3.2. SOLAR AND THERMAL ATMOSPHERIC RADIATION

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3.2.1. RADIATION MEASUREMENTS

Introduction

The CMDL Solar and Thermal Atmospheric Radiation (STAR) group provides supporting radiation information for baseline climate monitoring activities and investigates trends and variations in the observed surface radiation budget. Energy derived from the earth's radiation budget is responsible for not only maintaining the temperature of the planet but for atmospheric and oceanic motions. Predicted anthropogenic trends in surface radiation quantities at globally remote sites are near or below the level of detectability, on the decadal time scale, for the currently available instrumentation. However, fundamental climatological variability in the global surface radiation budget is not adequately understood. Therefore, STAR measurements contribute to this basic knowledge. These contributions include the definition of diurnal and annual cycles, effects of cloudiness, variations on daily to decadal time scales, effects of major volcanic eruptions, unexpectedly high concentrations of anthropogenic pollution in the arctic, effects of constituent variations on narrowband irradiance (e.g., ozone and UV changes), and possible anthropogenic modification to cloudiness. The STAR group also makes remote sensing measurements of various atmospheric constituents that are potentially responsible for variations in surface radiative quantities. In addition to the research conducted by CMDL, STAR measurements contribute to several international databases. International databases are needed to evaluate the radiation and energy budget necessary to diagnose the climatic time scale general circulation of the atmosphere. These observations also contribute to satellite-based projects by helping verify spot estimates and to allow features of the intervening atmosphere to be deduced. Still, a major goal of the monitoring program is to obtain as long and as complete a record as possible of surface radiation parameters that will permit examination of the record for all scales of natural and modified variability. Of particular interest is the determination of the magnitude, representativeness, and possible consequences of any observed changes. To this end, the STAR group maintains complete and continuous surface radiation budget observations at several globally diverse sites with various ancillary observations. The following describes those projects and recent changes.

Baseline Monitoring

Surface radiation measurements have been made at the four principal CMDL baseline observatories (BRW, MLO, SMO, and SPO) since the mid-1970s. The different environments and conditions at the various sites resulted in somewhat different programs evolving at each site. The basic measurements made at all sites include the downward components of solar radiation: global, diffuse, and direct. Broadband thermal infrared irradiance measurements were added over the past 15 years. Upward solar and thermal infrared irradiances are measured at sites where the surrounding terrain is representative of a larger regional area, as at SPO and BRW, for at least part of the year. The records acquired at these sites constitute some of the longest known in the U.S. for solar radiation research. The raw data are routinely transmitted over telephone lines or the Internet to the central data processing facility in Boulder, where data editing, final calibrations, graphical inspection, and archiving, are performed, as discussed in section 3.2.11.

Other Measurement Sites

Boulder Atmospheric Observatory (BAO tower). Observations of upwelling and downwelling solar and thermal irradiances began in 1985 at the top of a 300-m tower, known as the Boulder Atmospheric Observatory (BAO) located near Erie, Colorado. Nearly continuous observations of all quantities have been made with hourly resolution until 1992, 3-min resolution until 1998, and 1-min resolution thereafter. The upwelling radiation data provide a unique view of surrounding agricultural land making the data more representative than typical surface based solar radiation budget observations. The data from the site are being used by the National Aeronautics and Space Administration/Clouds and Earth's Radiant Energy System (NASA/CERES) and NOAA Geophysical Fluid Dynamics Laboratory (GFDL)/General Circulation Model (GCM) programs and have been used by *Nemesure et al.* [1994], *Cess et al.* [1995], *Dutton and Cox* [1995], *Garrett and Prata* [1996], and several earlier papers. Since 1990 observations of direct solar and downwelling solar irradiances have also been made near the base of the tower. This site has contributed data to the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN).

Kwajalein. Observations of direct solar and downwelling solar and thermal IR irradiance began at Kwajalein in 1989. Kwajalein is a small, <4 km^2, island in the tropical west Pacific. Data obtained at this location are virtually free of any effects of the island and therefore are often taken as representative of the open ocean in that region. Data from Kwajalein have been used as oceanic representative by *Dutton* [1993], *Whitlock et al.* [1995], and *Bishop et al.* [1997], and are currently being used by CERES and the European Center for Medium-Range Weather Forecasts (ECMWF) GCMs. Substantial upgrades to the Kwajalein radiation measurements were carried out in recent years, including the addition of spectral total and diffuse, broadband diffuse, UV-B, and PAR instruments, as well as improved solar tracking capability, including a shade disk pyrgeometer. Data from Kwajalein have been submitted to the BSRN data archive.

Bermuda. Observations of downwelling solar and thermal IR began at the NASA Bermuda Tracking Station at the eastern end of Bermuda in 1990. The rather small size and low relief of the island in the lower midlatitude westerlies has minimal influence on the irradiance measurements, although some clouds of orographic origin are known to exist there in the summer months under certain synoptic meteorological conditions. Data from Bermuda have been submitted to the BSRN data archive and have been used by *Whitlock et al.* [1995], *Bishop et al.* [1997], and currently by the CERES program in satellite comparison and validation studies and by ECMWF and GFDL in their GCM testing. On December 8, 1998, the monitoring site was moved from the NASA tracking station (32.2670ºN, 64.6670ºW) near the east end of the island to the top of Prospect Hill near the center of the island (32.3009ºN, 64.7659ºW). This move was necessitated by the imminent closing of the tracking station and by the desirability of operating further from the influence of occasional island-induced clouds that are generated at, and dynamically attached to, the east end of the island. The new site is ably tended by the Bermuda Biological Station for Research.

Basic Measurements

Broadband irradiance. The basic measurements currently conducted at each of the four baseline observatories for the past 24 years include normal direct and downward broadband solar irradiance, downward solar irradiance in the 0.695-2.8 µm band, and wideband spectral direct solar irradiance. Downward broadband thermal irradiance measurements were added at all sites in more recent years, as well as upwelling irradiance measurements at SPO and BRW. The wideband spectral direct observations are obtained manually with a filter wheel pyrheliometer under clear-sky conditions while the others are sampled at 1 Hz with 1-min averages recorded on computer media. Preliminary data from all CMDL radiation sites are generally available graphically within a couple of days of acquisition in the radiation section of the CMDL Web home page and subsequently as described in Section 3.2.11. Figure 3.11 shows different summaries of the 24-yr record of total solar irradiance collected at Samoa using the single pyranometer technique.

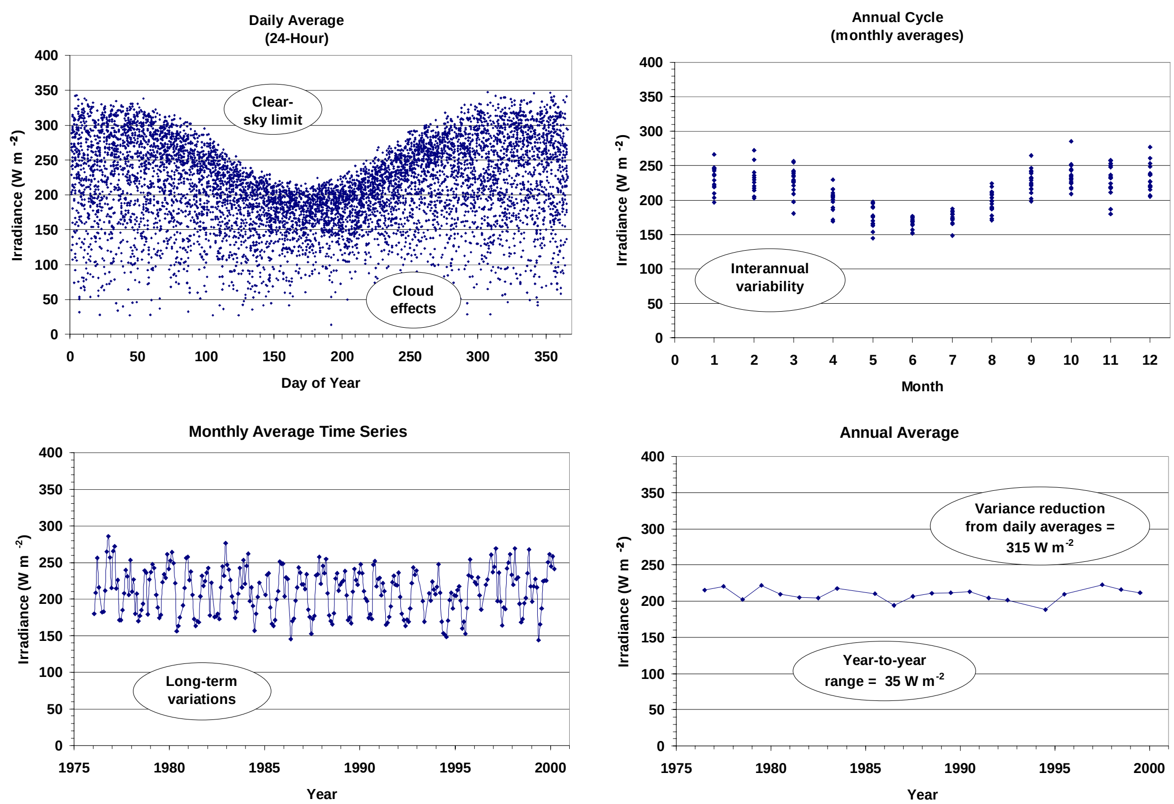

Fig. 3.11. Total solar irradiance record for American Samoa obtained from a pyranometer (1975-2000), summarized for four different presentation methods. The comments in the ovals in each figure section point out some of the highlights of that particular presentation.

Filter wheel NIP. The wideband spectral direct solar irradiance measurements are made with a filter wheel normal incidence pyrheliometer (FWNIP). The data from these observations are compared to a higher spectral resolution radiative transfer model [*Bird and Riordan*, 1986]. The model is based on Beer's law and is intended for use at the surface only. The aerosol optical depth and precipitable water are adjusted within the model to obtain a best match with the FWNIP observations. This provides a low precision but relatively stable estimate of mean visible aerosol optical depth and water vapor at the four baseline observatories. The accuracy of the method of obtaining aerosol optical depth and water vapor is limited by the dependence on the absolute values of the extraterrestrial solar spectrum and instrument calibration, unlike typical applications in sunphotometry. The data record from this observation is shown in Figure 3.12 through 1999. The accuracy of the data is no better than 0.03 optical depth units and should only be used accordingly when sunphotometer-derived data are not available.

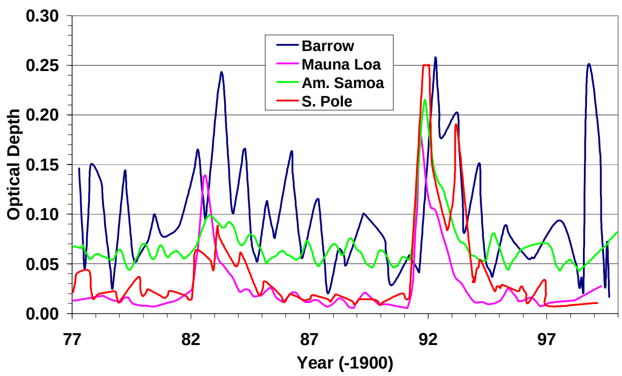

Fig. 3.12. Aerosol optical depth (monthly averages from wideband estimates) at the four CMDL baseline observatories. The values are derived from filter-wheel pyrheliometers that produce lower accuracy and precision measurements than sunphotometers but have proven to be more stable and viable than sunphotometers in the CMDL monitoring program. Seasonal, volcanic, and inter-site variations are seen in the figure. The recent spike at Barrow is believed to be caused by smoke events originating in Russia.

MLO apparent transmission. The transmission for direct broadband solar irradiance through the atmosphere above MLO is monitored using a quantity known as the apparent transmission. The quantity is computed by taking the average of three ratios of direct solar irradiance where each ratio is the quotient of the irradiance at an integer airmass divided by the irradiance at the next smaller integer air mass as first defined by *Ellis and Pueschel* [1971]. The apparent transmission measure-ment is inherently stable over time because it is independent of a radiometer calibration value and also, therefore, quite sensitive to small changes in transmission that can be due to aerosols, ozone, or water vapor. Previous studies [*Bodhaine et al.*, 1981; *Dutton et al.*, 1985] have shown that aerosols tend to dominate observed changes in the monthly averages of apparent transmission such that the major observed excursions in the record, given in Figure 3.13, are because of aerosols. The major observable features in Figure 3.13 are the effects of several volcanoes, particularly Agung in 1963, El Chichón in 1982, and Pinatubo in 1991 and an annual oscillation caused primarily by the springtime transport of Asian aerosol over the site [*Bodhaine et al.*, 1981]. Figure 3.13 is complete through 1999 and most recently shows that recovery from the eruption of Mt. Pinatubo required several years. The fact that the Mauna Loa apparent transmission record took several years to recover from Pinatubo is evidence of the sensitivity of the measurement since it is known from other measurements by CMDL and others that the optical depth of Pinatubo in 1995 was already very low, on the order of 0.005 at 500 nm.

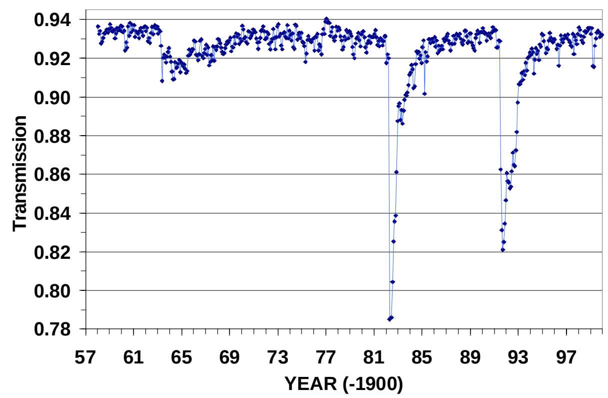

Fig. 3.13. Monthly means of apparent solar transmission for clear skies at Mauna Loa. Data are updated through the end of 1999 and show continued recovery towards the baseline conditions last established in the late 1950s. Another few years of data will be required to determine if the earlier baseline level will once again be attained or if a different background level exists.

Optimal Total Solar Irradiance Measurements

Total downwelling solar irradiance is the primary input component of the earth's energy budget. Instruments for measuring this quantity at the earth's surface first appeared in the 19th century with current single-instrument technology for routine observations maturing in the 1950s and 1960s. Many of the current commercially available instruments meet the highest standards of the World Meteorological Organization (WMO) for such measurements, but only specimen instruments are typically well characterized. The uncertainties in the measurements using these instruments are often given for extended averaging, days to months, which reduces the uncertainties inherent in instantaneous measurements. In recent years there has been increased interest in near-instantaneous solar irradiance observations for various research applications. These applications include comparisons to values derived from satellite overpasses and radiative transfer model calculations using a nearly instantaneous quantification of the atmospheric state. For these comparisons the full extent of the uncertainty of the irradiance measurement is important and needs to be low enough to be useful in improving the satellite algorithms and radiative transfer models, particularly when there are significant parameterizations used. While different individuals had ideas about improving surface solar irradiance observations, the first internationally organized effort to make improved irradiance measurements (solar and thermal IR) a primary goal was the BSRN (http://bsrn.ethz.ch/) project of the WCRP (http://www.wmo.ch/web/wcrp/wcrp-home.html). The first step in the improvement of the instantaneous surface-based solar irradiance measurements was the recommendation for the use of the combination of separately measured direct and diffuse irradiance, which incorporates the highly accurate direct beam measurement capabilities developed over the past 4 decades with the greatly reduced cosine response error inherent in the single-instrument flat-plate receiver of the pyranometer. This method of measuring total solar irradiance led to improvements discussed by *Ohmura et al.* [1998], *Michalsky et al.* [1999], and *Bush et al.* [1999]. As a result this measurement method has made a large amount of direct and diffuse solar irradiance data available to the research community, which was useful because the most sophisticated and physically complete radiative transfer models also separately calculate these quantities. The easiest to calculate and also easiest to measure is the direct component, and most significant problems in measurements and models have been solved so that the agreements between the two are very good, typically less than 3 W m^{-2}, if there are no blatant errors in either. Such is not the case for the diffuse component. For the diffuse, there are difficulties in specifying correct modeling procedures, specifying correct model input values, and knowing the measurement truth since no standards exist. From the instrument perspective, not only can signal strengths be low, but also there are no reference standards that exist to which the measurement can be compared to absolutely determine measurement error. This has resulted in some recent modifications in the way in which STAR is making diffuse irradiance measurements, both in the type of instruments used and the adjustments for thermal offsets induced in the certain diffuse pyranometers. The specifics of the new measurements and adjustments to older data are given by *Dutton et al.* [2000]. With these changes it is estimated that diffuse irradiance is currently measured to within about 5 W m^{-2}. This results in accuracies to within about 8 W m^{-2} for total solar irradiance when determined from the combined diffuse and direct measurements.

Improved Thermal IR Irradiance Measurements

Although there has been a substantial reduction in the uncertainty of thermal infrared irradiance measurements in the last 10 years, from nearly 30 W m^{-2} in the late 1980s to about 5 W m^{-2} now, there still appears to be room for further improvements and the potential for the establishment of a measurement reference standard for these measurements. Over the past 2 years, STAR has become involved in the efforts of BSRN and the World Radiation Center (WRC) in Davos, Switzerland, to work towards these potential improvements. This work is conducted through the recent establishment of new radiance measurement capabilities that rely on absolute, self-calibrating, sky-scanning instruments. CMDL, working with BSRN, organized and participated in the first International Pyrgeometer and All-sky Scanning Radiometer Comparison (IPASRC-I) in September 1998 where this process to establish such capabilities and reference standards was begun [*Philipona et al.*, 1998].