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A Review of Satellite Methods to Derive Surface Shortwave Irradiance

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Shortwave radiative fluxes at the earth's surface are of primary interest in climate research because they control the total energy exchange between the atmosphere and the land/ocean surface. Information on these fluxes is needed on a global scale, and therefore, has to be obtained by methods of remote sensing from observations made with instruments carried on satellites. The primary objective of this paper is to review current capabilities and activities to infer these forcing functions from satellite observations and to discuss future needs. Discussed will be fluxes of downward surface shortwave radiation (DSSR) and net surface shortwave radiation (NSSR). Methods for deriving DSSR fluxes on a global scale are becoming operational. They are being used increasingly to address climate issues, such as in determining the role of solar forcing in oceanic and atmospheric processes, hydrological modeling, and in carbon cycling. Based on extensive comparisons with ground-truth it is believed that estimates of DSSR fluxes can be obtained within 20 Wm^{-2} or better on monthly time scales, for areas of an average climate model grid size. Methods for deriving NSSR fluxes seem promising, but need to be further evaluated.

INTRODUCTION

Background

In a comprehensive review paper by Sellers et al. (1990), a discussion of satellite algorithms suitable for use in studies of the land surface was presented. The review was based on presentations given at the International Satellite Land Surface Climatology Project (ISLSCP) Satellite Data Algorithm Workshop held in January 1987 at the Jet Propulsion Laboratory, Pasadena, California. A broad range of topics was discussed, such as the derivation of downward surface shortwave radiation (DSSR) fluxes, surface albedo, downward and upward surface longwave radiation fluxes, surface temperature, net surface all-wave radiation fluxes, vegetation index, and soil moisture. The present summary is based on presentations given at the ISLSCP Americas Workshop on Remote Sensing of the Land Surface for Studies of Global Change, held in June 1992 at Columbia, Maryland. It focuses on methods to derive DSSR and net surface shortwave radiation (NSSR) fluxes. Progress made since the previous workshop in method development, validation, and implementation is emphasized.

Motivation

Information on the surface radiation budget (SRB) is of interest to all "three streams" of the World Climate Research Program (WCRP) (WCP-115, 1986), namely extended range forecasting, interannual variability and decadal changes. It may be used to address various aspects of climate, such as providing climate models with information for improved description of surface/atmosphere interactions (Morel, 1985); separating the radiative impact of clouds into surface and atmosphere contributions (Cess and Vulis, 1989); and understanding the global hydrological cycle (WCRP-5, 1988). Information on SRB is also required to meet the goals of international research projects such as the Global Energy and Water Cycle Experiment (GEWEX) (WCRP-74, 1992), the GEWEX Continental-scale International Project (GCIP) (WCRP-67, 1992), the ISLSCP activity (Rasool and Bolle, 1984; Sellers et al., 1988; Asrar, 1990) and the International Geosphere-Biosphere Program (IGBP) (NAS/NRC, 1983; Moore, 1993).

Several independent activities contributed to recent progress. For example, global satellite data under initiatives like the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow, 1983) became

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available. The World Climate Research Program (WCRP) of the World Meteorological Organization (WMO) initiated activities aimed at improving the performance of climate models and satellite methods for deriving climate parameters (WCRP, 1987). The WCRP / International Council of Scientific Unions (ICSU) sponsored the Intercomparison of Radiation Codes in Climate Models (ICRCCM) (Luther et al., 1988; Fouquart et al., 1991). The WCRP Committee for Space Research (COSPAR) and the National Aeronautics and Space Administration (NASA) initiated an international activity on Satellite Algorithm Intercomparison (Whitlock et al., 1990a). The global satellite data adopted for the intercomparison activity are the ISCCP C1 data (Schiffer and Rossow, 1985). In 1988 the Joint Scientific Committee (JSC) Working Group on Radiative Fluxes (WGRF) recommended that the WCRP should establish a Baseline Network of Surface Radiation (BNSR) stations to provide validation data for satellite methods for estimating surface radiation budgets and for monitoring climate change. This activity is presently in progress (WCRP-54, 1991; Gilgen et al., 1993; Heimo et al., 1993). After a long period of testing, guided by the WCRP Working Group on Radiation Fluxes and the SRB Science Working Group, some of the DSSR models matured to a stage where they are now implementable with known limits of accuracy (Whitlock et al., 1993). In the next section an update on recent retrieval methods of DSSR fluxes and their global scale implementation is presented. In the third section an attempt to derive NSSR directly from top-of-the-atmosphere (TOA) observations are discussed. In the fourth section, issues of concern to all satellite methods are addressed. In the last section, the status of the current techniques is summarized and recommendations for future efforts are given.

RETRIEVAL OF DOWNWARD SURFACE SHORTWAVE RADIATION

Introduction

During the last decade significant progress has been made in developing methods to derive shortwave SRB parameters from satellite observations (Suttles and Ohring, 1986; Schmetz, 1991a,b; Whitlock et al., 1994a). This was possible due to insight gained during early attempts to derive DSSR fluxes from satellites. About three decades ago Fritz et al. (1964) reported a high correlation (0.9) between satellite observations of reflected solar flux at the TOA and ground observations of DSSR fluxes over the United States. The first quantitative estimates of these fluxes were obtained by Hanson (1971) and Ellis and Vonder Haar (1978). Subsequently, new methods were developed and applied with satellite data on different temporal and spatial scales. The methods span a large range of complexity, from simple statistical / empirical to theoretical / physical. Examples are the work of Tarpley (1979); Rimozi-Paal (1988); Gautier et al. (1980); Möser and Raschke (1984); Pinker and Ewing (1985); Dedieu et al. (1987); Le Borgne and Marsouin (1988); Darnell et al. (1988, 1992); Chou (1991); and Pinker and Laszlo (1992a). In parallel, relevant simulation studies were performed with implications for the development of satellite methods (Cess and Vulis, 1989; Chou, 1990). In the following sections, an update on the work done since the early 1990s is presented, as well as a summary of the current status and availability of global data sets of DSSR fluxes.

Recent Work on DSSR Fluxes

Most of the studies on the derivation of DSSR fluxes that were published in the early 1990s either describe slightly revised versions of models and techniques proposed in the late 1980s, implement these techniques with various satellite data and address climate issues, or are reviews of past and current work. Each type will be addressed separately.

Improved Techniques

To this category belongs the work of Stuhlmann et al. (1990), Bishop and Rossow (1991), Chou (1991), and Pinker and Laszlo (1992a). The essentials of the models described in these papers is given. A comparison of model outputs is not attempted since the models were applied at different times, locations, and were driven with different satellite data.

Stuhlmann et al. (1990) improved the model of Möser and Raschke (1984) to derive DSSR fluxes from METEOSAT data by accounting for multiple reflection between the surface and the atmosphere, which allows separation of the direct and the diffuse component of DSSR. The improved model was implemented with ISCCP B2 data and monthly mean climatologies of the state of the atmosphere, to produce DSSR flux estimates over Africa during 1985–1986. Isotropy of radiation at the TOA was assumed in the modeling. Tests against ground observations obtained from local stations and those available from the World Radiation Data Center in St. Petersburg (Leningrad), Russia indicated that the estimates were within 10% of ground observations on a monthly time scale. The Stuhlmann et al. (1990) model is presently used operationally by the German Weather Service (DWD).

Bishop and Rossow (1991) presented a "fast scheme" for computing DSSR fluxes over ocean and land using ISCCP C1 data. They showed that their method yields results within 6–10 Wm^{-2} from those obtained with a detailed radiative transfer code. In the model, clear and cloudy sky conditions are treated separately. For the clear sky case the formula of Frouin et al. (1989) is used, whereas for the cloudy case a spherical cloud albedo is introduced. The cloud albedo is derived from ISCCP C1 optical thickness at 0.6 μm. It is assumed that there is no wavelength dependence of cloud albedo over the solar band and that radiation is isotropic. For oceans, surface albedo is kept constant at 0.06; for land, surface albedos are set to ISCCP-derived values. For clear-sky cases, visibility, a measure of aerosol turbidity, is assumed to be 25 km.

Chou (1991) developed a simple scheme to infer cloud amount, optical thickness, and height from satellite measured radiances, for use in SRB studies. He applied the scheme to ISCCP B3 radiances (Schiffer and Rossow, 1985) and used it as input to a radiative transfer routine to compute, DSSR as well as NSSR fluxes for the tropical and subtropical western Pacific Ocean. He demonstrated that the net solar flux at the surface can be linearly related to the solar flux at the TOA, which is the basis of methods to retrieve NSSR directly (see the third section).

The method of Pinker and Laszlo (1992a), based on the earlier work of Pinker and Ewing (1985), will be discussed in the section entitled "The Method of Pinker and Laszlo," which deals with experimental semi-operational algorithms for global processing.

Scientific Applications

In several studies the usefulness or potential of satellite-based estimates of SRB for climate research has been demonstrated and a number of case studies dealing with special aspects of implementation and testing of satellite methods have been performed.

For instance, Rodriguez et al. (1990) utilized satellite inferred DSSR fluxes from ISCCP C1 data for July 1983–December 1984, to study radiative effects in the equatorial Pacific Ocean. A 30–60 day Madden / Julian oscillation (Madden and Julian, 1972) was observed in the DSSR time series, believed to be associated with the propagation of convective activity and related to the 1982 / 83 ENSO.

Gautier and Frouin (1992) investigated net surface solar irradiance variability in the central equatorial Pacific during 1982–1985 between 4.6°N to 7.4°S and 142.6° to 117.1°W, using data from geostationary satellites for about 10 days for each month. They found that the monthly mean fields confirm the El Niño's effect on the net irradiance, in particular, during January–March 1983, by reducing the solar irradiance at the equator by more than 150 Wm^{-2}. They applied an empirical orthogonal function analysis on the monthly fields, to identify the main forcing periods for the study area.

Darnell et al. (1992) described surface radiation budgets for the mid-season months of July and October 1983 and January and April 1984, using ISCCP C1 and Earth Radiation Budget Experiment (ERBE) data (Barkstrom, 1984), both for shortwave and longwave fluxes. Their error analysis showed strong sensitivity to uncertainties in the input data.

Pinker and Laszlo (1992b) derived DSSR fluxes over the Amazon Basin for four July months (1983–1986) using observations from the AVHRR instrument on the polar-orbiting satellites and observations from the geostationary satellite GOES, at the ISCCP B3 resolution. They assessed the magnitude of interannual DSSR variability and showed the effect of El Niño on the patterns of temporal variability over the Amazon Basin, which may be linked to changes in convective activity.

Campana et al. (1992) presented a comparison between the National Meteorological Center (NMC) forecast-model (Kalnay et al., 1990) and satellite-retrieved DSSR fluxes at the surface and at the TOA, as derived with the model of Pinker and Laszlo (1992a), driven with the ISCCP C1 data. Results of the comparison indicated that the NMC model gives higher monthly means of DSSR by about 50-100 Wm^{-2} over land and about 50 Wm^{-2} in the Inter-Tropical Convergence Zone (ITCZ), as well as over mid-latitude / polar oceans. Values were about 50-100 Wm^{-2} lower in the marine stratus regions off the west coasts of the continents. Much of the effects reported could be attributed to differences between NMC model clouds and "true" clouds. The NMC model global mean cloud fraction is 0.4 (Campana et al., 1990), although published climatologies report values of 0.5-0.6. Efforts are currently underway to tune the stratiform clouds in the NMC model, using the daily cloud analysis as produced by the U.S. Air Force (Campana, 1990).

Laszlo and Pinker (1992) investigated the role of clouds in modulating shortwave radiant energy available at the surface, at the TOA, and in the atmospheric column, using ISCCP C1 data for the month of July for years 1983 to 1985. They found that the cloud forcing at the surface was almost identical to that at the TOA, indicating that the effect of clouds on the shortwave energy budget of the surface–atmosphere system is such that most of the cooling is at the surface.

Many types of case studies were undertaken. For instance, Chou et al. (1992) calculated the DSSR flux in an arid region using radiative transfer computations coupled with satellite cloud retrievals. They provided evidence that the large discrepancies found between observed and measured values might be attributed to the lack of information on aerosols, uncertainty in cloud retrievals, and temporal differences between surface and satellite measurements. Dubayah (1992) presented a method to estimate net solar radiation using Landsat thematic mapper and digital elevation data to model spatial variability in net solar radiation at fine spatial resolution, as applied to the 16 × 16 km Firsts ISLSCP Field Experiment (FIFE) site (Sellers et al., 1992). The results showed the importance of topographic effects on the modulation of net solar radiation even over gentle terrain.

Pinker et al. (1994) derived DSSR fluxes from GOES

7 over a basin scale water shed of 10 × 15 km and demonstrated that even under highly variable cloud conditions, the satellite estimates of daily means were within 10% of measured values whereas 5-day means were within 3% of measurements.

Review Articles

Several review papers on the topic of surface radiation budget retrieval were published recently (Schmetz, 1989, 1991a, 1991b; Katsaros, 1990). Schmetz explained the rationale for the success of the methodologies to derive DSSR fluxes, and assembled information on the accuracies of the various methods. His estimate for the standard error for monthly means is about 5%. Based on his theoretical simulations he concluded that in the 0.3–0.4 μm region there is a strong linear coupling between the solar radiation field observed by the satellite and the radiation field at the surface, and that the methods to estimate DSSR are sufficiently accurate for useful operational retrievals. He also pointed out that the 'direct' retrieval of the solar net flux (see the third section) is subject to similar uncertainties as the individual retrievals of both the downward and upward solar components. The review of Katsaros (1990) is comprehensive in scope; it deals with conventional as well as satellite methods to derive both shortwave and longwave fluxes at the surface, to enable the estimation of heating and cooling of the sea due to these fluxes. Possible sources of error in these estimates, both on monthly and hourly time scales are discussed, primarily those due to calibration, navigation, and difficulties in matching satellite and ground observations. It is stated that the DSSR flux can be estimated from geostationary satellite radiances to about 10% for daily averages. The satellite methods that were reviewed are those available till 1988.

Current Semi-Operational Methods for DSSR Fluxes

An SRB climatology project was established under WCRP, following recommendations made by numerous groups of scientists, as summarized in Suttles and Ohring (1986). Since 1986, a number of satellite methods to estimate shortwave and longwave fluxes have been tested under this activity, using data from special field experiments [e.g., Wisconsin / FIRE; (Starr, 1987)] and global satellite data sets (Schiffer and Rossow, 1985). Evaluation of the results has been done by two international groups, namely, the SRB Science Working Group (SRB / SWG) and the WCRP Working Group on Radiative Fluxes (WCRP / WGRF). A number of algorithms for DSSR fluxes have been shown to be accurate within 10 Wm^{-2} under ideal conditions, when satellites are well calibrated (Whitlock et al., 1990a). Results from experimental global processing with ISCCP C1 data with some of the existing techniques have led to the selection of two methods for use in processing long-term satellite data as an interim product for the period March 1985–November 1988, when the ISCCP C1 data are considered most accurate. These data are being produced at the SRB Satellite Data Analysis Center (SDAC) at NASA / Langley Research Center and are distributed to interested scientists for use in climate studies (Whitlock et al., 1993, 1994a). In what follows, the two methods that are currently used at SDAC to generate global data sets are described in some detail. For more information on model implementation the reader is referred to Whitlock et al. (1993).

The Method of Staylor

The method of Staylor for deriving DSSR fluxes at the surface is based on a modified version of a model described by Darnell et al. (1988) and subsequently implemented by Darnell et al. (1992). The model is tuned and is parameterized / physical in nature; it uses a broadband approach in which daily DSSR flux at the surface for all sky conditions, DSSR, is expressed as the product of DSSR at the TOA, $DSSR_{TOA}$, clear-sky atmospheric transmittance, T_A, and cloud transmittance, T_C, namely:

$$DSSR = DSSR_{TOA}\, T_A T_C \qquad (1)$$

Attenuation due to water vapor, ozone and Rayleigh scattering is parameterized according to Lacis and Hansen (1974); absorption due to carbon dioxide and oxygen is approximated according to Yamamoto (1962). Attenuation due to aerosols is parameterized based on models presented in WCRP (1983).

Cloud transmittance, T_C, is determined based on a threshold technique

$$T_C = 0.05 + 0.95(R_{ovc} - R_{meas}) / (R_{ovc} - R_{c\ell r}) \qquad (2)$$

where R_{ovc} and $R_{c\ell r}$ represent extreme TOA reflectance values determined for each C1 box (250 × 250 km) and each month. The R_{meas} value is the daily TOA reflectance obtained from the 3-hourly values. This procedure has the advantage of making the algorithm "self calibrating," because it adjusts monthly the radiance of each ISCCP satellite to conform to a directional model for highly reflecting clouds, using ISCCP reported optical depth of 80 or larger. Because of uncertainties in the ISCCP calibration, this technique will sample different highly reflecting clouds, and as such, can introduce errors. This procedure makes the method obviously less dependent on the "absolute" calibration of the satellite instruments.

The Method of Pinker and Laszlo

The method of Pinker and Laszlo (1992a) is based on radiative transfer theory, and produces direct and diffuse fluxes in five spectral intervals in the range of 0.2–4.0 μm, both at the TOA and at the surface. The radiative transfer model accounts for the absorption and scattering processes occurring in the atmosphere and for the interaction of radiation with the surface. The radiative fluxes at the boundaries of the atmosphere are computed by determining the atmospheric transmission and reflection (optical functions) and the surface albedo pertaining to a particular satellite observation.

First the spectral surface albedos are derived from satellite measured values of TOA radiances representing average clear sky conditions. Once the surface albedo is determined, the optical functions for instantaneous clear and cloudy conditions are obtained by matching the broadband TOA albedos, derived from the clear and the cloudy radiances of the ISCCP C1 data, respectively, with TOA albedos computed by the radiative transfer model of the surface-atmosphere system. The retrieved optical functions, along with the surface albedos are then used to compute the fluxes for clear ($DSSR_{clear}$) and cloudy ($DSSR_{cloudy}$) conditions. The all-sky flux, $DSSR_{all}$, is obtained by using information on cloud cover:

$$DSSR_{all} = \frac{(n_{clear}DSSR_{clear} + n_{cloudy}DSSR_{cloudy})}{(n_{clear} + n_{cloudy})}, \quad (3)$$

where n_{clear} and n_{cloudy} are the number of clear and cloudy pixels used to compute the mean clear and cloudy C1 radiances. The ISCCP C1 data provide most of the needed information: type of satellite used and clear / cloudy scene identification. Categorizations of surface scenes (ocean, land, desert, and snow) is based on the work of Matthews (1985). As an example for obtainable results, the DSSR fluxes for July 1983, 1984, and 1985 are displayed in Figure 1. The ability of the model to compute fluxes at both boundaries of the atmosphere allows to compare the TOA fluxes with independently derived estimates from other available satellite observations (Figure 2). The zonally averaged differences in DSSR fluxes computed with the methods of Staylor and Pinker and Laszlo (1992a) are given in Figure 3. For regions below 60°N or 60°S, differences do not exceed 30 Wm^{-2} in magnitude. At high latitudes the differences are larger because of different sources of information on snow that were used in model implementations. Additional model comparisons can be found in DiPasquale and Whitlock (1993) and Whitlock et al. (1994a).

RETRIEVAL OF NET SURFACE SHORTWAVE RADIATION

Introduction

The net surface shortwave radiation is defined as the difference between the downwelling and the upwelling shortwave radiation fluxes. In principle, the SSNR can be estimated from independent satellite retrievals of DSSR as reviewed in the section entitled "Retrieval of downward surface shortwave radiation," and of surface albedos, a_s derived by methods as discussed for example in Pinker (1985); Pinty and Ramond (1987); Gutman (1988); Barker and Davis (1989), Arino et al. (1991) and Nacke (1991), expressed as:

$$NSSR = DSSR(1 - A_s) \quad (4)$$

Such an approach was followed by Raschke and Preuss (1979) to generate the first maps of monthly mean NSSR on a global scale. In this component-by-component approach, errors in each retrieved parameter can accumulate (Cess and Vulis, 1989; Sellers et al., 1990). Moreover, the surface albedo from satellites is generally determined from clear-sky radiances; this limits the ability to monitor temporal variability (Cess et al., 1991; Schmetz, 1991a, 1991b). Knowledge of surface albedo is also a prerequisite for the determination of DSSR fluxes from satellites. Therefore, an error in surface albedo could lead to an error in DSSR flux estimates as well as in NSSR estimates under both clear and cloudy conditions. An alternative approach would be to deduce the NSSR directly from satellite observations at the TOA.

Review of Recent Work on Retrieval of NSSR Fluxes

Early attempts to relate directly radiation fields at the TOA to those at the surface were made by Pinker and Corio (1984). They found that the TOA net (all wave) radiation as observed by the polar orbiting satellite NOAA5 and the observed / modeled surface net radiation are strongly correlated. Pinker et al. (1985) and Pinker and Tarpley (1988) derived the daily net radiation at the TOA from GOES-E observations over ground targets in Canada and the U.S.A. where net radiation was observed. The daily average net radiation at the TOA was again found to be highly correlated to the daily average net radiation at the surface. Subsequently, Laszlo and Pinker (1994) investigated the relationship between shortwave net radiative fluxes at the TOA and at the surface using relationships determined from equations describing the transfer of solar radiation in the atmosphere. It was found that the relationship between surface and TOA fractional absorption is very closely linear. Changing amount of water vapor and aerosol induced the largest departure from linearity. Weare (1989) used outputs from the UCLA GCM and showed that monthly anomalies of net radiation at the earth's surface are linked to net radiation at the top of the atmosphere and that the statistical relationship was independent of geographical location.

Based on results from a climate model, Ramanathan (WCP-115, 1986) found a simple linear relationship between the net solar flux at the TOA and at the surface. Following, various methods have been developed aimed at the determination of NSSR directly from satellite observations at the TOA. The basic principle of these methods is the fact that atmospheric absorption remains relatively constant when compared to the variability of the radiation absorbed at the surface or the TOA.

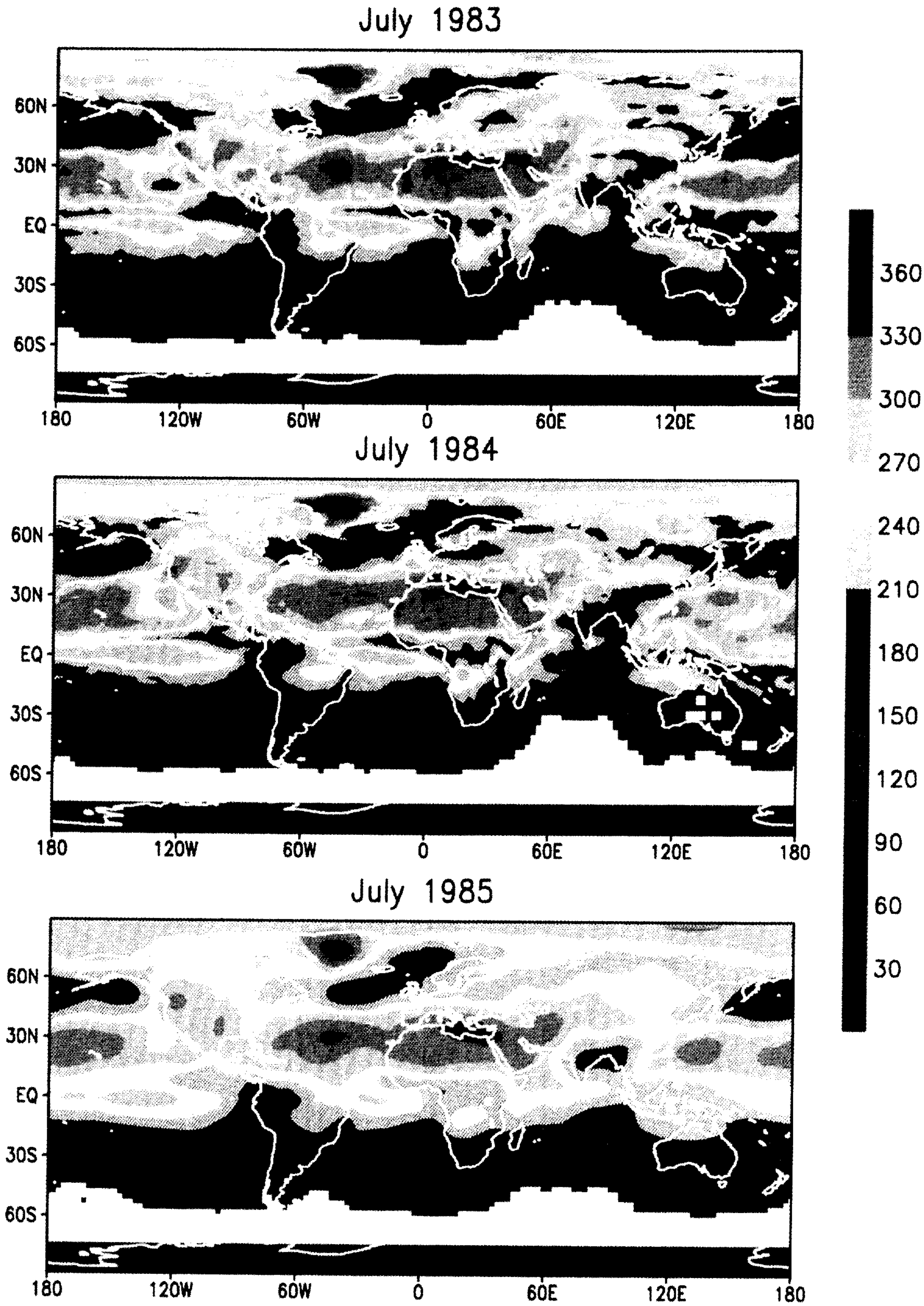

Figure 1. Monthly mean distribution of DSSR flux in Wm^{-2} as derived from ISCCP C1 data with the model of Pinker and Laszlo (1992a) for July 1983, 1984, and 1985.

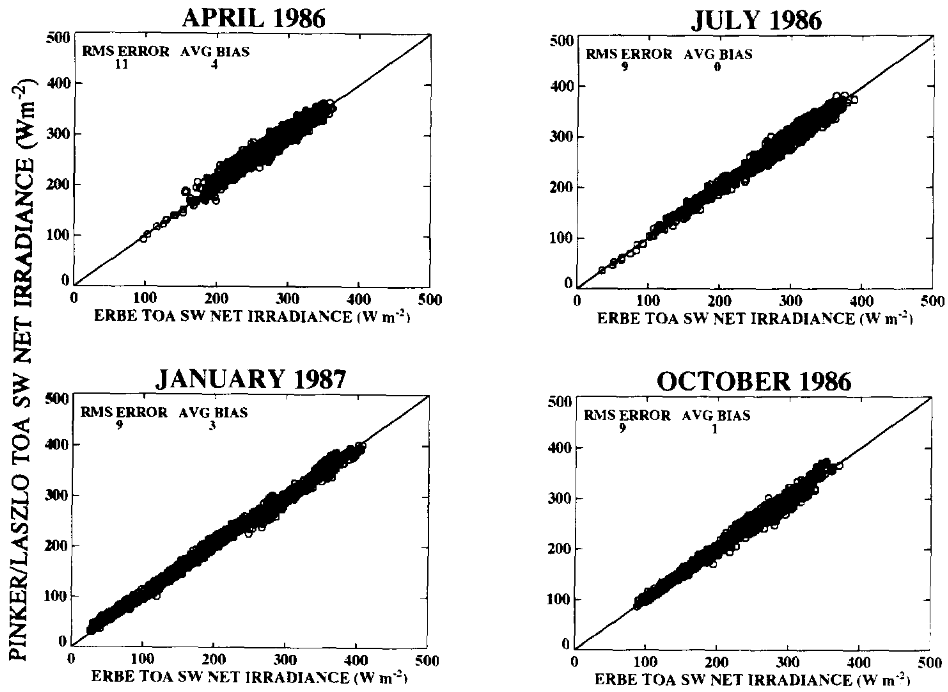

Figure 2. Comparison of net shortwave fluxes at the TOA as derived from ERBE and from ISCCP C1 with the model of Pinker and Laszlo (1992a) for April 86, July 86, October 86, and January 87.

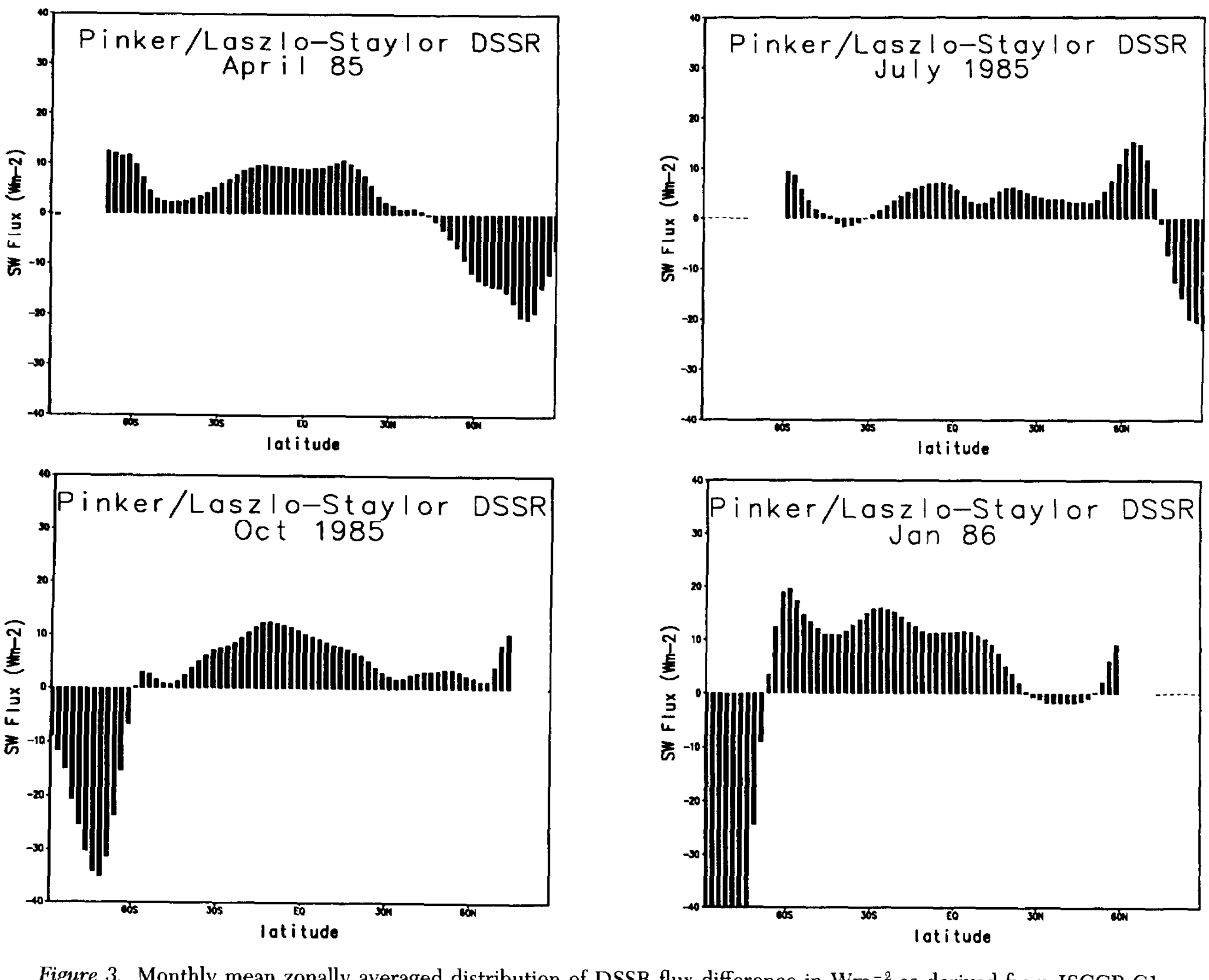

Figure 3. Monthly mean zonally averaged distribution of DSSR flux difference in Wm^{-2} as derived from ISCCP C1 data with the models of Staylor (Whitlock et al., 1993) and Pinker and Laszlo (1992a) for April 85, July 85, October 85 and January 86.

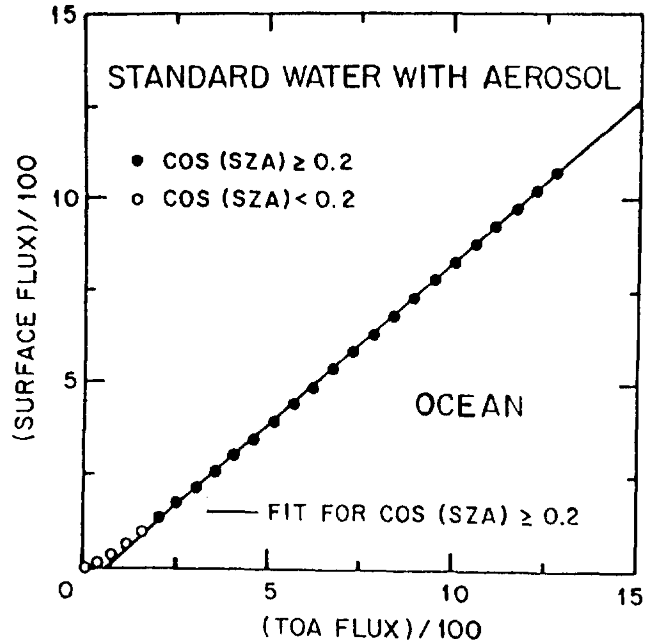

Figure 4. NSSR flux versus TOA NSSR as simulated by a radiative transfer model over the ocean surface. Solar zenith angles (SZA) range from 0° to 90° (Cess and Vulis, 1989).

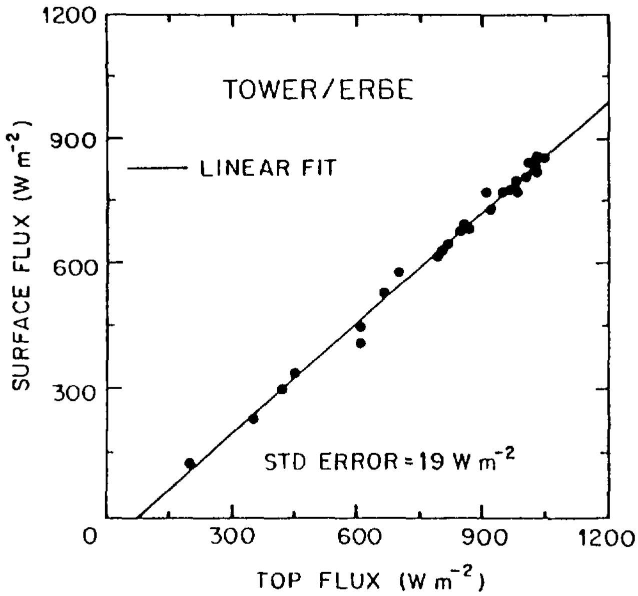

Figure 5. Relationship between NSSR flux measured at a tower located near Boulder, Colorado versus TOA NSSR flux as obtained from ERBS for clear skies (Cess et al., 1991).

These observed and derived linear relationships were further investigated by Cess and Vulis (1989) using radiative transfer calculations. They showed for various surface and atmospheric conditions that there is an almost linear relationship between the net fluxes at the TOA and at the surface for different solar zenith angles (SZA) except when the SZA is very large (Figure 4). The usefulness of a linear relationship for inferring the NSSR fluxes from net solar fluxes at the TOA was further illustrated by Cess et al. (1991). They related collocated and simultaneous measurements from pyranometers mounted on a tower located in Boulder, Colorado and satellite observations from the Earth Radiation Budget Satellite (ERBS), one of the three spacecrafts of the Earth Radiation Budget Experiment (ERBE) (Figure 5). They found that a linear slope-offset algorithm can retrieve the NSSR flux quite well for clear skies at a specific location, whereas a modest negative bias error was produced by applying the same clear sky algorithm to cloudy skies. The negative bias can be attributed to the fact that the relationship did not account for the effects of clouds, solar zenith angle (SZA), and surface albedo on atmospheric absorption. Chou (1989, 1991) demonstrated that the SZA has significant influence on the relationship between the net shortwave fluxes at the TOA and at the surface. Schmetz (1993) investigated the effects of cloud optical thickness and cloud top altitude on such linear relationship and found that a formulation that does not account for the above effects is unable to accurately estimate the NSSR fluxes. He proposed a simple parameterization using the SZA and vertically integrated water vapor content, or precipitable water, to compute clear-sky atmospheric absorption. Similarly, Chertock et al. (1991, 1992) and Frouin and Chertock (1992) developed parameterizations to compute all-sky atmospheric absorption, from which they derived DSSR at the ocean surface, using Nimbus-7 wide-field-of-view planetary albedo as input parameter. Because cloud optical thickness strongly modifies both planetary albedo and atmospheric absorption, a priori knowledge of planetary albedo could be used to estimate the influence of clouds on atmospheric absorption by radiative transfer modeling (e.g., Pinker and Laszlo, 1992a). A linear relationship between planetary albedo and atmospheric absorption was also noted by Schmetz (1984, 1989) from Monte Carlo calculations and by Rawlins (1989) from aircraft measurements.

Frouin and Chertock (1992) computed the NSSR fluxes as the difference between the DSSR fluxes at the TOA and the sum of the solar irradiance reflected back to space by the earth-atmosphere system (measured) and the solar irradiance absorbed by atmospheric constituents (modeled). The solar irradiance model assumes plane-parallel theory and isotropy of the radiance reflected by the surface and clouds. An underlying assumption is that the effects of clouds and of the clear atmosphere can be decoupled. The planetary atmosphere is therefore modeled as a clear-sky atmosphere positioned above an effective cloud layer. An advantage of such a model is that clear and cloudy regions within a pixel do not need to be distinguished.

The algorithm was applied to ERB WFOV planetary albedo data to produce monthly means of NSSR fluxes

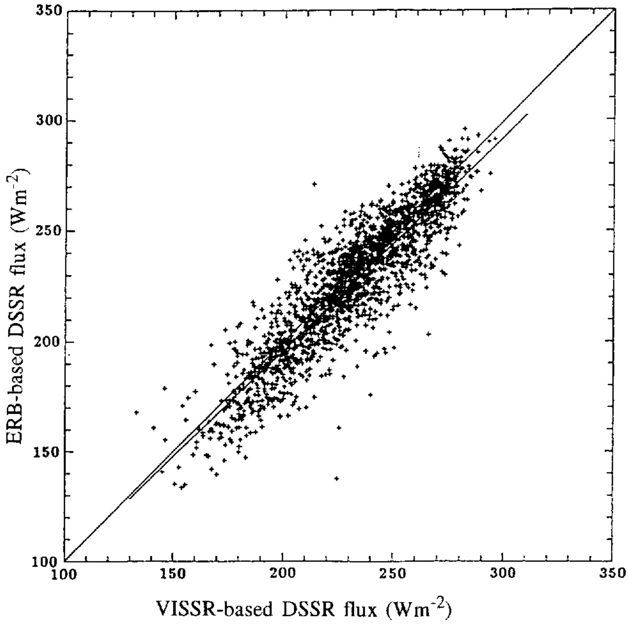

Figure 6. ERB-based versus VISSR-based estimates of NSSR flux over the Tropical Pacific (Chertock et al., 1992).

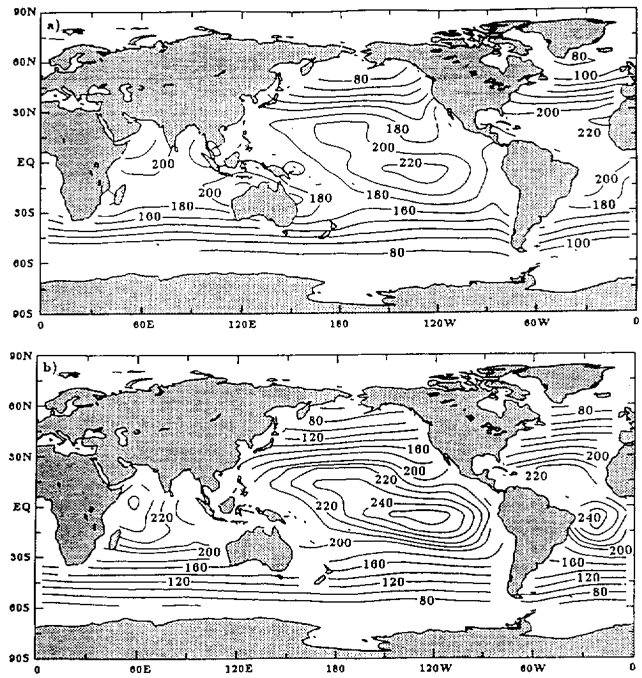

Figure 7. Long-term annual mean NSSR flux (Wm^{-2}) (a) after Esbensen and Kushmir (1981) and (b) computed from 7 years of ERB planetary albedo data (Chertock et al., 1992).

over the global oceans on a 9° latitude-longitude grid for November 1978–October 1985. The ERB-based NSSR flux estimates were compared with those of short-term, regional, high-resolution, satellite-based records (Chertock et al., 1992); Figure 6 shows typical results. Errors were found to lie between 10 and 20 Wm^{-2} on a monthly time scale. The ERB-based results, in the form of 7-year averages, were further compared to the ship-based climatology of Esbensen and Kushnir (1981). Both climatologies were found to exhibit the same typical gradients and large-scale features, but in general the ERB-based values remained higher, especially in the Atlantic (Figure 7). Chertock et al. (1991) demonstrated the ability of the derived NSSR fields to reveal large-scale seasonal and interannual phenomena, such as El Niño.

Bréon et al. (1993) generalized the algorithm of Chertock and Frouin (1992), which was designed for use over oceans. They distinguish now four surface types (ocean, vegetation, snow / ice and desert). The algorithm of Bréon et al. (1993) was applied to ERBE planetary albedo data (version S-4). Over the tropical Pacific the derived estimates based on ERBE compared well with those obtained from ISCCP B3 data. For the 9 months analyzed, the linear correlation coefficient and the standard difference between the two data sets were 0.95 and 14 Wm^{-2}, respectively. The bias, about 15 Wm^{-2}, was a strong function of ISCCP satellite viewing angle.

Li et al. (1993a) performed comprehensive radiative transfer calculations for over 100 combinations of different surface types (e.g., ocean, land, desert, snow / ice), cloud types (St, Sc, Cu, Ci) and atmospheric conditions for each SZA. The simulations were done with a doubling-adding model (Masuda and Takashima, 1990) as applied to a plane-parallel vertically inhomogeneous atmosphere-surface system in nine vertical layers and 108 wavelengths. The results of these simulations served as a database for the development of an algorithm used in their studies. In Figure 8a the relationship between the reflected flux at the TOA and the NSSR flux for clear skies over the ocean surface and different stages of snow / ice surface conditions are presented. For a particular SZA the relationship between the fluxes and the surface albedo is linear. For a given TOA reflected flux and SZA, there is a unique value of the NSSR flux. They claim that knowledge of the nature of the surface is thus unnecessary for the retrieval of the SSNR from satellite observations. A similar result is found for cloudy skies (Fig. 8b). Again, for fixed SZAs, the points corresponding to cloud optical thickness varying from 0 to 40 lie along parallel straight lines. This would indicate that information on cloud optical thickness is not needed in order to estimate the NSSR flux. A parameterization was developed in which the NSSR flux normalized by the irradiance incident at the TOA is related to the local planetary albedo, r, as follows:

$$\text{NSSR} / \text{DSSR TOA} = \alpha(\mu,p) - \beta(\mu,p)r. \qquad (9)$$

In Equation 9, the slope and intercept of the relationship are parameterized as functions of the cosine of

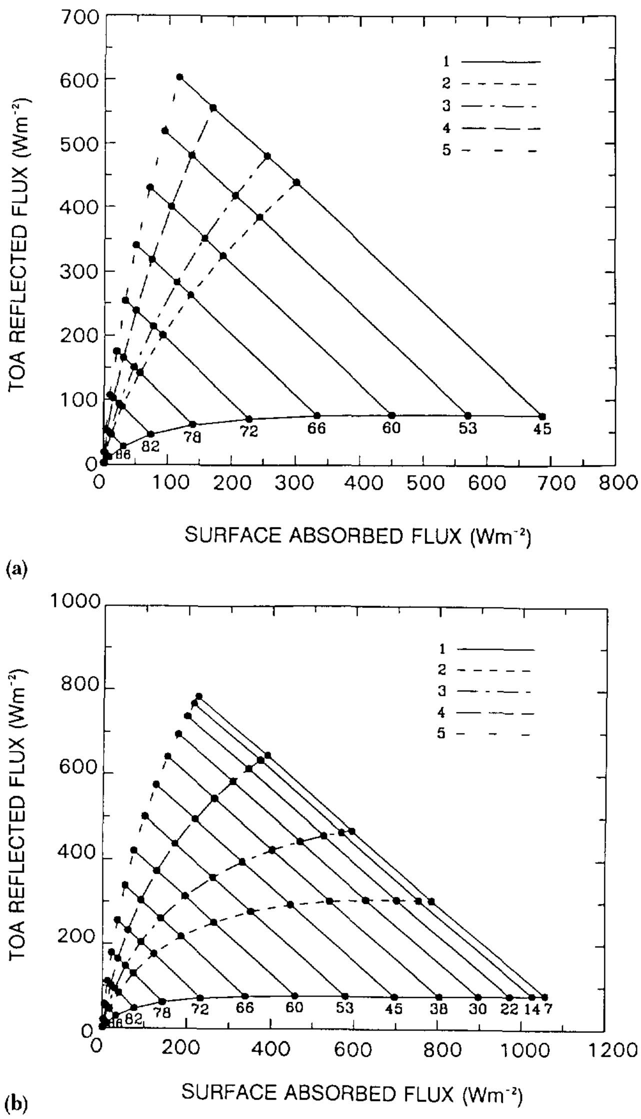

Figure 8. Relationship between NSSR and reflected flux at the TOA for (a) clear sky, and (b) cloudy sky. Curves 1–5 in (a) represent simulation results for ocean, melting, near melting, aging and fresh snow surfaces under clear sky condition (a), and for cloud optical depths of 0, 5, 10, 20, and 40 for Sc clouds over ocean (b) (Li et al., 1993a).

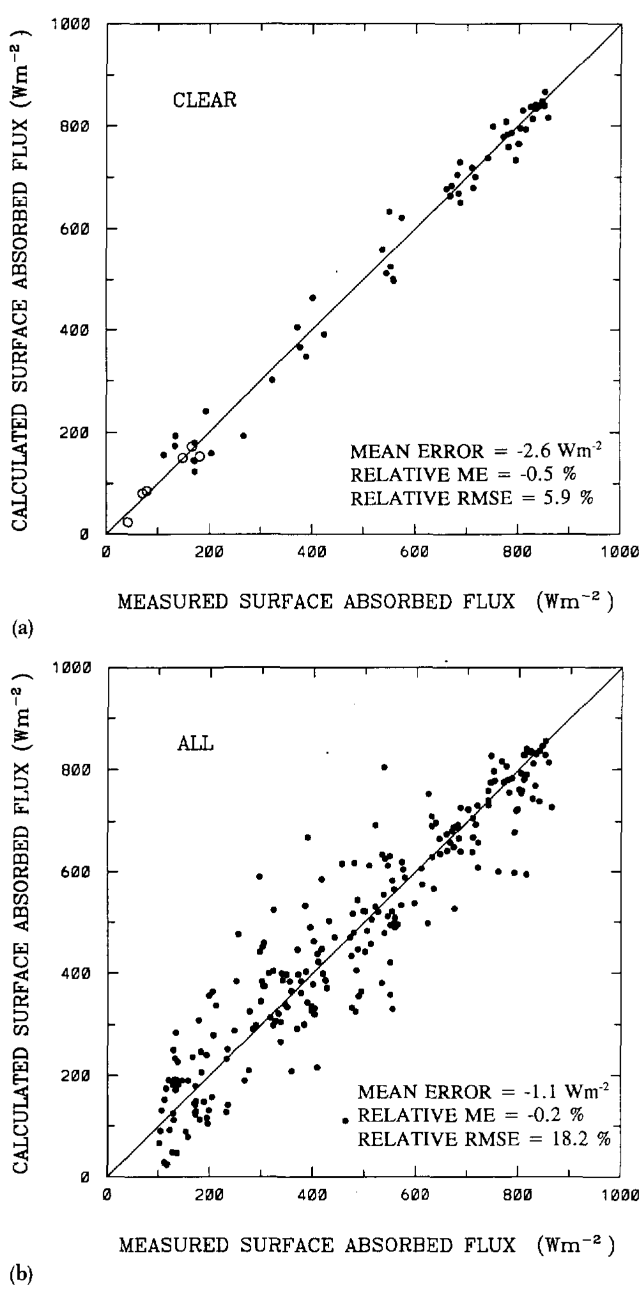

Figure 9. Comparison between NSSR as estimated from ERBS and as measured at two towers for (a) clear sky, and (b) all sky. For (a) data were available from a tower located in Boulder, Colorado, (solid points) during summer, and a tower in Saskatoon, Saskatchewan, Canada (open points) during winter. All-sky comparison includes the Boulder tower data only (Li et al., 1993b).

the SZA, μ, and precipitable water, p, to explicitly account for their effects on atmospheric absorption (Li et al., 1993a).

Independent tests of the algorithm were conducted using collocated satellite observations of the TOA reflected fluxes from Earth Radiation Budget Satellite (ERBS) and surface observations of the NSSR flux from two towers, one (BAO) located in Boulder, Colorado (Cess et al., 1991, 1993), the other near Saskatoon, Saskatchewan (Li et al., 1993b).

Figure 9a shows comparisons of the NSSR flux estimated from satellite observations and measured at the two towers for clear skies. Hourly means of ground data are used in the comparisons. For the period considered, April–September 1986 and July 1987, the agreement at both towers is good, and suggest, as predicted by theory, that the algorithm is insensitive to surface conditions. The relatively large scatter in the BAO data could be due to temporal differences between satellite and tower measurements. Comparisons for all-sky conditions

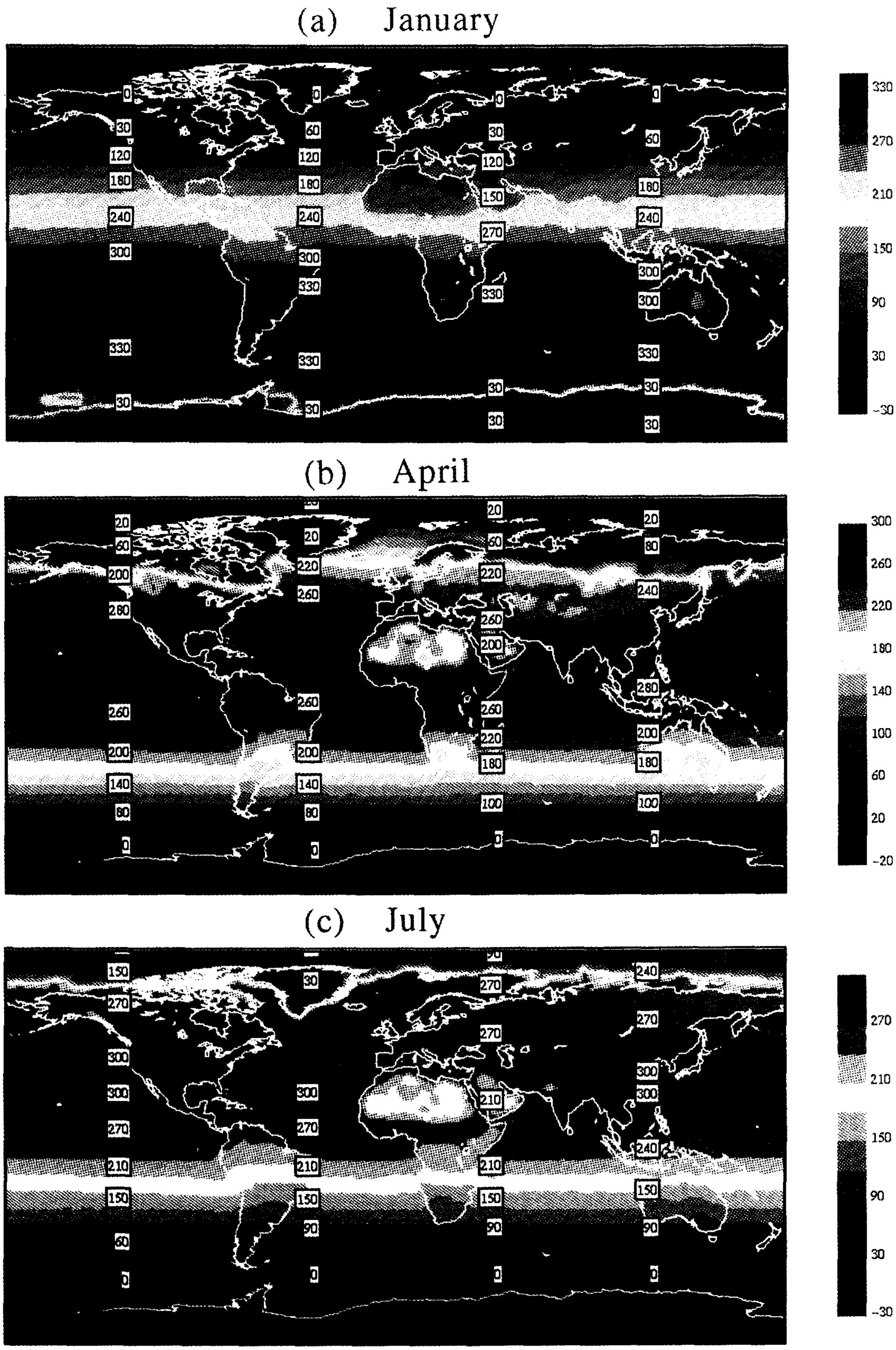

Figure 10. Global distribution of all-sky monthly mean NSSR fluxes for: (a) January, (b) April, and (c) July. The January and April cases are for 1986–1988 and 1985–1988, respectively, and the July case is for 1985, 1986, 1988. ERBE data for 5 years are available from the ERBS which does not cover polar regions.

using the clear sky algorithm are as good as for clear skies in terms of mean difference (Fig. 9b), suggesting that the parameterization is applicable to both clear and cloudy skies. The scatter is, however, larger under cloudy conditions. This is mainly due to collocation errors that are particularly larger when horizontally inhomogeneous clouds or broken clouds are present.

The algorithm has been used with ERBE and ECMWF data to generate a global climatology of the monthly mean surface radiation budget at 2.5° latitude-longitude grid for 1985–1989 (Li and Leighton, 1993). The ERBE data used are the monthly mean TOA albedo from the regional, zonal, and global average product (S-4).

Figure 10 shows the distributions of the NSSR flux for all sky conditions. Note that the NSSR flux is modified considerably by clouds, as well as by irradiance at the TOA and the surface albedo. The largest values are associated with subtropical highs over oceans with magnitudes larger than 300 Wm^{-2} in January, 260 Wm^{-2} in April, and 270 Wm^{-2} in July. The relative minima correspond to major cloud systems such as the ITCZ in the tropics, the summer monsoon over India, the stratocumulus clouds off the coast of California, and the low pressure over southwest China.

The estimated monthly means of the SNNR are validated against the Global Energy Balance Archive (GEBA) data (Ohmura and Gilgen, 1993) that include measurements of DSSR (Li et al., 1994). Because surface

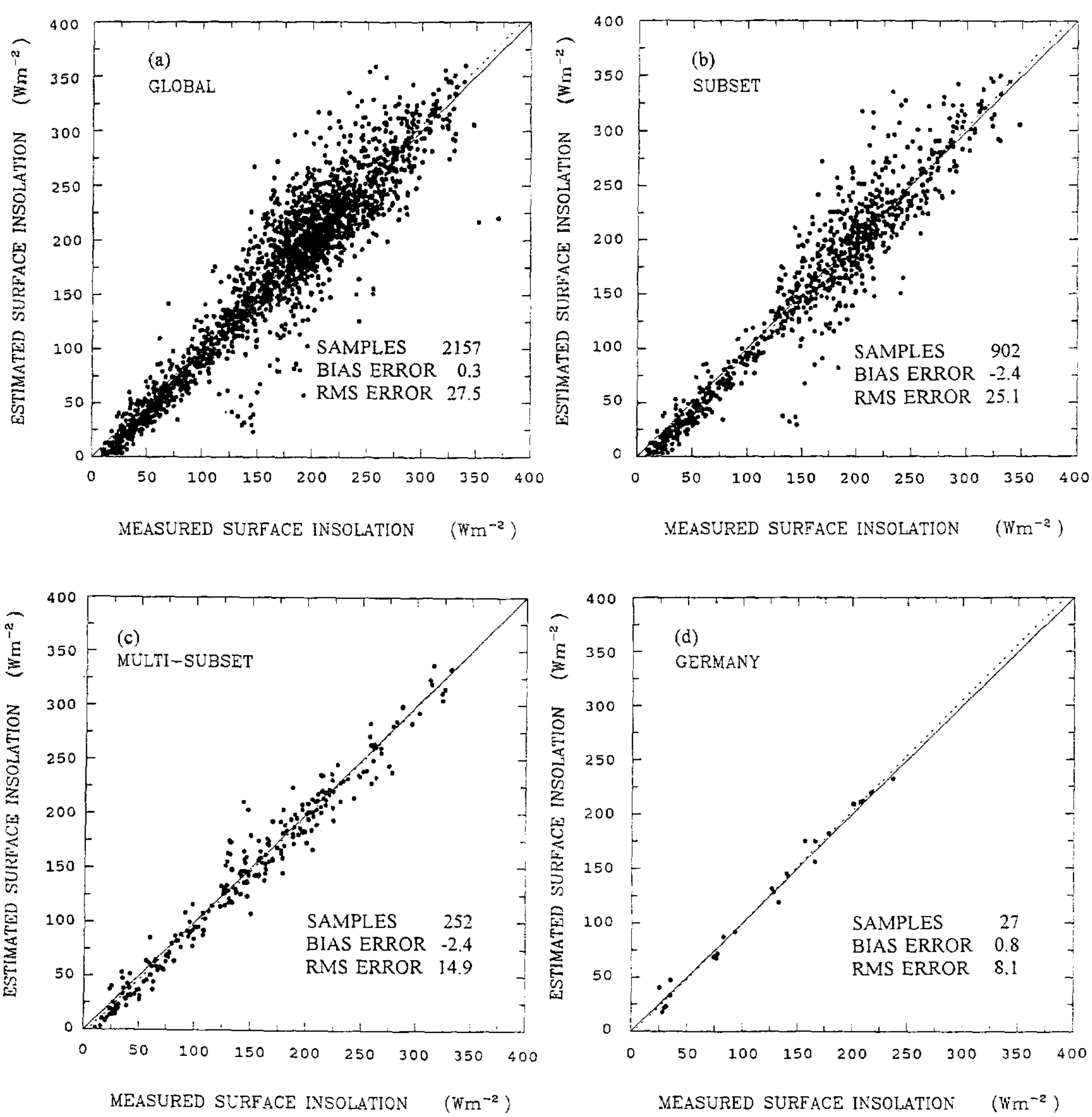

Figure 11. Comparison between satellite estimates of DSSR and surface observation. The latter are taken from the Global Energy Balance Archive (GEBA) for four combinations: (a) Total GEBA set; (b) GEBA subset; (c) Multi-site subset; and (d) German subset. The number of surface stations situated within a satellite grid-cell ranges from 1 to 10. The German subset contains the data with 7 or more surface stations (Li et al., 1994).

albedo measurements can only represent very small areas, ground-truth for SNNR is not provided in the GEBA archive. The comparison is thus for insolation by converting the estimated SSNR data into insolation data using the Staylor's surface albedo from the SRB project which is discussed in the section entitled "Current semi-operational methods for DSSR fluxes." Figure 11 shows such comparisons for four sets of GEBA data classified on the basis of data quality and the number of surface stations situating within a grid-cell of a satellite-based estimate (Whitlock et al., 1993). Note that the satellite-based estimates have bias errors near zero and random errors ranging from 8 to 28 Wm^{-2}. The finding that the random error decreases quickly as the number of surface stations increased suggests that the random error is mainly caused by poor representation of surface data. When the number of surface stations increases, the random error is estimated to be on the order of 5 Wm^{-2} (Li et al., 1994).

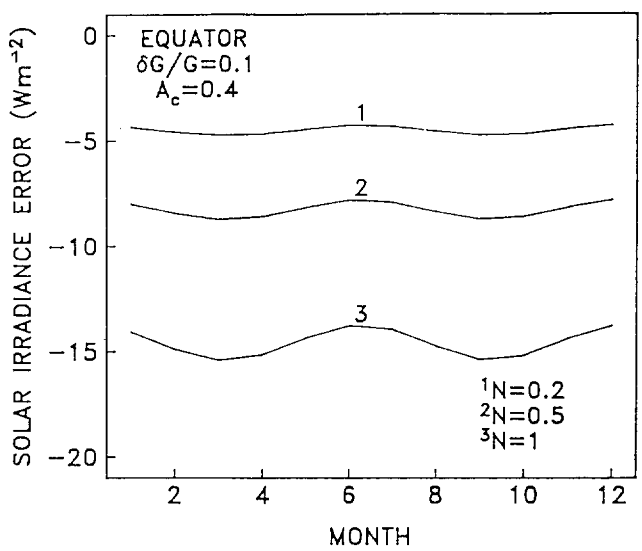

Figure 12. Typical error in satellite derived monthly mean NSSR flux due to a 10% increase in calibration gain of satellite sensor's solar channel. Clouds have an assumed albedo of 0.4; 0.3 atm-cm ozone; aerosols are of continental type; and aerosol optical thickness is 0.22 at 550 nm (Gautier and Frouin, 1992).

DISCUSSION

The various satellite algorithms used to estimate the variability of SRB utilize data from instruments that are generally not calibrated after launch [e.g., the Advanced Very High Resolution Radiometer (AVHRR); the Visible and Infrared Spin-Scan Radiometer (VISSR); the METEOSAT radiometer]. These instruments have been shown to exhibit large changes in sensitivity (e.g., Frouin and Gautier, 1987; Staylor, 1990; Whitlock et al., 1990b; Brest and Rossow, 1992; Whitlock et al., 1994b; Teillet and Holben, 1994). Theoretically, assuming that errors do not compensate, errors in the derived surface parameters can be large (Gautier and Frouin, 1992). For a cloud albedo of 0.4 at the equator, a 10% loss of sensitivity could translate into an error of up to 15 Wm^{-2} in monthly averages (Figure 12). Therefore, there is a need for instruments that have prelaunch calibration and on-board calibration capabilities. Such capabilities might prove to be more economical than satellite underflights by aircraft for calibration. Unless the calibration is monitored during the lifetime of the satellite, and instruments from various satellites are cross-calibrated, it will be difficult to extract useful signals for climate change studies unless the signals are strong as during an El Niño event.

The topic of cloud spatial heterogeneity also requires further attention. To what extent the plane parallel assumption in treating clouds, used in most current retrieval schemes affects the derived fields, is not known. On short time scales, broken clouds can significantly affect the spatial distribution of SRB when compared to computations from plane parallel fields.

In validation activities, care should be exercised when satellite-derived estimates are compared with in-situ measurements. Satellite-derived values are instantaneous and averaged spatially; surface measurements are local and averaged temporally. The space and time scales at which the comparisons are made should therefore be selected accordingly. The use of one ground instrument might not be as appropriate as a dense network. Such networks were operational during the various ISLSCP experiments but only for a limited time period. Preferably, they should be operated continuously at sites representing different climatic conditions and include measurements of additional atmospheric and surface parameters. Efforts to improve inference models should pay attention to spatial heterogeneity of clouds and experiments should provide the necessary information to test the actual impact of the more complex models. Current strategies to create long-term, large-scale satellite datasets could include such cloud characteristics from independent sources and be ready for implementation once satellites will be able to provide such information. Because many methods require a knowledge of cloud / no cloud conditions, efforts should be made to improve cloud screening especially over snow and bright surfaces where the problem is particularly difficult.

SUMMARY

During the last decade, progress has been made to develop, validate, and implement methods to derive DSSR fluxes from both polar orbiting and geostationary satellites. This activity expanded from local to global scales, and benefited greatly from independent activities under which the required satellite data became available as well as ground-truth for validation. Encouraging results, obtained by numerous investigators independently, helped to provide the motivation for progress made. It is generally believed that on monthly time scales, for areas of an average climate model grid size, it is possible to estimate DSSR fluxes to better than 20 Wm^{-2}, including bias errors. Such estimates are useful to validate climate models because they provide a consistent view of a key parameter for diagnosing cloud / radiation parameterizations in those models.

Several aspects of current satellite methods need to be re-examined. We have to improve available information on the state of the atmosphere and the surface, which is used as input to these models. There is a need for better cloud screening methods and more detailed information on cloud types or structure. At present, it is not obvious whether further improvements in the models' physics alone could improve results. There is also a need to learn more on sampling strategies at the ground in order to make satellite validation meaningful. The prospects for improvements within the next decade seem promising.

It is anticipated that during future experiments, attention will be given to acquisition of data that will be useful for validating satellite methods. As stated in Leese (1993), GCIP scientists will use data from instruments aboard the existing satellites to provide retrievals of atmospheric, hydrologic and land surface parameters. It is anticipated that the Atmospheric Radiation Measurement (ARM) program (DOE / ER-0441, 1990; DOE-ER-0495T, 1991) sponsored by the U.S. Department of Energy whose objective is to characterize empirically radiative processes in the earth's atmosphere with improved resolution and accuracy, will contribute to this objective under agreements between ARM and GEWEX programs.

The net surface shortwave radiation is one of the most important parameters for climate studies. Under the 'direct' approach to estimate NSSR from satellite measurements, estimates of DSSR and albedo are made independently and combined to produce the NSSR. Under the 'indirect' approach, the surface albedo is an implicit parameter and not required directly for deducing NSSR.

Based on observations and radiative transfer calculations, it was found that NSSR depends linearly on the TOA reflected flux, as the surface albedo and / or cloud optical thickness change for a fixed SZA. The relationship is insensitive to cloud amount and type.

Sensors suitable for SRB monitoring from space are not limited to those used so far in algorithm development. Other instruments, scanners as well as wide-field-of-view radiometers can be used, in particular, those from the Earth Radiation Budget Experiment, and current algorithms can be modified to become applicable to those sensors. Furthermore, their length of record, careful calibration and characterization, as well as the extension of the mission well beyond the end of the century by the follow-up Clouds and Earth's Radiant Energy System (CERES) mission (Wielicki and Barkstrom, 1991) make them a suitable tool for studying SRB's inter-annual variability and issues of climate change. Apart from future versions of meteorological satellites and the CERES scanner, other instruments will be available for SRB monitoring during the Earth Observing System (EOS) missions planned for the beginning of the next century. Of particular interest is the MODerate resolution Imaging Spectrometer (MODIS) (King et al., 1992) and the Medium Resolution Imaging Spectrometer (MERIS).

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