

**Surface Radiation Budgets in Support of the GEWEX Continental Scale  
International Project (GCIP) and the GEWEX Americas Prediction Project  
(GAPP), including the North American Land Data Assimilation System  
(NLDAS) Project**

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## **Abstract**

In support of the World Climate Research Program (WCRP) GEWEX Continental-scale International Project (GCIP) and the GEWEX Americas Prediction Project (GAPP), real time estimates of shortwave radiative fluxes, both at the surface and at the top of the atmosphere, are being produced by the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS), using observations from the GOES-8 Imager. The inference scheme used has been developed at the Department of Meteorology, University of Maryland (UMD), and atmospheric and surface model input parameters are produced and provided by the NOAA/National Centers for Environmental Prediction (NCEP). The derived radiative fluxes are evaluated on hourly, daily, and monthly time scales, using observations at about fifty stations. The satellite estimates were found to be within acceptable limits during snow-free periods, but in case of snow cover, cloud detection over snow affected achievable accuracy. In what follows, this activity is discussed, and results from the evaluation of the derived fluxes against ground observations for a one-year period, are presented.

## 1. Background

Information on the spatial and temporal distribution of surface and top of the atmosphere (TOA) radiation budget is required for modeling the hydrologic cycle, for representing interactions and feedbacks between the atmosphere and the terrestrial biosphere [*Dickinson, 1986; Henderson-Sellers, 1993; Betts et al., 1997*], and for estimating global oceanic and terrestrial net primary productivity [*Goward, 1989; Running et al. 1999; Platt, 1986*]. Such information is also needed for validating climate models [*Garrat et al., 1993; Wild et al., 1995; Wielicki et al., 2002*] and for improving understanding of transport of heat, moisture, and momentum across the surface-atmosphere interface [*Berbery et al., 1999; Baumgartner and Anderson, 1999; Sui et al., 2002*]. In the United States, the Interagency Committee on Earth and Environmental Sciences as well as the Intergovernmental Panel on Climate Change have identified clouds and the hydrologic cycle as the highest scientific priority for global change research [*Gates et al., 1999; Houghton et al., 2001*]. Studies of long-range weather forecasting, climate, climate change, and interannual variability, are presently conducted with the aid of numerical weather prediction and general circulation models. In order to use model results with confidence, there is a need to validate them on the same scales at which they are implemented. Ground observations, even of the most commonly measured parameters (e.g., surface air temperature), are very sparse. Satellite observations are considered the only source of global scale information that could be used for model evaluation. Of particular interest are surface radiative fluxes, due to their dominant role as forcing functions of surface energy budgets [*Wood et al., 1997; Wielicki et al., 1995; Mitchell et al., 2002*]. Information on surface radiative fluxes can also

improve our understanding of physical processes associated with heat, moisture and momentum transfer across the surface/atmosphere interface, and therefore, improve model parameterizations [*Chen et al., 1996*]. In the last two decades, it was demonstrated that radiative fluxes could be derived from satellite observations with reasonable accuracy [*Pinker et al., 1995; Frouin and Pinker, 1995; Rossow and Zhang, 1995; Whitlock et al., 1995; Ohmura et al., 1998; Gupta et al., 1998*]. Long term satellite observations over large spatial scales are now available to implement inference schemes for deriving radiative fluxes [*Schiffer and Rossow, 1995; Rossow and Schiffer, 1999*]. Among the objectives of the GEWEX Continental-scale International Project (GCIP) [*WCRP-67, 1992*] are:

- o determination of the time/space variability of the hydrologic cycle and the energy budgets over a continental scale;
- o development and validation of macro-scale hydrologic models; and,
- o utilization of existing and future satellite observations to achieve these objectives.

The GEWEX Americas Prediction Project (GAPP) is a continuation of GCIP, having the ultimate objective of developing a capability for predicting variations in water resources, on time scales up to seasonal and interannual (NRC, 1998).

NOAA/NESDIS is supporting GCIP/GAPP activities by developing new operational products from satellite observations [*Leese, 1994; 1997*]. This is a collaborative effort between NOAA/NESDIS, NOAA/National Centers for Environmental Prediction (NCEP), and the University of Maryland. Shortwave (0.2-4.0  $\mu\text{m}$ ) radiative fluxes at the surface and at the top of the atmosphere, as derived from GOES observations, are part of

this product. The inferred shortwave radiative fluxes include upwelling and downwelling total and diffuse quantities, as well as spectral components (e.g., the photosynthetically active radiation (PAR)). At NOAA/NESDIS, the interface between the satellite data and the inference models has been developed [Tarpley *et al.*, 1996]. NOAA/NCEP provides information on the state of the atmosphere and surface conditions, as available from the Eta model analyzed output fields [Rogers *et al.*, 1996]. The University of Maryland is involved in model development, modifications [Pinker and Laszlo, 1992a; 1992b; Pinker *et al.*, 2002], sensitivity studies [Meng *et al.*, 2002], validation against ground observations, data archiving, and data distribution. The Surface Radiation Budget (SRB) model is implemented at NOAA/NESDIS in real time on an hourly basis, for 0.5-degree targets for an area bounded by 66°-126° W longitude and 24°-54° N latitude belts. For each target, at appropriate forecast times, selected data from the NCEP regional forecast model are delivered to the satellite data stream, to serve as inputs to the SRB model. This approach ensures timely and high quality information input to the satellite inference scheme. In turn, the derived radiative fluxes help to diagnose the NCEP forecast model as to its ability to predict correctly radiative fluxes. Initial evaluation of the SRB product was done at several levels, such as running the model operationally and off-line for some cases, as well as evaluation against ground truth, as available from independent projects such as the Baseline Surface Radiation Network (BSRN) [Ohmura *et al.*, 1998; Whitlock *et al.*, 1995], the Surface Radiation Monitoring Network (SURFRAD) [Hicks *et al.*, 1996, Augustine *et al.*, 2000], by independent investigators [Meng *et al.*, 2002], and within the framework of the North American Land Data Assimilation System (N-LDAS) activity [Lou *et al.*, 2002].

## 2. Current Status of Data Availability

The first version of the experimental real time product is available from January 1996. All the input and output parameters, produced in support of GCIP/GAPP (currently, a total of 71), are stored at the University of Maryland, where the SRB data are evaluated against ground observations, partially quality controlled, and prepared for distribution via the World Wide Web and an anonymous ftp site, as described at:

<http://www.meto.umd.edu/~srb>

Four types of information is archived:

- satellite based information, used to drive the model;
- auxiliary data used to drive the model;
- Eta model output products relevant for hydrologic modeling;  
independently derived satellite products.

Examples of surface shortwave radiation fields at various time scales, as well as examples of other products, such as net absorbed radiation at the surface and within the atmosphere, cloud amounts and cloud optical depths, are illustrated in **Figure 1**.

Information on instantaneous, daily, monthly mean surface and TOA shortwave and photosynthetically active radiative fluxes are provided at the University of Maryland World Wide Web site almost in real time.

### 3. The inference model

#### 3.1 General features

A modified version of the GEWEX SRB algorithm [*Pinker and Laszlo, 1992a; Whitlock et al., 1995; Ohmura et al., 1998*] (Version 1.1), developed at the University of Maryland, is used. The model is driven with GOES-8 satellite data, as preprocessed at NOAA/NESDIS, and auxiliary information on the state of the atmosphere and the surface, as available from the NCEP Eta model (e.g., column water vapor), and from independent inputs to the Eta model (e.g., snow information, that till recently came from the United States Air Force products). In the model, radiative fluxes are determined by inferring the transmittance from the reflected radiation observed by the satellite. The inference technique is based on a radiative transfer scheme and is implemented spectrally. Thus, it is possible to compute shortwave fluxes at spectral intervals known to be of significance (e.g., photosynthetically active radiation). This is important, because current GCMs are run in a mode that separates shortwave fluxes at  $0.7 \mu\text{m}$  [*Roesch et al., 2002*], to allow incorporation of newly derived satellite based parameters, such as fractional vegetation cover, derived from the Normal Difference Vegetation Index (NDVI), and for improving parameterizations of surface/atmosphere interactions [*Gallo and Huang, 1998; Goward and Huemmrich, 1992; Townshend and Justice, 1995; Gutman et al., 1995*]. In the model, shortwave fluxes are separated into direct and diffuse components, of interest for improved modeling of radiative interaction with vegetation and oceans. Other parameters that are derived include clear-sky and all-sky albedos at the top of the atmosphere and at the surface, and aerosol and cloud optical depths. The shortwave and spectral fluxes can be computed separately for clear and all-sky

conditions, thus making it possible to derive information on the radiative effects of clouds, known as "cloud radiative forcing" [*Ramanathan et al.*, 1989].

In the SRB algorithm, the shortwave radiative fluxes are computed in the following five spectral intervals: 0.2-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7 and 0.7-4.0  $\mu\text{m}$ . In each of the five spectral intervals, upward and downward fluxes at the top of the atmosphere and at the surface are computed by determining the spectral transmittance from the top-of-atmosphere shortwave reflectance. The latter is estimated from the narrowband radiance observed by the satellite, using a transformation between narrowband radiance and shortwave reflectance [*Zhou et al.*, 1996] (for details see section 3.2). The spectral transmittances are determined by matching the satellite-derived shortwave reflectance with a shortwave reflectance obtained from modeled simulations. The spectral transmittance-reflectance relationships are available in the form of a table look-up. They are derived for discrete values of the solar zenith angle, amount of water vapor and ozone, aerosol and cloud optical thickness, using a delta-Eddington radiative transfer method described in *Joseph et al.* [1976]. Radiative properties of aerosols and clouds are taken from the Standard Radiation Atmospheres [*WCP-55*, 1983] and from *Stephens et al.* [1984], respectively. Absorption by ozone and water vapor are parameterized following *Lacis and Hansen* [1974]. In deriving the fluxes, first the surface albedo is estimated from the "clearest radiance" observed over a number of days (clear-sky composite radiance), corrected for Rayleigh scattering, aerosol extinction, and absorption by ozone and water vapor. In this step, the amount of aerosol is specified according to the Standard Radiation Atmospheres [*WCP-55*, 1983]. Column amounts of ozone are as provided in the McClatchey atmospheres [*Kneizys et al.*, 1988] and water vapor is from

the NCEP Eta model. Atmospheric transmittance-reflectance pairs are selected from the look-up table according to the solar zenith angle, water vapor and ozone amount, and are combined with the surface albedo to yield shortwave top-of-atmosphere reflectances. One set is for varying values of aerosol optical depth (clear sky case) and the other, for varying values of cloud optical depth (cloudy atmosphere). Finally, the shortwave reflectances derived from the instantaneous satellite-observed clear-sky and cloudy-sky radiances are matched with the clear and cloudy sets of transmittance-reflectance pairs, and clear-sky and cloudy-sky transmittances and fluxes are obtained. The clear-sky and cloudy-sky fluxes are then weighted according to the cloud cover (defined as the ratio of number of cloudy pixels to the total number of pixels) to get the all-sky fluxes. The various elements of the model have been tested in a number of different ways. The radiative transfer component has been evaluated in the framework of the Intercomparison of Radiation Codes in Climate Models (ICRCCM). The results were found to be in good agreement with those from high-resolution radiative-transfer models [*Fouquart et al., 1991*]. The differences in atmospheric absorption, when compared to high-resolution computations, are about 2% and 7% for the clear and the cloudy cases, respectively. Surface down-flux estimates have been compared with values measured at several locations and in the framework of various activities, such as the Satellite Algorithm Intercomparison sponsored by WCRP and NASA [*Whitlock et al., 1995*], reporting agreement with ground observations within  $10 \text{ Wm}^{-2}$  on a monthly time scale. The implementation of the model requires preprocessing of the satellite data and separation of clear and cloudy radiances. This is performed at NOAA/NESDIS [*Tarpley et al., 1996*], as described in section 4.

### 3.2 *Modifications for GOES-8*

Prior to the operational implementation of the SRB model at NOAA/NESDIS, spectral/angular corrections appropriate for the filter functions of GOES-8 [Menzel and Purdom, 1994] were developed [Zhou et al., 1996]. The visible channel on the GOES-8 satellite is a narrowband channel. To derive broadband fluxes requires development of narrow to broadband transformations for this satellite. A study was undertaken to obtain angularly dependent relationships between the broadband reflectance and the narrowband reflectance, as observed from the visible channel of GOES-8 (0.52- 0.72  $\mu\text{m}$ ). Top of atmosphere broadband and filtered narrowband reflectances (representing the visible channel of GOES-8) were simulated using the LOWTRAN 7 radiation code for various viewing and solar geometries (represented by angular bins) and considering different amounts of water vapor, ozone, aerosol and clouds (**Figure 2**). Surface albedo was also varied according to the spectrally and angularly dependent models of Briegleb et al. (1986), as representative of four broad surface types: ocean, vegetation, desert and snow. For each surface type, two sets of transformation coefficients were derived by performing linear least-square regressions between the simulated narrowband and broadband reflectances. One set of coefficient was obtained from regressions for individual angular bins, while the other was derived using all angular bins. The difference in the broadband albedo obtained from the two sets of transformation coefficients depended on the solar zenith angle and the narrowband reflectance. Large solar angles and bright scenes produced large differences of the broadband albedo. For narrowband reflectances less than about 0.15, the broadband albedos derived from the two sets of transformations generally differed by less than 1%. In the current version of the SRB model as

implemented by NOAA/NESDIS, the transformation based on the ensemble of simulations is in use.

#### **4. The implementation process**

The process of inferring surface radiative fluxes from the satellite observations involves: the interception of the real time satellite data at NOAA/NESDIS; building transfer capabilities between the Eta model products and the satellite data; building an interface between the satellite data and the inference model; executing the inference scheme; displaying the data in real time on the World Wide Web; and storing the data at the University of Maryland for quality control and data distribution. The latter includes parallel processing, preprocessing of original data into information at different time scales, model improvements, and archiving and distribution, as illustrated in **Figure 3**. In what follows, each activity will be described independently.

##### **4.1 Real-time operation at NOAA**

In **Table 2**, a list of quantities required as input to the algorithm is presented. In **Table 3**, the algorithm outputs are listed. The satellite input to the model for each grid cell is clear sky radiance, composite clear sky radiance (this is the “clearest radiance” seen during several days), cloudy radiance, and fractional cloud-cover over the selected grid. Total precipitable water and, if available, the total ozone are accessed from the NCEP Eta weather forecast model.

##### **4.2 Processing of GOES-8 Imager Data**

The GOES GCIP products are derived hourly for targets that are centered at  $0.5^\circ$  latitude/longitude intervals. Coverage extends from  $24^\circ$  to  $54^\circ$  N latitude and  $66^\circ$  to  $126^\circ$

W longitude. The targets consist of 9 x 8 arrays of 4 km center-to-center pixels (at nadir), where the visible data have been averaged up to 4 km resolution, to coincide with the 4 km resolution infrared pixels. The methodology to derive quantities that are directly computed from the hourly GOES data is based on the one used at NESDIS in the early stages of insolation estimates [Tarpley, 1979; Justus, *et al.*, 1986]. The cloud detection algorithm is based on the fact that from geostationary orbit, the clear-sky surface brightness at each location for a given hour changes very slowly in time. Changes that occur are caused by seasonal change in solar illumination geometry, and by changes in surface albedo, caused by seasonal variations in vegetation and surface conditions. The algorithm assumes that any partial cloud cover in a target increases the variance in the visible and infrared radiances over the target.

The clear composite radiance (CCR) is an input to the model and serves as a threshold in the cloud detection algorithm. The CCR represents the target radiances under clear sky conditions with minimum aerosol and atmospheric contribution to the signal. The fields of CCR are maintained for every target at every daylight hour for which the solar zenith angle is less than 75°. Updating of the CCR fields is done very conservatively, to avoid cloud contamination. The CCR fields are maintained for the visible data (Channel 1). Corresponding fields of clear sky visible standard deviations,  $\sigma_1$ , and thermal standard deviations (Channel 4),  $\sigma_4$ , are also maintained.

For a specific target at a given observation time, the target is updated if it is certain that there are no clouds in the target. To insure completely clear conditions, a target is updated if the following tests are met:

1. There is no snow cover
2.  $A_1 < A_1(\text{min}) + k_0 \sigma_1(\text{min})$
3.  $\sigma_1 < k_1 \sigma_1(\text{min})$
4.  $\sigma_4 < k_2 \sigma_4(\text{min})$

where  $A_1$ ,  $\sigma_1$ , and  $\sigma_4$  are the currently observed mean albedo and channels 1 and 4 standard deviations respectively, and  $A_1(\text{min})$ ,  $\sigma_1(\text{min})$ , and  $\sigma_4(\text{min})$  are the clear sky values in the CCR fields. The value of  $k_0$ ,  $k_1$ , and  $k_2$  are specific for each target, although that the current practice is to use the same values everywhere. Values are 1.5, 4.0 and 4.0 respectively. When the observation from a target meets the above criteria, the CCR is updated with a weighted average of the new and the old values, with the new given a weight of 0.25. The coefficients are strictly selected to prevent sub-pixel cloud cover from being included in the radiances. This conservative approach prevents cloud contamination from slowly brightening the CCR fields. If specific targets in the CCR field do not require an update for a prolonged period of time, the above criteria are relaxed, until new values are obtained.

### **4.3 Cloud Detection**

The values of  $A_1(\text{min})$  and  $\sigma_1(\text{min})$  are used to define thresholds between clear and partly cloudy pixels, in the cloud detection algorithm. Each pixel in each target is classified by its top of the atmosphere albedo as being clear, partly cloudy, or cloudy, according to the following criteria:

If

$A_i < A_1(\text{min}) + k_3 \sigma_1(\text{min})$  the pixel is clear

$A_1(\text{min}) + k_3 \sigma_1(\text{min}) \leq A_i \leq 35\% \text{ albedo}$  the pixel is mixed,

$A_i > 35\%$  albedo,

the pixel is cloudy,

$k_3$  is currently set to 9.0 everywhere. The above criteria were chosen by taking images of different scenes and calculating the cloud amounts with varying thresholds, until the cloud amounts matched the visual observations, particularly, for optically thick clouds that have a large effect on insolation. For each category of pixel in the target (clear, mixed, and cloudy), mean albedo and mean brightness temperatures in each thermal band are calculated, and the number of pixels in each is counted. The mixed pixel count is redistributed into the clear and cloudy counts, by weighting the number of mixed pixels by the mean albedo of the mixed pixels, according to the following procedure:

$$n'(\text{cloudy}) = n(\text{cloudy}) + f * n(\text{mixed})$$

$$n'(\text{clear}) = n(\text{clear}) + (1 - f) * n(\text{mixed})$$

where

$$f = (A(\text{mixed}) - A_{\text{th}})/(35\% \text{ albedo} - A_{\text{th}}).$$

$A(\text{mixed})$  is the mean albedo of the mixed pixels,

and

$$A_{\text{th}} = A_1(\text{min}) + k_3 \sigma_1(\text{min})$$

is the brightness threshold between clear and mixed pixels. The final number of clear and cloudy pixels,  $n$  and  $n'$ , respectively, are converted to clear and cloudy fraction dividing by 72 the number of pixels in the target. The clear and cloudy sky albedos, the cloudy and clear fractions, and the composite clear albedo are then provided to the insolation algorithm, along with target snow cover, and the total precipitable water. The cloud detection method described here is successful in identifying optically thick cloud cover,

but it is less reliable for detecting thin cirrus clouds. However, thin cirrus has much less effect on insolation, which is the primary quantity that is being retrieved, so more complex cloud detection schemes are not required. Until late 1998, the U.S. Air Force daily snow cover data were used. The snow cover currently used is the NESDIS operational daily snow product [Ramsay, 1998]. The total precipitable water is from 6 and 12 hour Eta model forecast fields, interpolated to the target location and observation time

## 6. Results and Discussion

About fifty ground observing stations are used to evaluate the satellite estimates of the surface shortwave fluxes. These include four Surface Radiation (SURFRAD) stations (Goodwin Creek, MS; Boulder, CO; Bondville, IL; Fort Peck, MT) [Hicks *et al.*, 1996], twenty one stations from the Arizona Meteorological Network (AZMET) [Brown, 1989], about 20 stations from the Illinois State Water Survey [Hollinger *et al.*, 1994] and about ten stations from the Integrated Surface Irradiance Study (ISIS) [Hicks *et al.*, 1996]. ISIS provides basic surface radiation data with repeatability, consistency, and accuracy based on reference standards maintained at levels better than 1% to address questions of spatial distributions and time trends, at sites selected to be (1) regionally representative, (2) long-term continuous, and (3) strategic foci. It should be noted that the SURFRAD network is also part of ISIS, which operates at two levels: Level 1 monitors incoming radiation only, and Level 2 (SURFRAD) focuses on surface radiation balance. The stations used in the validation effort are unevenly distributed over the United States or within the respective states as shown for Illinois and Arizona in **Figure 4**. The evaluation

against ground truth is done at the following time scales: 1) hourly; 2) daily; and 3) monthly. At the SURFRAD sites, data of high temporal resolution are available. The three-minute observations are being used here in experiments to evaluate time/space compatibility between ground and satellite observations. The quality of all model input parameters is not fully known. While there is confidence in the precipitable water information, as discussed and evaluated in *Yarosh et al.* [1996], less confidence can be placed on the snow information. Consequently, the Air Force snow information was replaced at the beginning of 1999 by the new NOAA/NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) product [*Ramsay*, 1998]. The ground observations on SW radiative fluxes are accepted as provided by each investigator, who follow calibration and quality control procedures, as described in each relevant publication. There is no cross-calibration between the various networks. Some of the results presented, include all available ground truth, as well as all available satellite observations, while others include preliminary quality controlled data, such as eliminating observations outside a 3-sigma limit. The options followed will be specified in each case.

### **6.1** *Validation results on hourly time scale*

Results are presented for eleven months of 1996, except for ISIS stations for which only five months of data have been processed. For December 1996, satellite observations were available only for about two weeks, and therefore, December was not included in the statistics. In **Figures 5(a), 5(b), 5(c), and 5(d)**, results on hourly time

scales for Arizona, Illinois, SURFRAD, and ISIS stations, respectively, are presented. Due to the large amount of data, the figures include data points from only one month. Statistical results, independently for each month, are presented in **Figures 9 and 10**. The data used in the comparison were subjected to preliminary quality control measures, by eliminating cases outside a 3-sigma limit. Experiments have indicated that for most cases, such a limit is below  $300 \text{ W m}^{-2}$ . To simplify computations, the elimination criteria were set to that latter limit. Given are the root mean square (rms) error, the bias, correlation coefficient, total number of available observations, the number of observations that were out of the 3-sigma limit, and the percentage of points eliminated from the total number of observations. The average rms for Arizona, Illinois, SURFRAD, and ISIS stations were 87, 100, 104 and  $77 \text{ W m}^{-2}$ , respectively. As evident from **Figures 9 and 10**, the largest errors occur during the wintertime in regions affected by snow. As discussed, information on snow cover is deficient, and the methodology to identify clouds over snow requires improvements. Were we to eliminate the snow months from the statistics over Illinois and the SURFRAD locations, the rms error would be reduced to 83 and  $90 \text{ W m}^{-2}$ , respectively. This amounts to about 15% of the mean value. The corresponding biases were  $29 \text{ W m}^{-2}$  and  $30 \text{ W m}^{-2}$  respectively, indicating that the satellite tended to overestimate the surface observations. The reason for this overestimate is not yet fully understood. Possibly, this is related to changes occurring in the calibration of the satellite sensor, needed improvements in cloud screening methods, or incorrect information on aerosol optical depths. Preliminary investigations indicate [Meng *et al.*, 2002], that correcting for possible degradation of the visible sensor could reduce the bias substantially. No large differences were found for these different

locations during the snow free months. The average percentage of points eliminated from the analysis under the 3-sigma limit was 1.7% for Arizona, 8.5% for Illinois (for snow free conditions), 6.3% for the SURFRAD, and 4.9% for ISIS.

## **6.2** *Evaluation of results on daily time scale*

In **Figures 6(a), 6(b), 6(c), and 6(d)** results on daily time scales for Arizona, Illinois, the SURFRAD and the ISIS stations, respectively, are presented. Due to the large number of data points only four months have been included in these figures. For Arizona, data are included for January, May, June, and November. For Illinois and the SURFRAD stations, data from January, May, August, and November were used. For the ISIS stations, data from May-September were used. Statistical results, computed independently for each month, are presented in **Figures 9 and 10**. Given are the rms error, the bias, correlation coefficient, number of days when ground observations were available for the entire day, number of days when satellite observations were available for more than four observations per day (statistics were computed only for days when more than four satellite observations were available), and the percentage of cases eliminated because of above reasons, namely, not a complete or compatible record of either ground or satellite observations. The average rms for Arizona, Illinois, the SURFRAD and ISIS stations were 21, 28, 29  $\text{W m}^{-2}$ , and 26, respectively. Were we to eliminate the snow months from the statistics over Illinois and the SURFRAD locations, the rms error would reduce to 21 and 26  $\text{W m}^{-2}$ , respectively. This amounts to about 10 % of the mean value. The corresponding biases were 29  $\text{W m}^{-2}$  and 30  $\text{W m}^{-2}$ , respectively, indicating that the satellite tended to overestimate the surface observations. No large differences were

found for these different locations. As evident, the larger errors for the Illinois and SURFRAD stations were found during the winter months, and most likely, are related to errors in snow cover. It should be noted that in subsequent years, the number of missing satellite data during the course of the day was reduced, as NOAA readiness for producing routinely this product improved.

### **6.3** *Evaluation of results on monthly time scale*

In **Figures 7(a), 7(b), 7(c) and 7(d)** results on monthly time scales for Arizona, Illinois, SURFRAD and ISIS are presented. Statistical summaries for the SURFRAD stations are presented in **Figures 9 and 10**. The average rms for Arizona, Illinois, SURFRAD and the ISIS stations were 12, 16, 14 and 15  $\text{W m}^{-2}$ , respectively. In **Figure 8**, results for the diurnal variation of the shortwave fluxes are illustrated for the SURFRAD stations during May 1996. The results are encouraging, because until now, no information was available for validating or driving models that resolve the diurnal cycle.

### **6.4** *Validation experiments at high temporal resolution*

In **Figure 11**, we present preliminary results from comparisons between the satellite derived SW fluxes and measurements from the SURFRAD network, using a range of time scales. The following two experiments were performed over the SURFRAD stations at Bondville, Illinois: a) using ground observations averaged over one hour, centered at the time of the satellite overpass, and satellite observations averaged over 3, 9, 15, and 60 minutes; b) using ground observations averaged over 3, 9, 15, and 60 minutes, and instantaneous satellite inferred surface flux. As evident from the figure, the best results were obtained when both the satellite and ground observations

were averaged over a one-hour interval. It is reasonable to expect that this particular time averaging depends on the average speed of cloud movement in this climatic region, and that at other locations, different optimal averaging periods would be found.

### 6.5 *Special results*

At some locations, data from more than one source were available. For example, at Bondville, Illinois, observations are being made by the Illinois Water Survey, and by SURFRAD, at a distance of several meters from each other. Preliminary comparisons between these two stations for several months indicated discrepancies as illustrated in **Figure 12a**. After discussions with site scientists, the sources of such discrepancies were found, and corrected (Appendix A). Similarly, at Tucson, AZ, data were available from the AZMET network (32.17° N; 110.57° W; 713 m elevation), as well as from the University of Arizona (W. D. Sellers, private communication). The differences between these two stations are illustrated in **Figure 12b**. As evident, they can be quite high, and the causes of these differences are not fully known. In **Figure 13**, we present the frequency distribution of the hourly ground observations (G) (upper panel) and satellite observations (S) (middle panel), in intervals of  $40 \text{ W m}^{-2}$ , using data from all the stations in Arizona (a), SURFRAD and ISIS. The difference between the satellite estimates and the ground observations is illustrated in the lower panel. As evident, this difference is in the range between 0 to 5 %, indicating that both types of observations represent a similar radiation climate.

## 6.6 *Estimates of accuracies of surface observations*

In the framework of the ARM activity, radiation measurements are being made at the Oklahoma Central Facility site located near Billings, Oklahoma using three sets of independent radiometers. These are operated and maintained per BSRN specifications [Michalsky *et al.*, 1991]. The instruments include an Eppley PSP, 8-48 Black and White, NIP and PIR. Sci Tech trackers are used; the instruments are calibrated once per year and cleaned daily. Such observations for five years (1997-2001) are used to develop best estimate criteria. Calculated are mean and average absolute deviations of the yearly 95% level values. Defined are yearly “best”, “typical” and “worst” disagreements [Shi and Long, 2002]. The operational limits are presented in **Table 1** and are reported in units of  $W/m^2$ : The best estimates of global shortwave are believed to be obtained by adding the direct and diffuse beams. Most instruments are not operated under “best” conditions, and therefore, these documented errors need to be considered when interpreting the evaluation of the satellite estimates against the ground observations.

## 7. **Selected examples of data use**

Estimates of surface radiative fluxes from GOES satellite observations, both SW and PAR, as well as albedo values, have been used in various investigations, spanning a broad range of topics. Examples will be presented in the areas of meso-scale model improvements, hydrologic modeling, estimation of net primary productivity, and oceanic applications.

### 7.1 *Assessments of operational models*

Assessment of land surface energy budgets, from regional and global models has been performed by *Berbery et al.* [1998; 1999] for one summer month (August 1997) and for one winter month (January 1998). The operational models are: the Eta model, the Mesoscale Analysis and Prediction System (MAPS) and the Global Environmental Multiscale (GEM). The National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis model outputs, also were used for comparison purposes. Surface energy budgets, derived from various models, were compared against ground truth, using data from the Southern Great Plains Region. Additionally, the NOAA/NESDIS satellite estimates were used to evaluate the shortwave surface radiation. It was shown that the shortwave radiation biases of the models were of the order of 25-50 W m<sup>-2</sup>. Daily time series showed that model estimates tended to miss the amplitude of the day-to-day variability. It is currently believed that this is the result of difficulties in parameterizing the total cloud cover. Results of *Berbery et al.* [1999] showed that the previous adjustments to the radiation scheme in the Eta model still require further corrections; similarly, their results prompted improvements to the parameterizations in MAPS, which as a result performed closer to the other models during the second month. The WCRP GEWEX Continental-scale International Project was originally aimed to assess the accuracy at which water and energy budgets can be “closed” on a continental scale [NRC, 1998]. The Mississippi River Basin was chosen as a first continental scale experiment because the Mississippi River Basin is one of the major river systems of the world and it has a very dense observational infrastructure and is rich in historic meteorological data. Results summarizing the findings on the Water

and Energy Budget Synthesis (WEBS) in the Mississippi River Basin are presented in *Roads et al.* [2002]. Information on radiative fluxes as derived from satellite observations was used in the evaluation process.

## **7.2 Assessments of research models**

Climate and numerical weather prediction models support now sophisticated land surface process schemes for partitioning energy and moisture fluxes at the surface. These schemes are responsible for maintaining soil moisture fields for model initialization, and for use in estimating runoff. These schemes are normally driven by model estimates of precipitation, radiation, cloud cover and air temperature and humidity. The models do not estimate precipitation accurately, nor do they forecast cloud cover or radiation well. Errors and bias in model forecasts of these quantities cause the soil moisture to drift away from reality. Uncoupled surface models are being tested in Land Data Assimilation Schemes (LDAS) [*Mitchell et al.*, 2002] in which surface models are forced as much as possible with real observations instead of model output. Satellite observations of cloud cover and insolation and rain gage and radar observations of precipitation are used to force the uncoupled models. The assumption being that the real observations are not affected by the NWP model biases and therefore will maintain better soil moisture fields that can be used to initialize NWP models. Examples of such applications are given in *Cosgrove et al.* [2002] and *Lou et al.* [2002].

## **7.3 Hydrologic modeling**

Climate and numerical weather prediction models have advanced to fairly sophisticated land surface process schemes for partitioning the energy and moisture

fluxes at the surface. These schemes are responsible for maintaining soil moisture fields for model initialization, and for use in estimating runoff. The schemes are normally driven by model estimates of precipitation, radiation, cloud cover and air temperature and humidity. The models do not estimate precipitation accurately, nor do they forecast cloud cover or radiation well. Errors and bias in model forecasts of these quantities cause the soil moisture to drift away from reality. Uncoupled surface models are being tested in Land Data Assimilation Schemes (LDAS) in which surface models are forced as much as possible with real observations instead of model output. Satellite observations of cloud cover and insolation and rain gage and radar observations of precipitation are used to force the uncoupled models. The assumption being that the real observations are not affected by the NWP model biases and therefore will maintain better soil moisture fields that can be used to initialize NWP models.

#### **7.4 *Net primary productivity***

At the Midwestern Climate Center, Illinois State Water Survey, work is in progress on estimating operationally, large area corn and soybean yield estimates. The area of study is the nine-state region of Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin that account for about 70% of the United States production of both corn and soybean. The yield estimation models [*e.g.*, Jones and Kiniry, 1986; Wilkerson *et al.*, 1983] require a set of variety coefficients, soil characteristics, daily weather data such as precipitation, max and min temperature, solar radiation (from which the photosynthetically active radiation (PAR) is estimated), and planting dates, depth and density. Till now, solar radiation was estimated from such parameters as cloud cover. The surface observing cloud networks are being replaced

with the Automated Surface Observing System (ASOS) stations, which do not measure cloud cover above 12,000 ft. Therefore, there is a concern about the effect this might have on the estimation of solar radiation by conventional methods. An experiment was conducted (K. Kunkel, private communication), to derive corn yields for the 1996 growing season, once using conventionally derived information on PAR which enters the model, and once, satellite derived estimates as produced for GCIP. The model yields were generated for 87 crop-reporting districts in the central United States, where each data point represents a value for a single crop-reporting district. These preliminary results indicate that replacing the current sources of information on surface radiative fluxes with satellite inferred values, is a viable option.

### **7.5 *Oceanic applications***

As discussed in *Baumgartner and Anderson* [1998], in middle to low latitudes, the net shortwave radiation is the largest daytime component of the net air-sea heat flux. Errors in this component will also propagate into estimates of net heat fluxes. Currently, most coastal ocean models rely on surface fields as available from Numerical Weather Prediction models for surface boundary conditions. Using buoy observations made during a recent one year Coastal Mixing and Optics (CMO) Experiment at a mid-shelf location south of Cape Cod, Massachusetts, surface flux fields as available from three regional Numerical Weather Prediction models, that were in operation during 1996 and 1997 at the U.S. National Centers for Environmental Prediction (NCEP), were evaluated against the observations. The models used are: the Eta-48, Eta-29, and the Rapid Update Cycle (RUC-1) version. It was found that the models overestimated the net ocean-to-atmosphere heat flux by about 83 and 74  $\text{W m}^{-2}$  for the Eta-29 and RUC-1 models,

respectively. Experiments were conducted for the period July through September 1996, where the shortwave fluxes as produced in support of GCIP were used. It was found that the use of such fluxes in the CMO flux fields reduced the variability in the net heat flux errors by 46%. It is also claimed that the accuracy at hourly time scales would have improved. The correlation coefficients between the observations and the flux fields with and without the GCIP shortwave information over the same period are 0.929 and 0.863, respectively.

## **8. Current and Future Activities**

During GCIP, operational numerical weather prediction models and associated 4-D data assimilation systems have been implemented at NCEP [*Chen et al.*, 1996], and the operational output from the Eta model, as it evolves, is provided to NESDIS, for input to the SRB model. On the other hand, to meet the needs for the validation of the Eta model, NOAA/NESDIS is preparing a unique validation data set that contains Eta model forecast data mapped to the GCIP product output. They extract the 00Z run of the Eta model and pick up the 12, 18 and 24 hour forecast fields of total cloud amount, components of the SW and LW radiation budgets, skin temperature, vegetation fraction, albedo, snow cover, latent and sensible heat flux, surface heat flux, and total soil water content. This data is accessed only once a day, then mapped to 0.5 lat/long grid. Added are to the current GOES products: surface temperature (gridded ASOS, albedo, delta T(12-6) and delta T(18-12). Since February 1999, snow information, that was originally available from the Air Force product was replaced by a new product, as developed at NESDIS, and cloud screening methods, in particular, over snow, are being revisited. As of this writing, the

SRB data have been used by numerous investigators to evaluate meso-scale models [Berbery, 1998], computations of surface fluxes over the Atlantic Bight (*Baumgartner and Anderson, 1999*), evaluating crop production models (*K. Kunkel, private communication*), and snow melt [*Cline and Carroll, 1998*].

## 9. Summary

A joint activity between several branches of NOAA and the University of Maryland, to develop, implement, and use surface shortwave radiative fluxes, as recently available from operational GOES satellites, has been described. This capability was implemented by NOAA/NESDIS in real time, starting in mid 1995, and is continuing into present time. Based on results of evaluation against ground truth for 1996, it was found that the rms errors on hourly time scale were about  $90 \text{ W m}^{-2}$ , about  $25 \text{ W m}^{-2}$  on daily time scale, and about  $20 \text{ W m}^{-2}$  on monthly time scale. Experiments were also performed with different averaging time periods and different spatial integrations. The satellite estimates used are as obtained from the real-time runs, without adjustments for satellite sensor degradation and without "tuning" to local conditions. The accuracy of this product has been found to be better than currently believed to be achievable from numerical models. Therefore, the product in its present form has been found useful in a wide range of studies and applications. Still, many unresolved outstanding issues require further development and improvement. The key areas where improvements are needed are related to information about snow cover distribution, and cloud detection over snow. This is a difficult issue, and would require the use of additional channels, that are available on the GOES satellites. During the winter months, difficulties were encountered with reported snow amounts. This led to errors in cloud estimates and,

subsequently, in the surface fluxes, as evident from the statistics presented in **Figures 9 and 10** for the winter months, in areas known to have snow. Strikingly, Arizona did not have this problem during the winter. Calibration of the satellite sensors is still a problem, and will require additional attention. To obtain accurate assessments of satellite capabilities to estimate surface radiative fluxes, there is a need to improve the quality of the ground observing stations, as well as their representativeness for each satellite grid cell. Work is in progress to remove known problems, and to expand the validation process to other climatic regions of the United States.

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## APPENDIX A

The differences found in the observations from the two adjacent radiometers at Bondville, Illinois were investigated in depth (J. Augustine, private communication). One station belongs to the SURFRAD network, which operates an Eppley PSP, while the other is operated by the Illinois Water Survey Network, under the direction of Dr. S. Hollinger, using alternating black and white sectors as detectors. Initially, we compared observations for November and December, 1995 with satellite inferred values and found that the SURFRAD measurements were always lower than those from the Bondville BEARS site (here after, the Bondville instrument). The initial suspicion was that the differences appeared to be the result of a calibration offset in one of the instruments, because the absolute difference between measurements increased with the degree of downwelling irradiance. The calibration of the SURFRAD instrument was traced to National Renewable Energy Laboratory (NREL) during the summer of 1995. To resolve this issue, it was agreed (J. Augustine and S. Hollinger), that after the routine SURFRAD instrument exchange at Bondville, all instruments will be sent to Boulder, Colorado to be compared to the Surface Radiation Research Branch (SRRB) of the NOAA's Air

Resources Laboratory standard set of Eppley PSP instruments. For this purpose, the SRRB standard PSPs were recalibrated at NREL during September of 1996. The new sensitivity factors were applied to the standards, and the sensitivity factors that have been used while they were at Bondville, were applied to the returning pyranometers. The intercomparison has shown that qualitatively, all instruments saw the same signal, and none has shown anomalous behavior. It is usual for these instruments to produce slight negative signals at night owing to the inner dome cooling to space. The magnitude of these signals was evaluated, and found to be in a range that did not explain the differences between the two radiometers. Subsequently, the returning radiometers were gauged against each other, by forming ratios to the mean of the three standards. During two clear days of calibration, ratios of the SURFRAD radiometers to the mean of the standards are clustered near 1.0, but they did show a slight cosine error with respect to that of the standards. The Bondville instrument showed a systematic offset and a more severe cosine problem. During the cloudy period of the calibration, the SURFRAD instruments and the Bondville instrument showed unexplained random differences with respect to the standards. The mean ratio at 50 degrees of solar zenith angle (at this angle NREL computes sensitivity factors) for one SURFRAD instrument was 0.994, while for the other, it was 0.999. For the Bondville instrument, it was 1.051, which translates to a bias of 5.1%, close to what we have.

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**Table 1.** Operational limits on measured short-wave [after *Shi and Long*, 2002]

	Best	Typical	Worst
Diffuse SW	4.0 + 1.4	9.0 + 3.1	12.0+3.8
Direct Norma;	6.3 + 3.3	13.3 + 6.3	12.0 + 3.8
Upwelling SW		11.1 + 2.8	

**Table 2.** Quantities required by the GCIP/SRB model.

Input Parameter	Function
Clear-sky radiance	Calculate fluxes for clear-sky conditions
Cloudy radiance	Calculate fluxes for cloudy conditions
Composite clear radiance	Calculate surface albedo
Target fractional cloud cover	Weight clear and cloudy fluxes
Water vapor and ozone amount	Select atmospheric transmittance
Snow cover	Weight snow-free surface albedo and snow albedo
Solar and satellite zenith angles, sun-satellite relative azimuth angle	Geometric corrections
Target latitude and longitude	Scene type, surface albedo model, and climatological aerosol loading

**Table 3.** Output parameters from the GCIP SRB Model.

**clr-clear; cldy-cloudy.**

Parameter	Unit
aerosol optical depth at 0.55 $\mu\text{m}$	-
cloud optical depth at 0.55 $\mu\text{m}$	-
top of atmosphere down-flux (clr+cldy)	$\text{W m}^{-2}$
top of atmosphere up-flux (clr+cldy)	$\text{W m}^{-2}$
surface down-flux (clr+cldy)	$\text{W m}^{-2}$
surface up-flux (clr+cldy)	$\text{W m}^{-2}$
top of atmosphere up-flux (clr)	$\text{W m}^{-2}$
surface down-flux (clr)	$\text{W m}^{-2}$
surface up-flux (clr)	$\text{W m}^{-2}$
diffuse surface-down flux (clr+cldy)	$\text{W m}^{-2}$
diffuse PAR	$\text{W m}^{-2}$
global (direct+diffuse) PAR	$\text{W m}^{-2}$

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- a) Instantaneous surface short-wave radiative flux ( $\text{W}/\text{m}^2$ ), for 17:15 UTC, September 15, 2002.
- b) Same as above, hourly averaged for 12:00 noon. The hourly averaged data are stored and displayed in LST, making the time zones visible. To minimize this effect, the noon hour was selected for the hourly integration.
- c) Same as above, for the daily mean values for September 15, 2002.
- d) Same as above, for the monthly mean values for September 2002.
- e) Monthly mean atmospheric short-wave absorption, namely, the difference between the top of the atmosphere and the surface monthly mean values, for September 2002.
- f) Monthly mean surface net short-wave flux for September 2002.
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  - c) all four SURFRAD ground stations, and corresponding satellite estimates for the ground observing locations, for eleven months of 1996.
  - d) all ten ISIS ground stations, and corresponding satellite estimates for the ground observing locations, for five months of 1996.

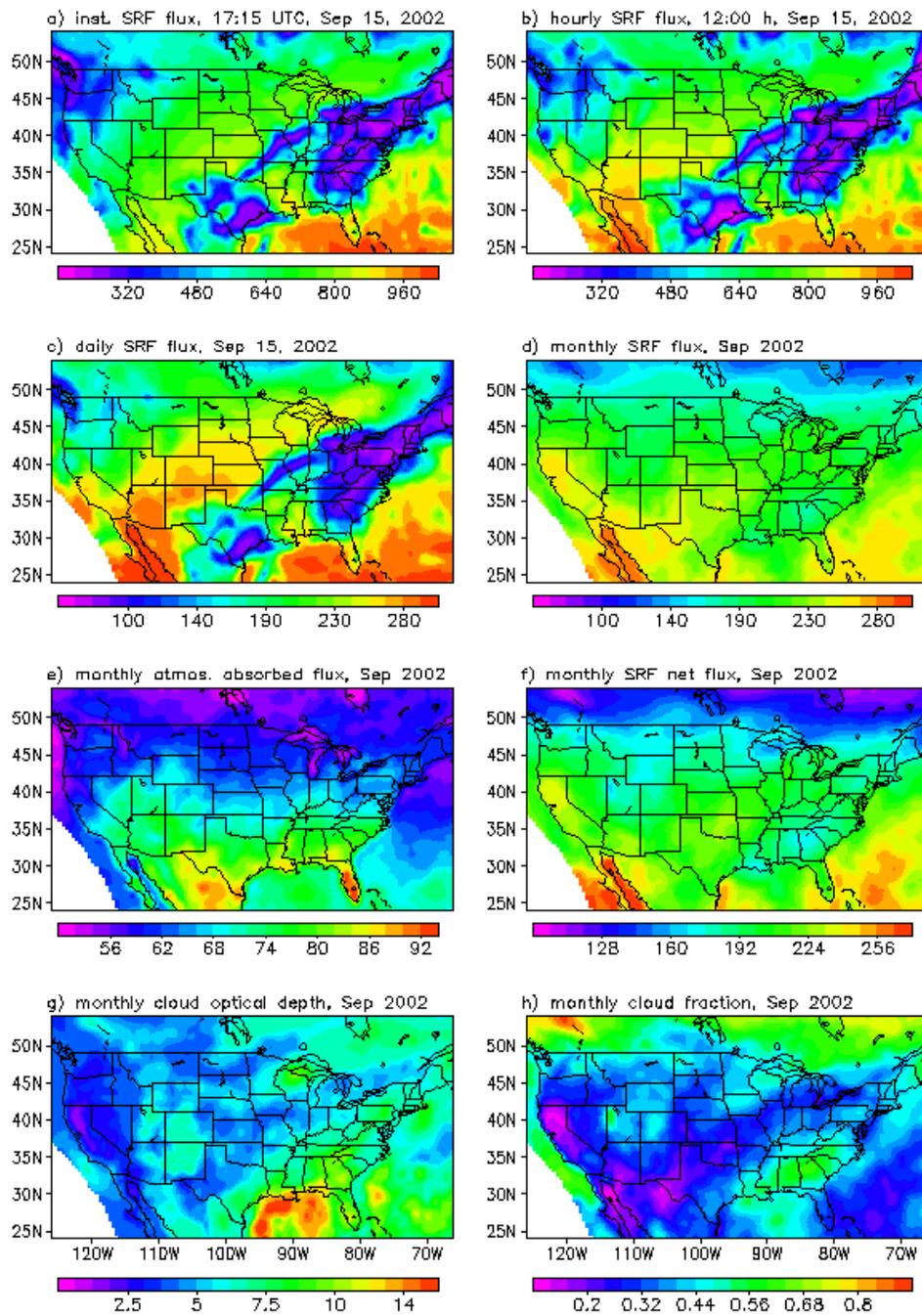


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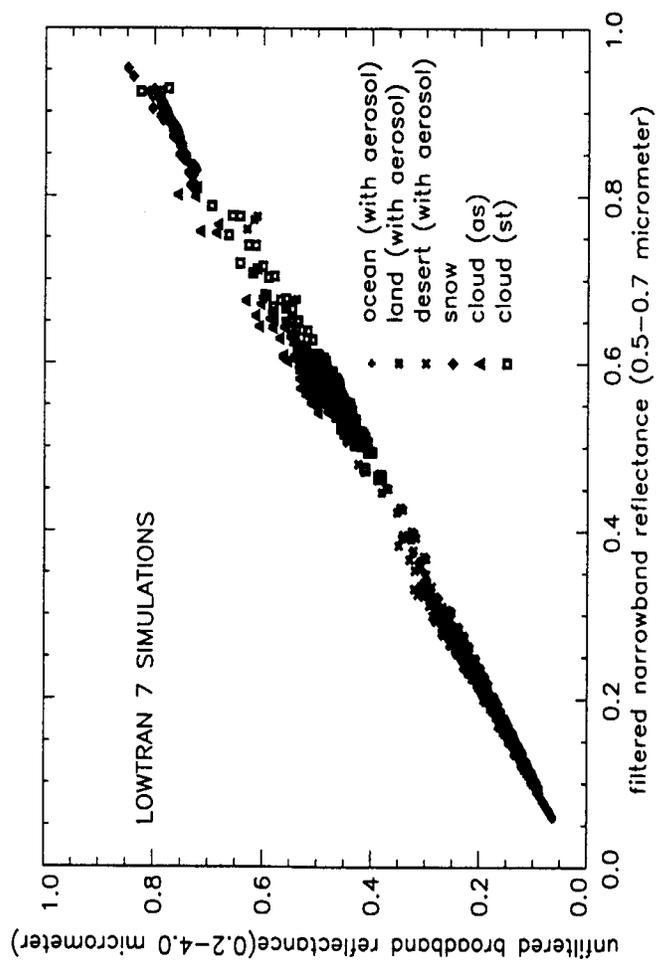


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### GOES-8 GCIIP Products Processing Stream

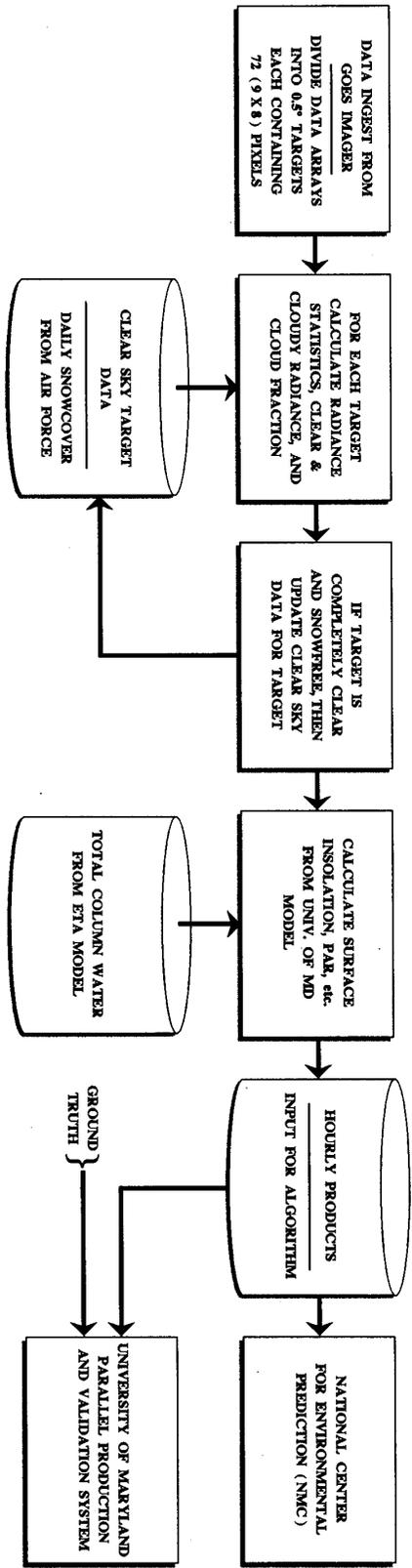


Figure 3. A summary of the processing sequence of the SRB product.

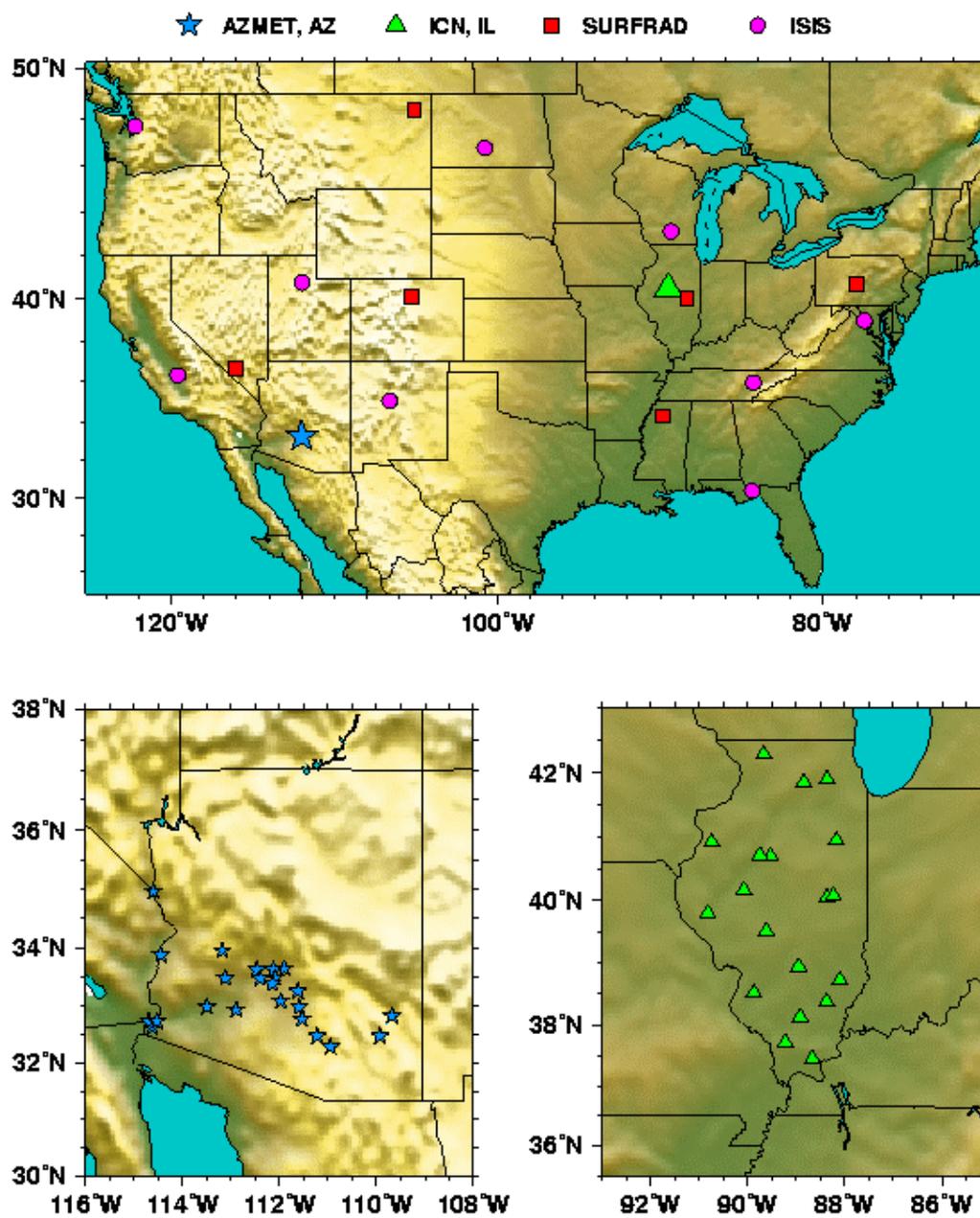
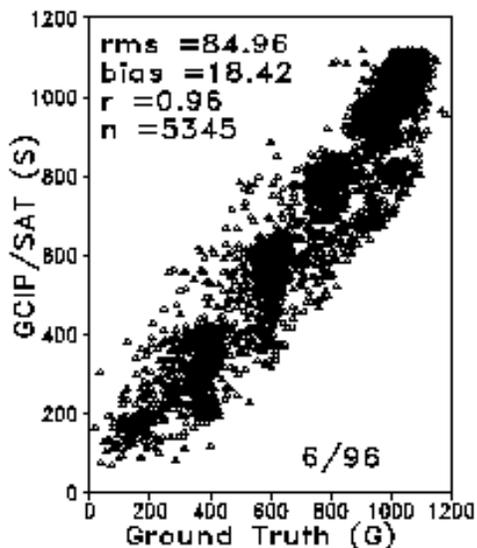


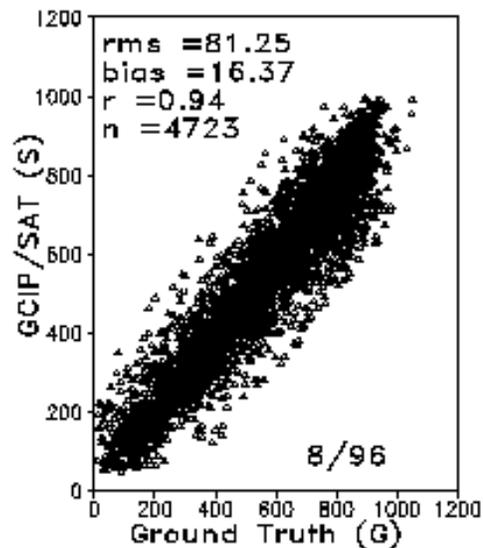
Figure 4. Location of ground stations used in the validation effort.

Hourly mean SWD Flux ( $Wm^{-2}$ )  
21 sites, Arizona



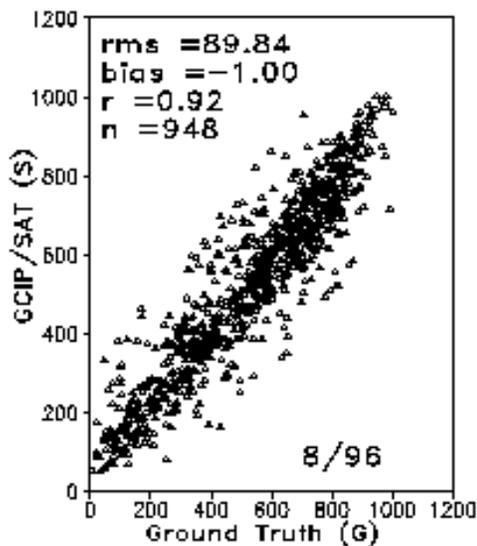
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Hourly Mean SWD Flux ( $Wm^{-2}$ )  
19 sites, Illinois



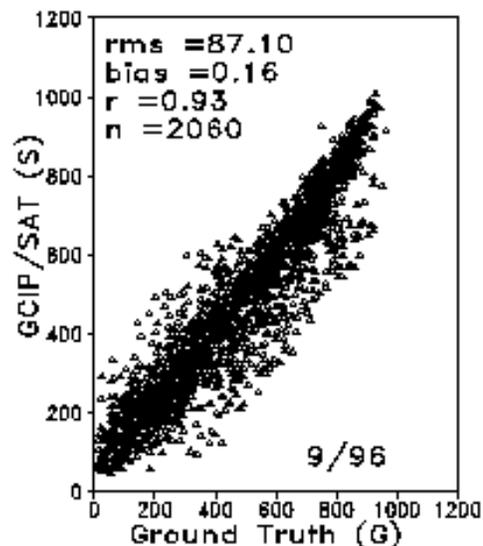
5b

Hourly Mean SWD Flux ( $Wm^{-2}$ )  
4 sites, Surfrad



5c)

Hourly mean SWD Flux ( $Wm^{-2}$ )  
10 sites, ISIS



5d)

Figure 5. Evaluation of results on hourly time scale for: a) 19 Arizona AZMET stations; b) 21 Illinois stations; c) four SURFRAD stations; and d) ten ISIS stations. Due to data density, only one month of data is presented here.

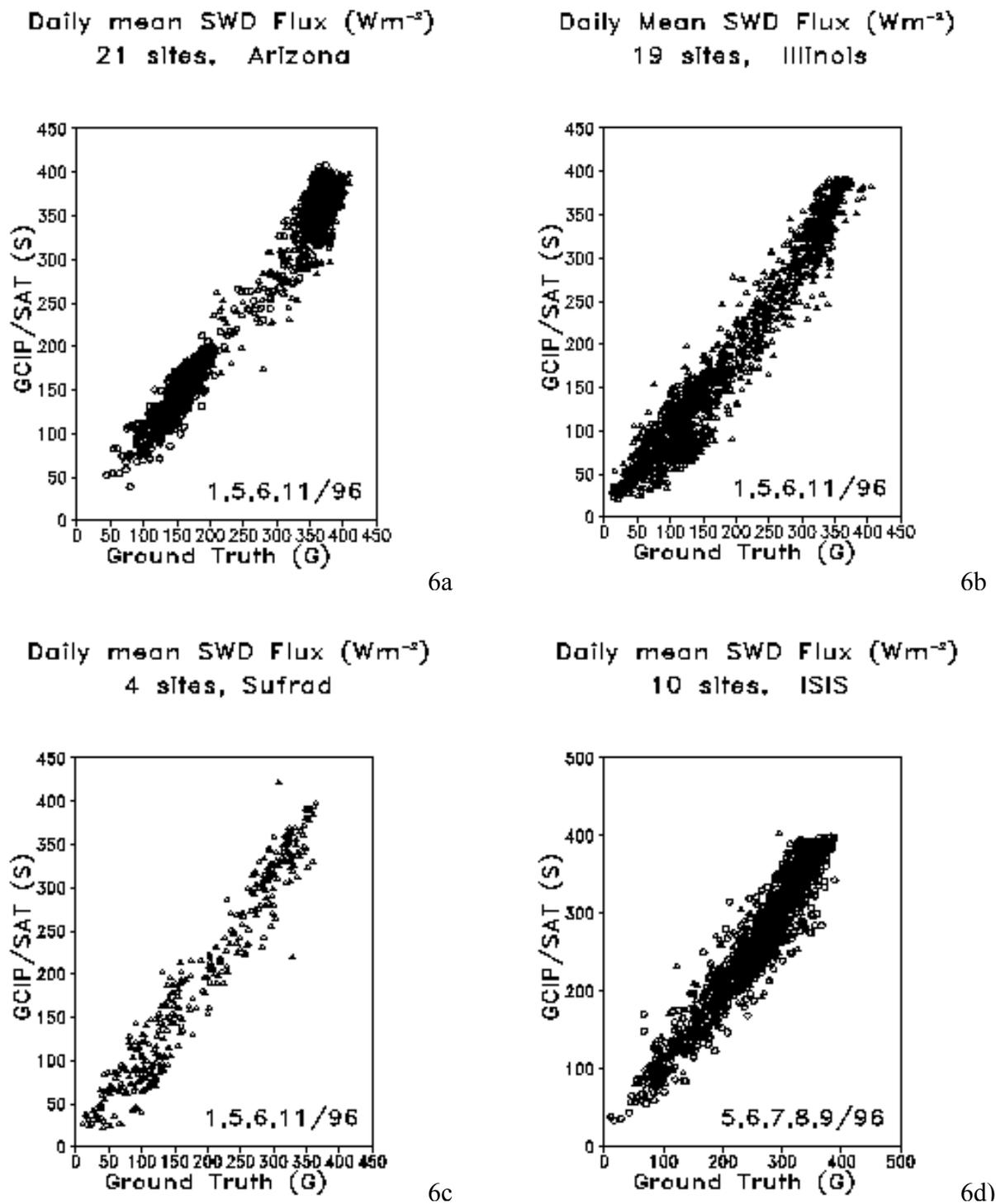
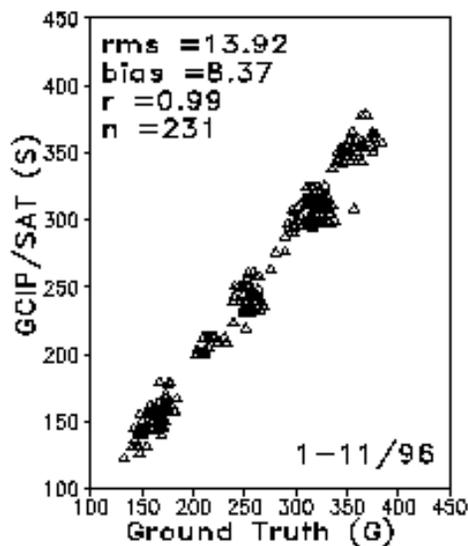


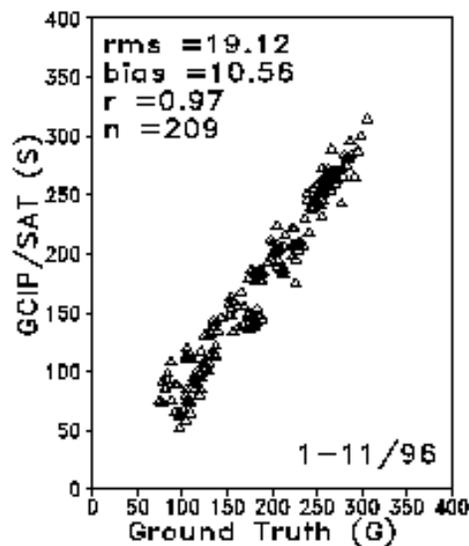
Figure 6. Evaluation of results on daily time scale for: a) 19 Arizona AZMET stations; b) 21 Illinois stations; c) four SURFRAD stations; and, d) ten ISIS stations. Due to data density, only four months of data is used (five months for ISIS).

Monthly Mean SWD Flux ( $\text{Wm}^{-2}$ )  
21 sites, Arizona



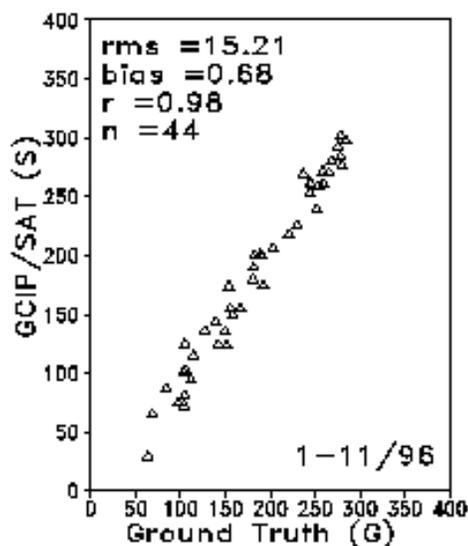
7a

Monthly Mean SWD Flux ( $\text{Wm}^{-2}$ )  
19 sites, Illinois



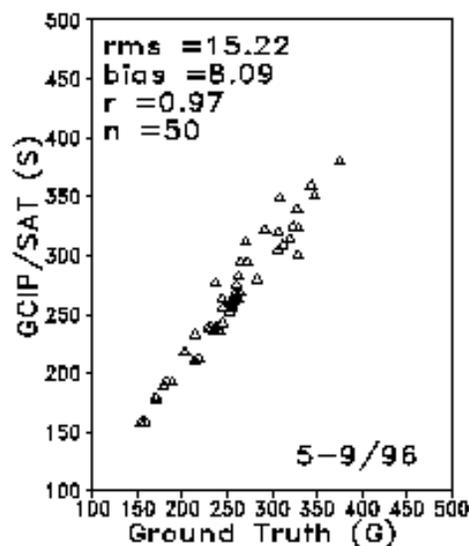
7b

Monthly Mean SWD Flux ( $\text{Wm}^{-2}$ )  
4 sites, Sufrad



7c)

Monthly Mean SWD Flux ( $\text{Wm}^{-2}$ )  
10 sites, ISIS



7d

Figure 7. Evaluation of results on monthly time scale for: a) 19 Arizona AZMET stations; b) 21 Illinois stations; c) four SURFRAD stations; and d) ten ISIS stations. Eleven months of data were used (five for ISIS stations).

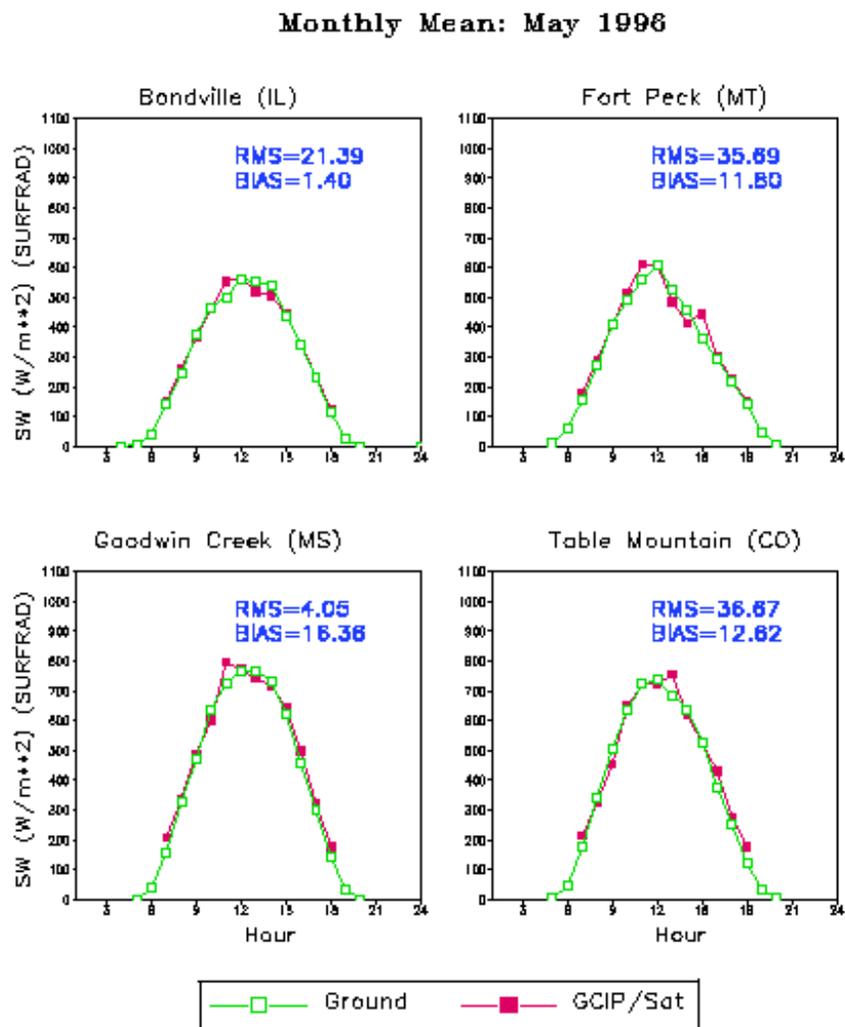


Figure 8. Evaluation of results for the monthly mean diurnal cycle for the SURFRAD stations for May 1996.

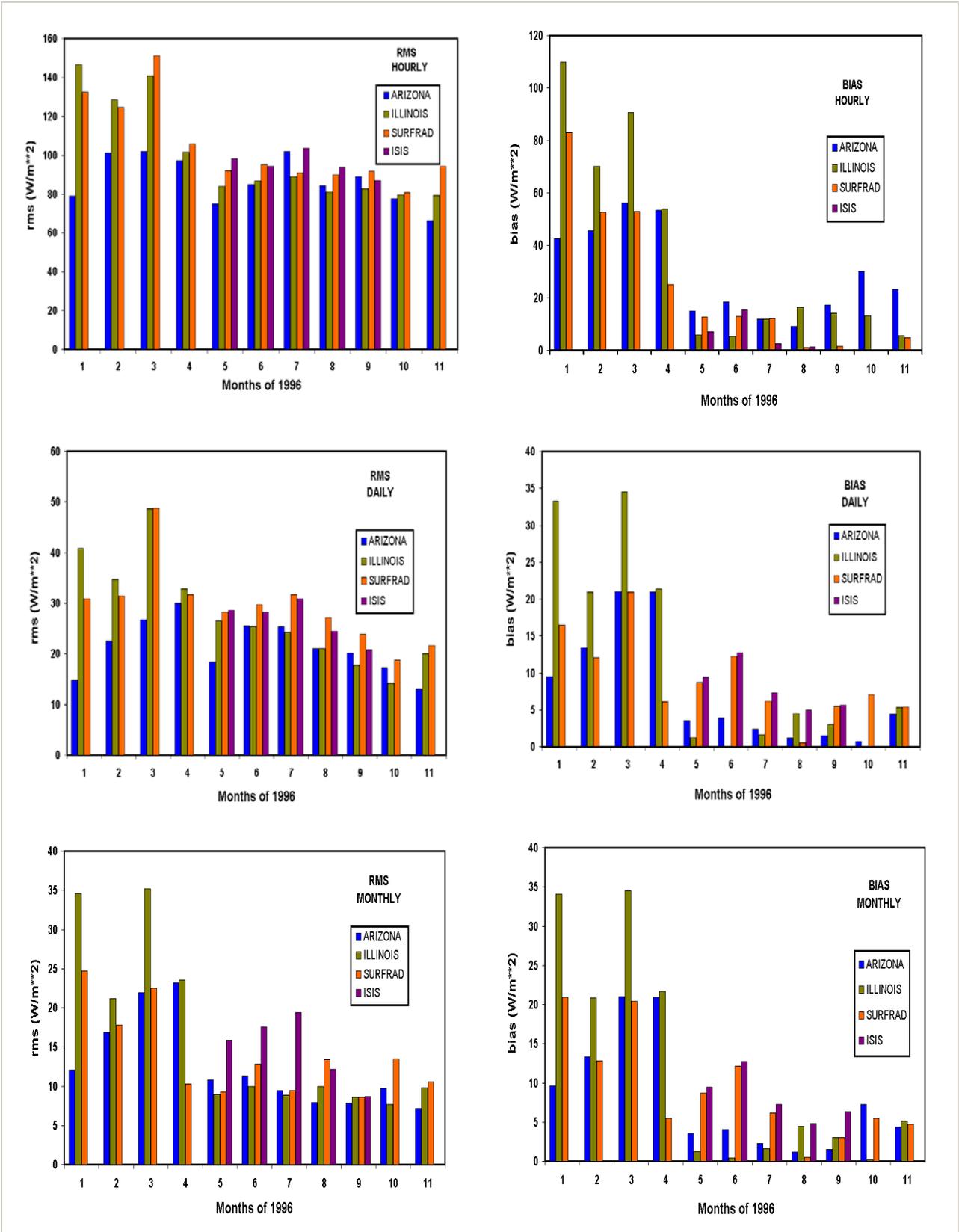
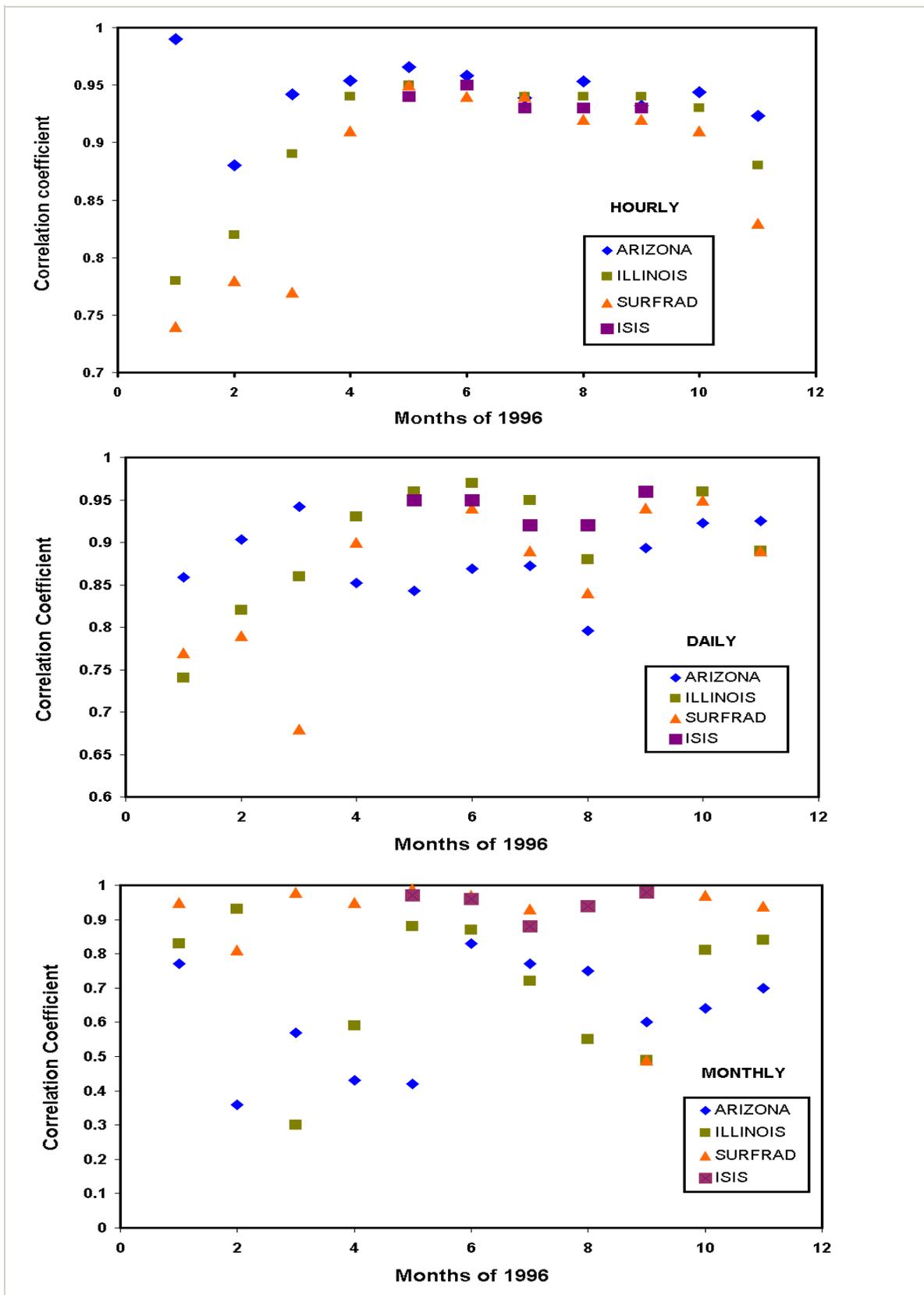


Figure 9. The rms and bias for the four groups of stations (Arizona, Illinois, SURFRAD, ISIS), on hourly, daily, and monthly time scales (above).

Figure 10. Same as above for the correlation coefficient (below).



Comparison of GCIP satellite-estimates of surface SW  
 downward flux ( $W/m^2$ ) with SURFRAD ground truth  
 at Bondville, Ill. at four temporal resolution  
 April 1996 (test1)

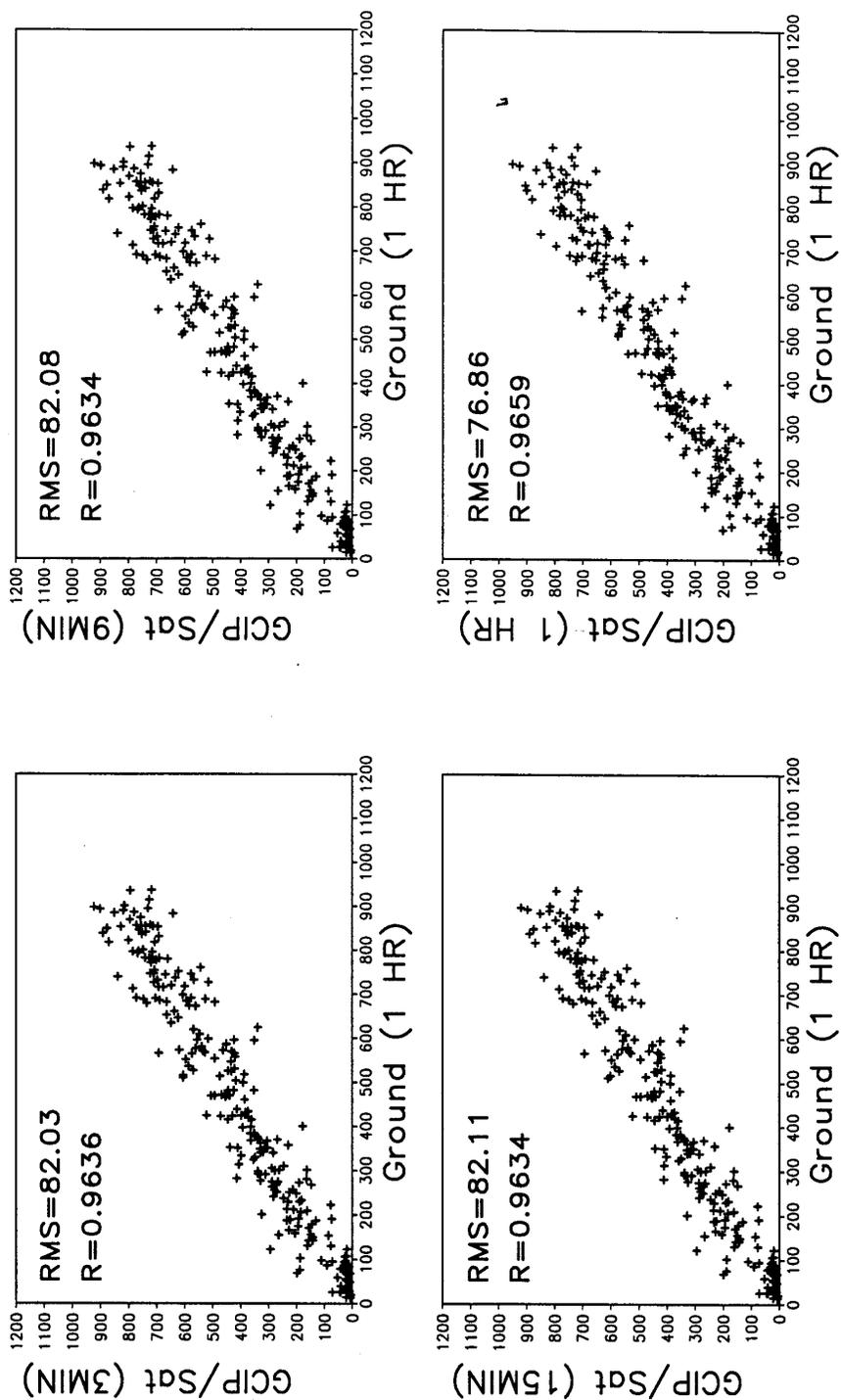


Figure 11a. Experiments in validation using different averaging of satellite observations

Comparison of GCIIP satellite-estimates of surface SW  
downward flux ( $W/m^2$ ) with SURFRAD ground truth  
at Bondville, Ill. at four temporal resolution  
April 1996 (test2)

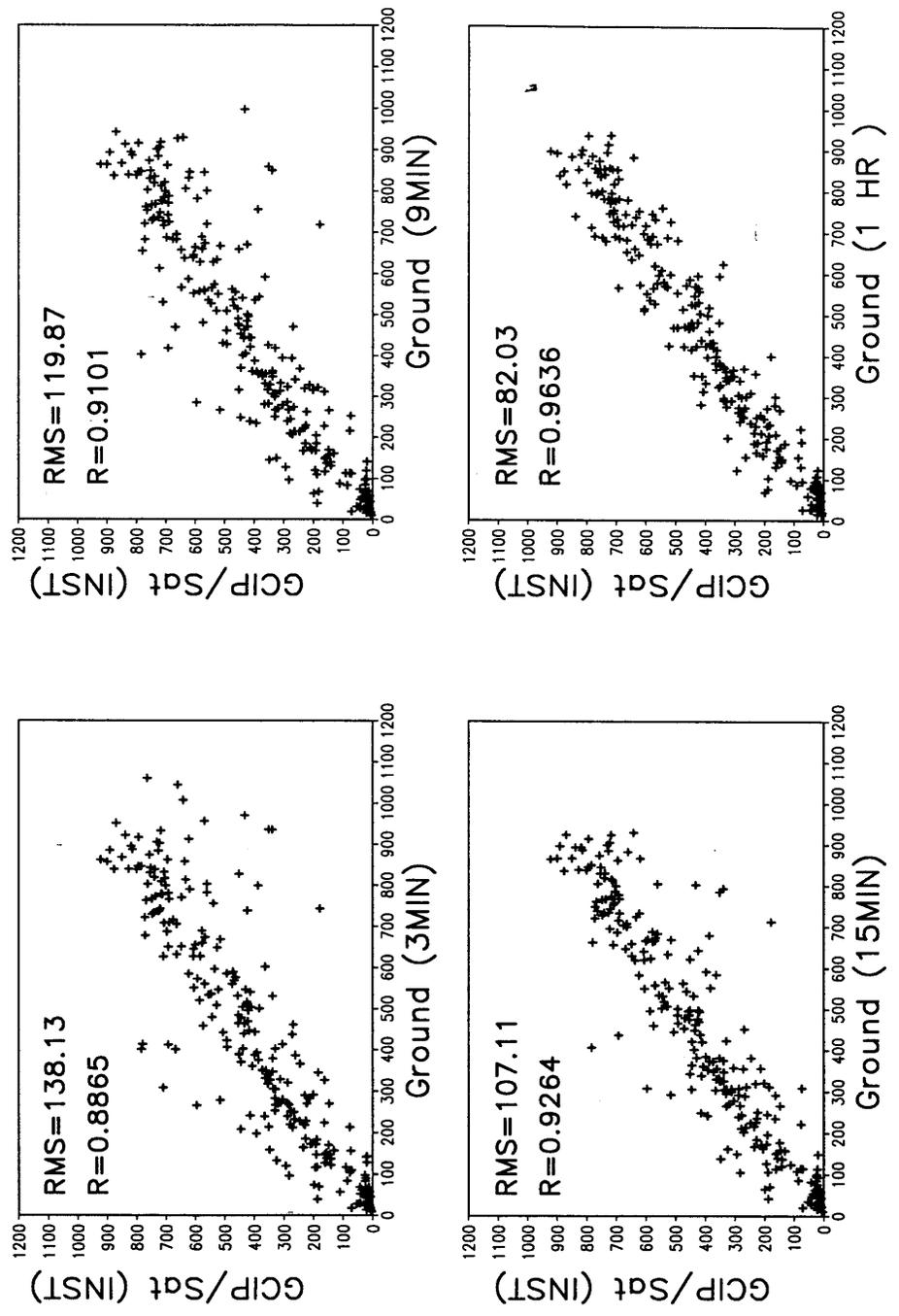


Figure 11b. Experiments in validation using different averaging of ground observations.

Bondville: Hourly SW Flux ( $W/m^{**2}$ )

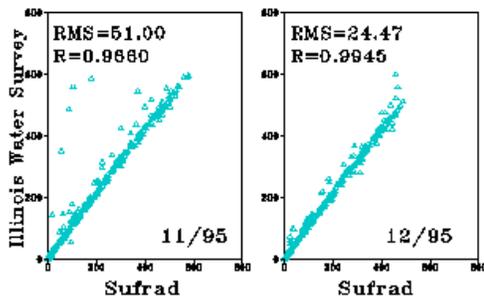


Figure 12a. Comparison of observations from two adjacent stations in Bondville, Illinois. One station belongs to the Illinois Water Survey and the other is a SURFRAD station.

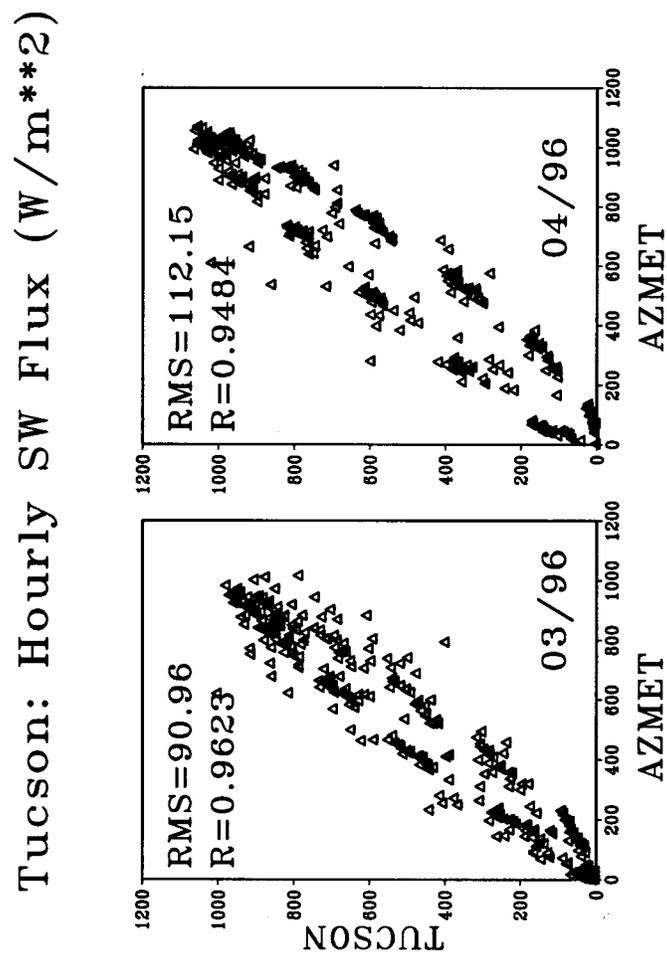


Figure 12b. Comparison of ground observations from two adjacent stations in Tucson, AZ. One station belongs to the AZMET network and the other is located on the Campus of the University of Arizona.

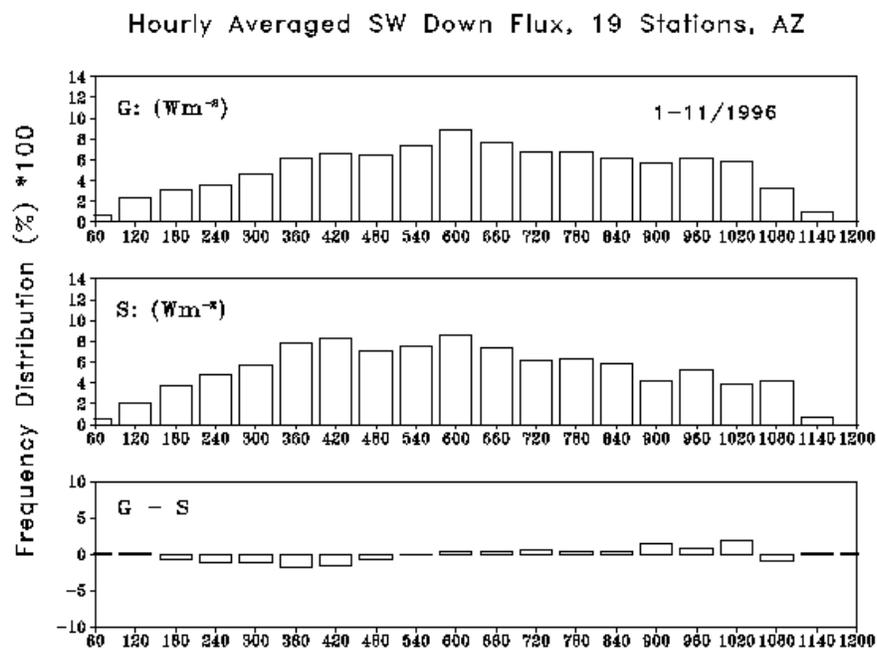


Figure 13a. The frequency distribution of the hourly averaged SW downward flux using observations made at all 19 AZMET ground stations and corresponding satellite estimates for eleven months of 1996.

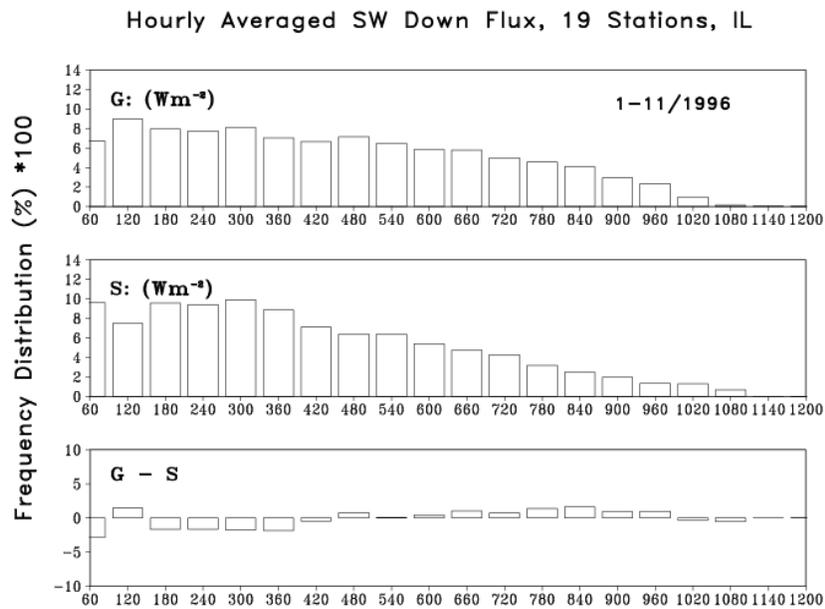


Figure 13b. The frequency distribution of the hourly averaged SW downward flux using observations made at all 21 Illinois ground stations and corresponding satellite estimates for eleven months of 1996.

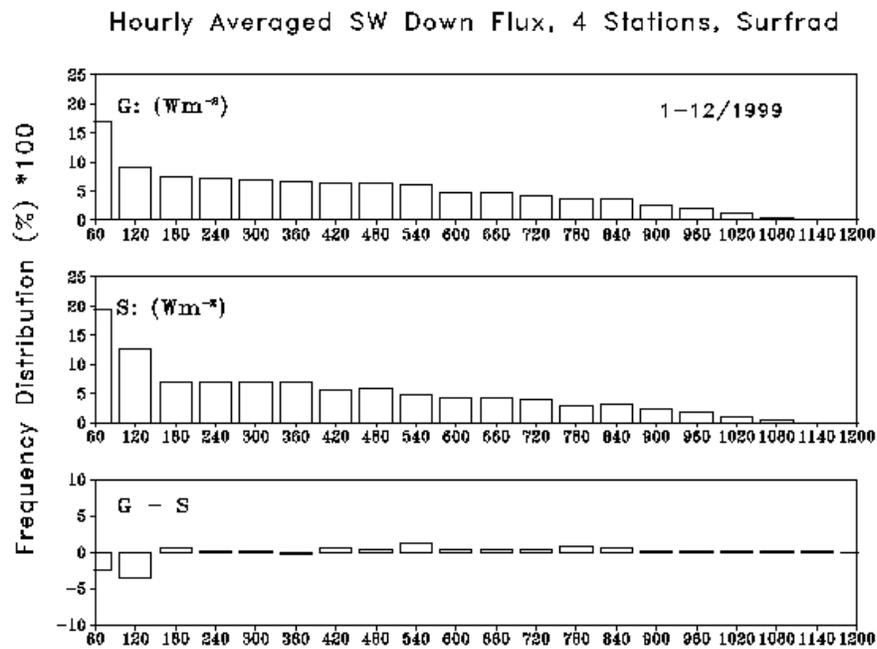


Figure 13c. The frequency distribution of the hourly averaged SW downward flux using observations made at four SURFRAD ground stations and corresponding satellite estimates for eleven months of 1996.

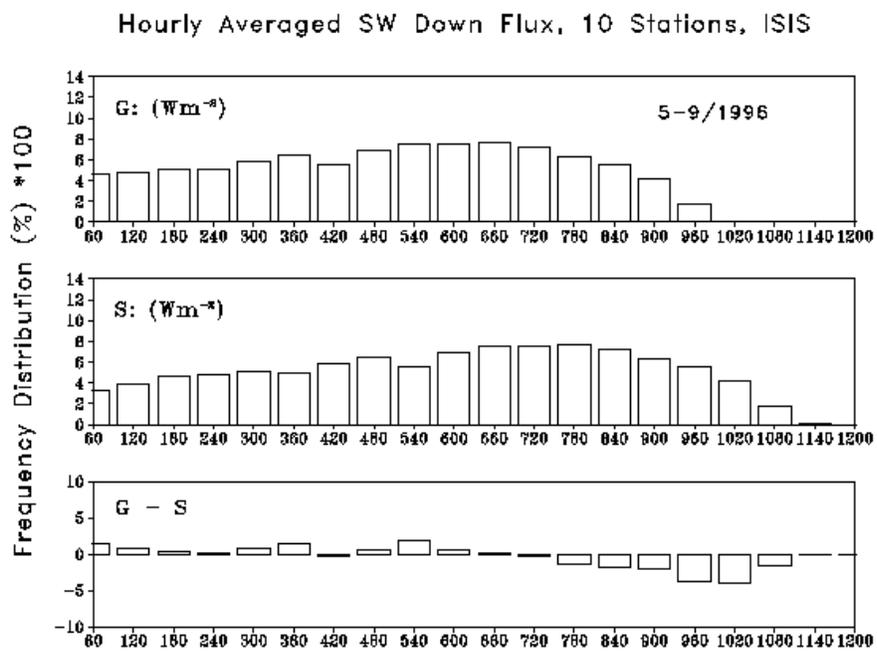


Figure 13d. The frequency distribution of the hourly averaged SW downward flux using observations made at all 10 ISIS ground stations and corresponding satellite estimates for five months of 1996.