufficient to introduce an unacceptably large bias into the mean agreement for the sites, as shown in Table 1.   Similar outliers appear at Kwajalein and Bermuda. These biases should not be interpreted as deficiencies in either the ground-based or satellite product, but rather result from

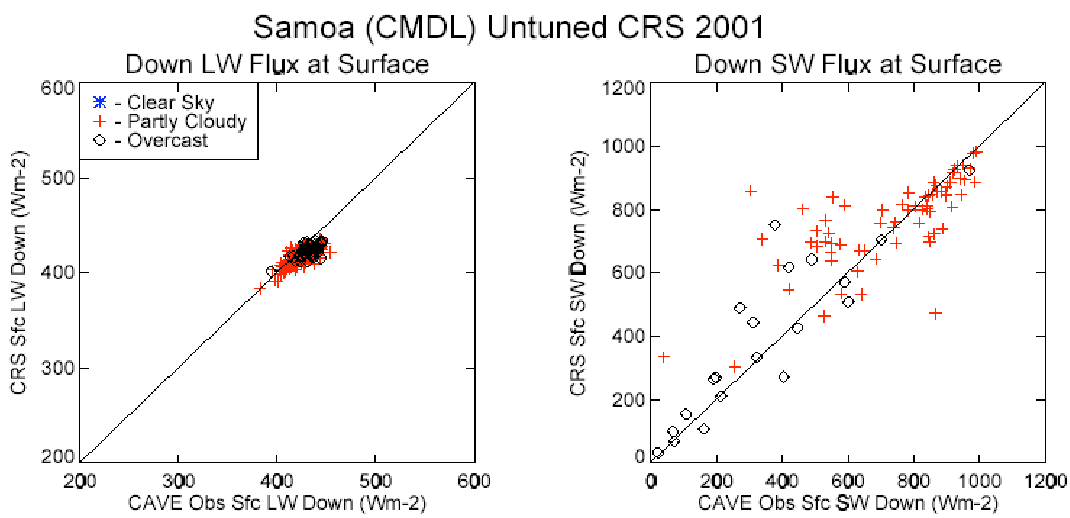

Figure 2. Same as Figure 1 except for American Samoa.

Comparisons made at inappropriate times. With the exception of these few anomalous cases, generally good agreement is seen in both the solar (SW) and thermal IR (LW) where in all cases the Std. Dev. is much greater

SARB (CRS) - CMDL

	SW Mean bias	SW Std. Dev.	LW mean bias	LW Std. Dev.
Barrow	12.5	54.9	0.86	23.8
Boulder (BAO)	-2.6	101.8	12.0	16.6
Bermuda	21.9	114.2	-2.62	15.5
Kwajalein	50.4	91.3	-5.2	9.3
Amer. Samoa	37.9	135.8	-7.3	8.1
South Pole	-25.2	37.5	28.0	35.0

Table 1. CAVE comparisons of SARB and CMDL surface irradiances. SARB results are from the CRS untuned model for all-sky conditions. Note: Mauna Loa is not included because local orographics restrict applications to a few special cases not yet examined. The tropical sites' solar biases are excessive as explained in the text.

than the bias due to dissimilar observing geometries for the individual comparisons and because of the uncertainties in the input parameters used for the satellite retrievals.

Another comparison between CERES/SARB data and CMDL observations at Mauna Loa is shown in Figure 3 as provided by Dave Rutan. There are numerous largely biased points due to cloudiness conditions that are routinely different near the radiometer than used in the satellite analysis. The satellite resolution is insufficient to capture the local variability and exemplifies an inappropriate comparison for the purpose

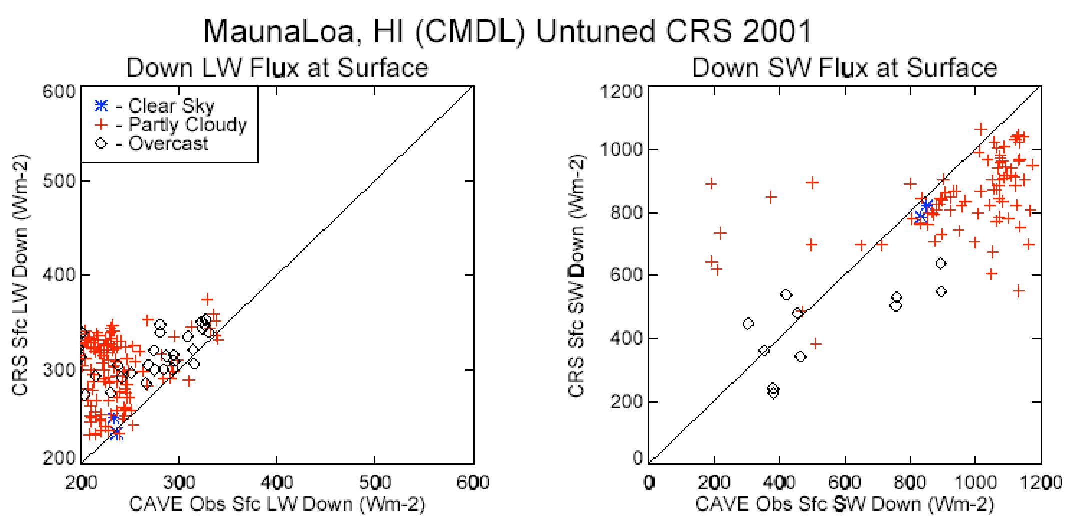

Figure 3. Same as Figure 1 except for Mauna Loa.

of validating the satellite observations. This P.I. suggests that the Mauna Loa be considered a mid-tropospheric site during clear-sky conditions only. This would provide unique opportunities for comparison to SARB atmospheric profiles, as long as special consideration is given for the local terrain.

The CERES S-O project accesses the CMDL and other sites' data through the CAVE web site, but uses independent parameterized retrievals of surface irradiance to compare to the ground based observations. The results of the S-O TRMM comparisons are given by *Gupta et al.* [2003], with an example comparison shown in Figure 4. Only Kwajalein and Bermuda data were used in the validation comparison presented by *Gupta et al.* [2003]. The preponderance of points well above and to the right of the fit line result from cases were the surface measurement was substantially reduced relative to the satellite retrievals because clouds that impacted the ground based instruments were not included in the retrieval process. These few points contribute disproportionately because of the magnitude of their departure from the mean bias of 12 W m^{-2}, but the departure is even larger for the individual sites that contribute the outlying points.

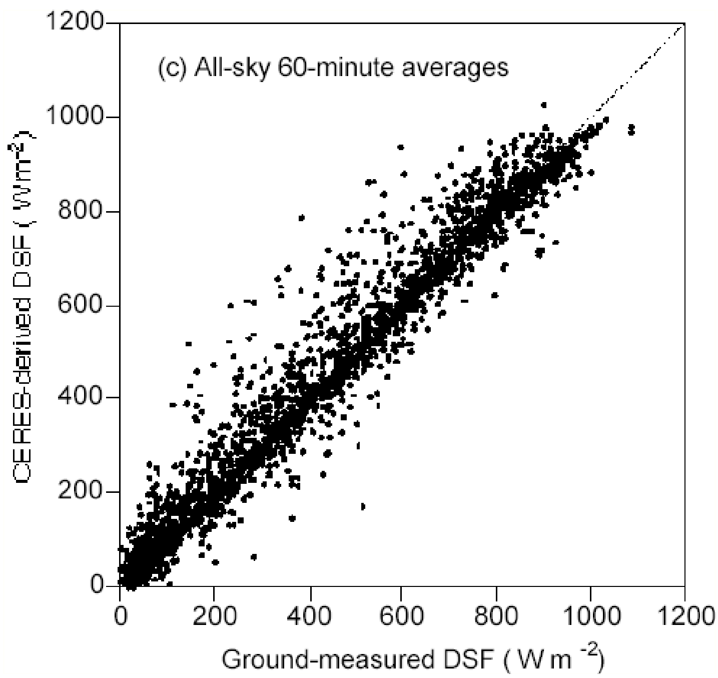

Figure 4. Comparison between the CERES S-O retrievals and CAVE ground based data. The mean bias is 12 Wm^{-2} with a residual standard deviation of 61 W m^{-2}.

Additional sources of departure between individual observation pairs in the above comparisons can be due to temporary contamination on the optical surfaces of the ground-base radiometers that are inspected and cleaned as necessary on a quasi daily basis. Because of reflections off contaminates on the optical surfaces, the resulting error can be either positive or negative with a tendency to result in a blockage of the observed irradiance that contributes to a net bias in comparisons. Also, temporary radiometer alignment errors can occur resulting in direct solar irradiances that are too low and diffuse solar irradiance that are too high. These effects tend to cancel when the direct and diffuse are combined to form the total solar irradiance. Another type of radiometer alignment error occurs when the hemispheric field of view sensors are not exactly horizontal. This alignment is most critical when a flat plate sensor measures the vertical component of the direct beam, but becomes detrimental for diffuse and thermal IR sensors if the misalignment is large enough. Such sources of errors are temporary and are corrected when detected by the site attendants or by quality control procedures. The extent of these potential errors in the processed ground-based observations is minimized by the careful and thorough review of the data in post analysis that enables such errors to be recognized and removed from the distributed data. Nonetheless, small but potentially significant temporary errors can defy detection and are present in a small percent of the available data. Typically, the uncertainties in the CMDL observations, when free of temporary errors, are generally less than 10 W m^{-2} for the solar and 5 W m^{-2} for the IR.

The most rigorous comparisons like those previously shown are be done for clear sky cases. In those cases the absolute accuracy of both the satellite and ground based irradiances are most critical. Generally, the reported irradiance comparisons show a better agreement between the two methods for clear skies, but there is still room for some improvement. The steps taken to further improve ground-based irradiances are described later in sections 2.4 and 2.6. Comparisons under overcast or partly cloudy conditions are subject to larger uncertainties due, for the most part, to the nature of the clouds that affect the point ground-based measurement being different that affecting the area-wide view of the satellite-based estimate. Typically in the comparisons to date, the cloud state is determined from the satellite vantage point, but some improvement in the comparisons could be achieved if both the satellite scene and the ground-based data are examined to determine the extent of cloudiness influences and if comparisons are performed only when the two are in general agreement. Methods for determining cloudiness in high-time resolution surface-based irradiance data were recently published by *Long and Ackermann* [2000] and *Dutton et al.* [2003].

2.3 Comparability of point ground-based and area-wide average irradiances

To help address the question of appropriate averaging for the comparison between area-wide estimates and point ground-based irradiance observations (and for other reasons), we initiated an investigation into the persistence of the undesirable point measurement features in surface solar irradiances under variable cloud conditions as a function of temporal averaging. This work [*Dutton et al.,* 2003] shows that conditional averaging times in excess of one solar day are required to eliminate essentially all cases in which there is selective scattering towards or away from a surface measurement point; hence biasing the surface measurement and having a detrimental effect on the comparison to satellite based observations. Consistent results were obtained for four globally diverse sites where averaging times of up to three days were required to eliminate these effects. For this result, conditional averaging was done only for those daylight times when clouds were determined to be affecting the observations. This work demonstrates that much of the variance in the surface to satellite comparison of irradiance is due to the point verses area-wide nature of the observed quantities.

2.4 Improvements to instrumentation and other measurement capabilities

Improvements to the surface instruments and measurement methodology were implemented virtually without interruption to the continuous measurements. In some cases, measurement capability improvements were applied in post processing of the data and therefore could be applied retroactively to the beginning of the measurement record. Major improvements made in the extent and quality of the solar tracking at the field sites permitted the measurement of the widely recommended total components, diffuse and direct irradiance. New commercial solar trackers have become available over the past decade and we were able to upgrade several sites with that capability. These trackers not only assure more accurate tracking for the acquisition of the direct solar beam, but also allow for continuous reliable diffuse solar irradiances to be measured, as well as providing shading of the pyrgeometer IR measurements. Pyrgeometer shading is important to reduce dome thermal error corrections and to block the solar IR component. Another improvement implemented during this time was the recognition and correction of thermally induced offset errors in the diffuse solar irradiance observations as discussed by *Dutton et al.* [2001] and others. The recognition of the thermal offset problem led to new developments in commercial instrumentation and recognition of viable alternatives using current instrumentation. Methods for the correction and adjustment of existing diffuse data were developed, published, and applied to existing earlier data.

While much of the efforts related to this proposal went to the activities associated with the acquisition and processing of the field data, some longer-term improvements to the measurement programs were also implemented. These include the enhancing and stabilizing of both the physical and administrative structure of the field measurement programs as well as investments in materials and instruments that are intended to function for a number of years during which issues relating to climate variability are expected to receive scientific attention, and while EOS continues to produce surface irradiance products from current and future CERES or similar missions.

2.5 Aerosol optical depth and all-sky imagery

Although funding for the full implementation of the proposed aerosol optical depth (AOD) measurements and all-sky camera imagery and analysis was cut from the final award, some progress was made that provides a lasting benefit. Sunphotometers and rotating shadow band radiometers from which aerosol optical depth and other parameters can be derived were deployed at some of the CMDL sites for part of the time covered by the proposal award. The effort continues to maintain and improve these deployments along with the associated data processing and analysis. A small amount of AOD reduced from these instruments was supplied to CAVE, although the majority of the data were not processed and are for waiting further funding. Two all-sky camera systems that produce an analyzed digital image for percent cloud cover using a commercial algorithm were deployed and those data are available for future investigations.

2.6 Reference standards and measurement accuracy

During the course of this work, we contributed to international efforts that promote the continued development of measurement reference standards that are not currently available to the solar and thermal irradiance measurement community. Although not explicitly identified in the proposal, the need for these standards is highly relevant to the CERES validation activities. Accuracy goals were set for both the satellite and surface-based measurements, and the best way to confirm the accuracy of the surface measurements is in comparison to widely recognized reference standards. These standards, unfortunately, do not exist for all surface irradiance measurements, but only for the direct solar beam. Parallel efforts to develop thermal IR and solar diffuse reference standards were conducted by the PI and other colleagues during the course of this work [*Philipona et al.,* 2001; *Marty et al.,* 2003; *Michalsky et al.,* 2003). This work suggests that a common reference measurement for both thermal IR and diffuse solar irradiances can be identified and maintained, at least for the short-term, to within about 3 W m^{-2}. Since the methods and instruments used in the reference standard investigations are similar to those used in the field for the CMDL observations, there is some confidence that the CMDL observations meet the expected accuracy requirements set forth in the proposal. However, alignment and optics cleanliness problems during routine continuous operation of radiation sensing instrumentation can result in episodic departures from expected accuracy. Also, while considerable work was done towards developing and establishing permanent internationally recognized radiation reference standards as described earlier, the tasks were not completed for solar diffuse and thermal

IR. The state of affairs is better in the case of thermal IR where a candidate absolute reference was identified in the case of the Absolute Sky Scanning Radiometer developed by R. Philipona. In the case of solar diffuse, the effort has consisted of determining the level of relative agreement between instruments provided by willing participants and direct comparison to what is considered consensus agreement. Inherently absolute measurement of the diffuse irradiance was not achieved leaving open the potential for some future adjustment to what are currently considered the best solar diffuse irradiance measurements.

2.7 Work in conjunction with related activities

The work conducted by CERES and the CMDL surface radiation project blends well with ongoing efforts in both the World Climate Research Program's (WCRP's) Baseline Surface Radiation Network (BSRN) and the DOE Atmospheric Radiation Measurements (ARM) program. The PI has encouraged the joint efforts of the participants in both of these programs and in others. The joint effort resulted in validation data from more surface sites being provided to EOS than specifically funded by this NRA.   A general spirit of cooperation and determination among these projects to improve the state of the art while acquiring useful irradiance data from climatologically diverse sites contributed to this success.

While the main purpose of this proposal was to provide useful examples of high quality ground based data to the CERES and other to EOS projects for the purpose of validating their retrieval algorithms for surface irradiances, the acquired data contribute to a continuing time series of surface irradiance data that extends beyond the lifetime of these validation efforts and beyond the typical lifetime of a satellite data record. These data are valuable in the own right as a record of local and, in some cases, regional radiation climatology. Changes and variations in those records related to climate processes also serve for comparison to numerical model computations because the aspects of comparing the point surface measurements to climate model estimates requires many of the same considerations as the comparisons to satellite retrievals.

3. Expected future applications.

Most the applications of the acquired and delivered data are yet to come because virtually no Terra CERES data were ready for validation when the funding for this proposal expired. The CERES S-O and the SARB projects are just beginning to address this work. The data collected under this project were submitted to and archived at the WMO BSRN archive, the NASA LaRC CAVE archive, and at the CMDL archives for the Solar and Thermal Atmospheric Radiation (STAR) project. Since methods of analyzing surface data for the extent of cloud influences were introduced recently, it is expected that considerable improvements will be made in the efforts to validate satellite data by more selectively choosing the cases for evaluation. The recognition that no surface site is continually 100% representative of the satellite pixels that significantly exceed the spatial representativeness of the ground-based observations aids in case evaluation. The data collected as part of this work also forms the backbone of a baseline reference set of measurements that serves the climate community as general circulation model references and as independent records of local and regional radiation climatology.

4. Meetings attended and future interactions

The P.I. or his representative attended about half of the CERES Science Team meetings during the time this proposal was funded. The P.I. and his staff were also readily available on many occasions for consultation and discussions regarding the details and less apparent aspects of the acquired irradiance data. The P.I. also attended meetings of the American Meteorological Society and the World Meteorological Organization where the work under this proposal was presented. For the 2004 incarnation of the CERES Science Team, the P.I. was invited to be a member of the team and will be receiving funds to attend those meetings and interactions that concern the data collected over the past six years and in the future will continue.

5. Publications and reports completed at least in part under this proposal

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Acknowledgements:

We would like to thank Drs. Tom Charlock, Dave Rutan, David Kratz and Shashi Gupta who supplied material for this report.