JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D13, PAGES 16,235–16,249, JULY 20, 1998

NOAA 11 Solar Backscattered Ultraviolet, model 2 (SBUV/2) instrument solar spectral irradiance measurements in 1989-1994
1. Observations and long-term calibration

Richard P. Cebula and Matthew T. DeLand

Raytheon STX Corporation, Lanham, Maryland

Ernest Hilsenrath

NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract. Measurements of solar ultraviolet (UV) irradiance are a valuable diagnostic of physical processes in the solar atmosphere and a key component in characterizing the external forcing of the Earth's atmosphere. However, the deleterious effects of solar UV radiation on satellite instrument components have complicated efforts to determine the magnitude of long-term solar variations for almost 30 years. The NOAA 11 Solar Backscatter Ultraviolet, model 2 (SBUV/2) instrument, primarily designed to measure stratospheric ozone, also made daily spectral scan measurements of solar UV irradiance in the 160-405 nm region from February 1989 to October 1994. An onboard calibration system and comparisons with coincident Shuttle SBUV (SSBUV) measurements were used to correct for long-term NOAA 11 instrument sensitivity changes. Time series of the NOAA 11 solar irradiance data indicate a long-term accuracy of approximately ±0.9-2.3% (2σ) over the 5.5-year data record. Long-term solar irradiance changes of approximately –3% are observed between 215 and 250 nm, increasing in magnitude to approximately -7% at 200-205 nm. Additional discussion of solar variations observed by NOAA 11 SBUV/2 are presented by *DeLand and Cebula* [this issue].

1. Introduction

Solar ultraviolet (UV) irradiances generated at wavelengths shortward of ~310 nm are largely absorbed in the Earth's atmosphere. In order to obtain information on absolute solar UV irradiance and temporal variations, measurements are needed from high-altitude platforms such as rockets, balloons, and/or satellites. Rockets were used extensively from the late 1940s through the 1980s for absolute irradiance measurements (see *Lean* [1987] for a summary). However, the calibration uncertainties for these instruments were typically large enough (±10-20%) that differences between the sporadic observations could not be used to establish long-term solar variability with any confidence. The accumulation of extended data sets suitable for characterizing solar UV variability on different timescales requires orbiting satellites. Early satellite instruments used one or more broadband photodiodes [e.g., *Heath*, 1969; *Prag and Morse*, 1970; *Heath*, 1973] or spectrometers such as the Backscatter Ultraviolet (BUV) instrument [*Heath*, 1973] to measure solar UV irradiance. These early instruments confirmed the existence of solar UV variability on rotational timescales and provided initial estimates of its magnitude and spectral characteristics. However, they also experienced such rapid changes in overall instrument sensitivity, particularly in optical components such as diffuser plates that were continuously exposed to UV radiation, that long-term solar changes could not be estimated with any degree of confidence.

The next generation of satellite solar spectral UV measurements adopted strategies to reduce and better quantify instrument response changes. The Nimbus 7 Solar Backscatter Ultraviolet (SBUV) instrument was launched in October 1978 to measure stratospheric ozone profiles and also made daily spectral solar UV measurements until February 1987 in the wavelength region 160-400 nm [*Heath et al.*, 1975]. Deploying the diffuser plate only for solar observations reduced the overall degradation rate, and varying the frequency of solar observations provided data used to model long-term changes in diffuser reflectivity and instrument throughput [*Cebula et al.*, 1988; *Herman et al.*, 1990; *Schlesinger and Cebula*, 1992]. Daily solar spectral UV data over the range 120-300 nm were taken from January 1982 to April 1989 by the Solar Mesosphere Explorer (SME) satellite [*Rottman et al.*, 1982; *Rottman*, 1988]. Long-term response changes in SME were characterized using an onboard test diffuser and comparisons with several rocket observations [e.g., *Mount and Rottman*, 1983]. The solar cycle spectral irradiance variation results from the Nimbus 7 SBUV and SME instruments are in general agreement (e.g., ΔF_{cycle} = 5-8% at 205 nm for SBUV [*Schlesinger and Cebula*, 1992], ΔF_{cycle} = 6(±4)% at 200 nm for SME [*Rottman*, 1988]). However, since neither of these instruments carried an onboard calibration system capable of end-to-end responsivity monitoring, the range of uncertainty in the estimates of $\Delta F(\lambda,t)$ for solar cycle timescales was still fairly large, approximately ±3-7% for the 200-300 nm wavelength region.

For solar cycle 22, additional satellite data sets are available to help quantify long-term solar UV spectral variability. The NOAA

Paper number 98JD01205.
0148-0227/98/98JD-01205$09.00

9 SBUV, model 2 (SBUV/2) instrument [*Frederick et al.*, 1986] made daily solar spectral measurements from March 1985 to May 1997 over the wavelength region 160-405 nm. Although NOAA 9 was designed with an onboard calibration system to monitor diffuser plate changes during flight, the system did not operate correctly [*Frederick et al.*, 1986; *Ahmad et al.*, 1994], and absolutely calibrated irradiance data are not currently available. The NOAA 11 SBUV/2 instrument, which also carried an onboard calibration system, was launched in September 1988 and made daily solar observations from December 1988 to October 1994, covering the entire maximum and most of the declining phases of solar cycle 22. The diffuser reflectivity calibration system worked well for this instrument [*Weiss et al.*, 1991; *Hilsenrath et al.*, 1995]. However, both spectrometer throughput and solar diffuser changes must be known to accurately measure solar spectral irradiance variations. The NOAA 14 SBUV/2 instrument was launched in December 1994 and commenced regular solar observations in February 1995. Unfortunately, this instrument began experiencing grating drive problems in July 1995, and spectral scan solar measurements were terminated on October 6, 1995. Other satellite-based instruments making solar UV measurements during cycle 22 include Airglow-Solar Spectrometer Instrument (ASSI) [*Schmidtke et al.*, 1985], which flew on the San Marco 5 satellite between March 25 and December 6, 1988; the Upper Atmospheric Research Satellite (UARS) Solar Stellar Irradiance Comparison Experiment (SOLSTICE) [*Rottman et al.*, 1993; *Woods et al.*, 1993] and Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) [*Brueckner et al.*, 1993], which began operations in October 1991 and continue to the present; and Global Ozone Monitoring Experiment (GOME) [*Peeters et al.*, 1996; *Burrows et al.*, 1998; *Weber et al.*, 1998] from May 1995 to the present. SOLSTICE and SUSIM are the first satellite solar UV instruments capable of determining end-to-end calibration changes using inflight measurements.

The space shuttle has become a valuable platform for solar irradiance measurements because it can overcome some of the disadvantages inherent in both rocket and satellite measurements. Shuttle missions typically last 5-15 days, providing much more observing time than a rocket flight, as well as opportunities for inflight calibration measurements. Shuttle instruments can also be returned to the laboratory for postflight calibration, which is impractical for most satellite instruments. The first shuttle solar UV experiment was the Solar Spectrum (SOLSPEC) instrument on the Spacelab 1 mission in December 1983 [*Labs et al.*, 1987]. Later experiments have included the SUSIM instrument on Spacelab 2 in August 1985 [*VanHoosier et al.*, 1988]; the Shuttle SBUV (SSBUV) instrument on various individual flights between 1989 and 1996 [*Cebula and Hilsenrath*, 1992; *Cebula et al.*, 1994]; the ATLAS payload containing the SSBUV, SOLSPEC, and SUSIM instruments in 1992, 1993, and 1994 [*Woods et al.*, 1996; *Cebula et al.*, 1996; *Thullier et al.*, 1997]; and the Solar Constant and Variability (SOVA-2) experiment on the European Retrievable Carrier (EURECA) from August 1992 to May 1993 [*Wehrli et al.*, 1995]. The SSBUV missions are of particular interest here, because SSBUV was designed to validate the SBUV/2 satellite instruments through coincident underflights [*Hilsenrath et al.*, 1988, 1995]. In this paper, we describe the use of solar irradiance data from the first seven SSBUV flights between October 1989 and November 1994 to correct the NOAA 11 SBUV/2 irradiance data for long-term changes in instrument throughput, resulting in a 5.5-year data set of absolutely calibrated solar UV irradiances. Section 2 summarizes the NOAA 11 SBUV/2 instrument and the solar data produced by using internal corrections only. Next, we demonstrate how data from coincident SSBUV flights were used to characterize spectral and temporal changes in the NOAA 11 calibration. Finally, we show examples of the corrected NOAA 11 irradiance data, and discuss absolute and time-dependent uncertainties. *DeLand and Cebula* [this issue] examine the spectral and temporal characteristics of these data in more detail and present comparisons with UARS SOLSTICE and UARS SUSIM measurements during the period December 1991 to October 1994, when all three instruments were operational. A brief description of the irradiance correction technique described herein was presented by *Cebula et al.* [1994], and results of a preliminary investigation were presented by *DeLand et al.* [1998].

2. Irradiance Data Sets

The SBUV/2 instruments are Ebert-Fastie double monochromators with nominal resolutions of 1.1 nm, designed to determine stratospheric ozone profiles through the measurement of the terrestrial backscattered albedo in the 252-340 nm region [*Frederick et al.*, 1986]. Terrestrial radiance measurements are made at 12 specified wavelengths in a 32-s scan ("discrete" mode), where each data sample is integrated for 1.25 s. The SBUV/2 instruments, which are flown on polar-orbiting spacecraft, also observe the Sun after crossing the northern terminator by deploying a ground aluminum diffuser plate to direct solar radiation into the nadir-viewing aperture. Weekly discrete solar irradiance measurements are made at the 12 ozone wavelengths, and daily discrete solar measurements are made at 12 wavelengths bracketing the Mg II absorption feature at 280 nm. The SBUV/2 instruments also operate in a spectral scan ("sweep") mode, making a continuous scan over the 160-405 nm wavelength region with nominal sampling of ~0.147 nm and a 0.1-s sample integration. Solar spectral irradiance measurements are typically made on one orbit each day, with two spectra taken during each observation period. This paper presents the analysis of the NOAA 11 SBUV/2 solar spectral irradiance data. These data are generally available on a daily basis between December 1988 and October 1994, but some gaps should be noted. Although NOAA 11 measurements began on December 2, 1988, solar observations were sporadic during the initial check-out period until the beginning of regular operations on February 14, 1989. All NOAA 11 SBUV/2 data for March 1991 are unavailable. Precession of the satellite's Sun-synchronous orbit towards the terminator led to shadowing of the diffuser plate by other spacecraft elements during certain periods in 1993-1994, causing a loss of irradiance data. Finally, the diffuser deployment mechanism malfunctioned on October 19, 1994, ending the NOAA 11 solar observations. Periods of five or more consecutive days with no solar data are listed in Table 1.

Uncorrected changes in diffuser plate reflectivity represent a significant source of long-term variation in SBUV/2 observed solar data. Knowledge of diffuser reflectivity changes is also critical to the derivation of the ozone profile, because the diffuser is the only optical element not common to both the radiance and irradiance

Table 1. NOAA 11 Solar Data Gaps ($\Delta t > 5$ days)

Start Date	*End Date*	*Description*
Dec. 30, 1988	Jan. 3, 1989	no solar observations made
Jan. 28, 1989	Feb. 13, 1989	no solar observations made
March 1, 1991	March 31, 1991	data unavailable
Sept. 15, 1993	Dec. 30, 1993	diffuser shadowing
Jan. 19, 1994	April 20, 1994	diffuser shadowing
Aug. 17, 1994	Sept. 21, 1994	diffuser shadowing

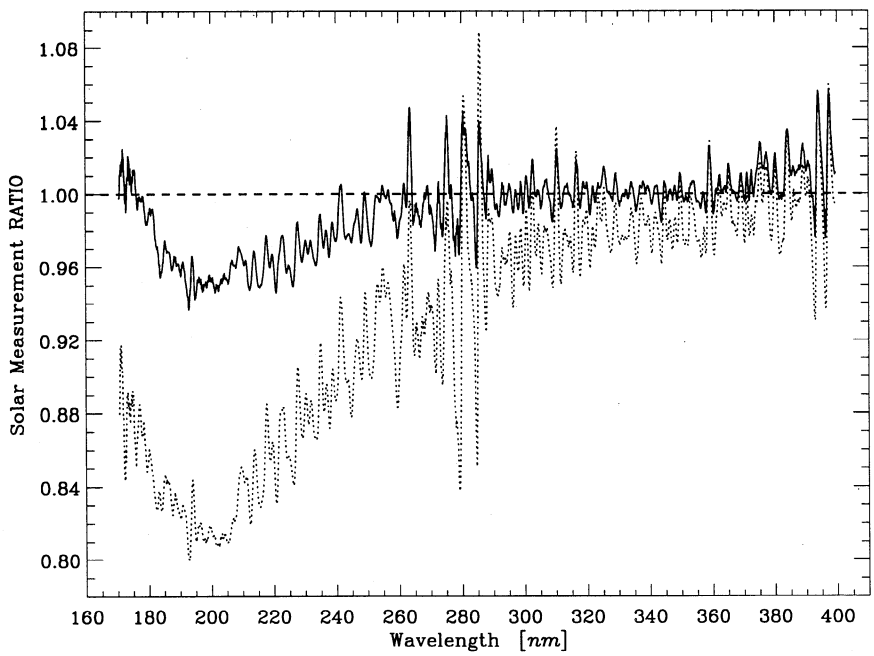

Figure 1. NOAA 11 spectral instrument sensitivity change between 170 and 400 nm at ~1 year (solid line) and 5 years (dotted line) after "day 1" (December 5, 1988), using daily average solar spectra. A seven-point running average has been applied. No wavelength scale drift or solar activity corrections were applied.

measurements. The NOAA 11 instrument used an onboard mercury lamp calibration system to track the diffuser reflectivity as a function of both wavelength and time [*Weiss et al.*, 1991]. Data taken through December 1992 were used to characterize diffuser reflectivity changes, which varied in magnitude from –0.7(±0.3)%/yr at 340 nm to –1.2(±0.4)%/yr at 252 nm (2σ) [*Hilsenrath et al.*, 1995]. Diffuser reflectivity changes observed in 1993 and 1994 were consistent with the spectral and temporal dependences previously derived by *Steinfeld et al.* [1997]. Changes in other instrument calibration parameters which may affect the observed response, such as the goniometric response of the diffuser plate and time-dependent changes in the electronic gain ratio, are thoroughly characterized prior to reprocessing the ozone data.

Hilsenrath et al. [1995] describe the process of updating the NOAA 11 SBUV/2 long-term calibration in detail, including revisions to the goniometric response function and corrections for instrument temperature variations related to its drifting orbit. All of these corrections were applied to produce the best internally calibrated NOAA 11 solar measurements. These data do not represent absolute solar irradiance, because no correction has been applied for instrument throughput changes. Equation (1) gives the form used to calculate these results, which will be referred to as "internally corrected solar data" in the following sections:

$$C = (S - D)\, N\, T_{Corr}\, G\, R\, A\, f_{Diff}\, f_{AU} \tag{1}$$

$C(\lambda,t)$	internally corrected solar data [mW m^{-2} nm^{-1}];
$S(r,t)$	raw signal (r is gain range) [counts];
$D(r)$	electronic offset [counts];
$N(r,S)$	nonlinearity correction;
$T_{Corr}(r,\lambda,t)$	photomultiplier tube (PMT) temperature correction;
$G(r,\lambda,t)$	interrange ratio (PMT and electronic gain);
$R(\lambda)$	initial instrument responsivity [mW m^{-2} nm^{-1} count^{-1}]
$A(\lambda,\alpha,\beta)$	goniometric correction;
$f_{Diff}(\lambda,t)$	diffuser reflectivity correction;
$f_{AU}(t)$	solar distance correction (to 1 AU).

The nomenclature used in (1) was chosen for consistency with the *Woods et al.* [1996] presentation for UARS SOLSTICE and SUSIM.

NOAA 11 internally corrected solar data still exhibit significant spectrally dependent response changes over time. Figure 1 shows the ratio of the solar spectral measurement at 1 year and 5 years after the start of observations to the initial, or "day 1", measurements. No correction has been made for solar activity variations between these dates. Note that the change in corrected solar data increases in slope for $\lambda < 270$ nm and maximizes at ~200 nm before becoming smaller at $\lambda \leq 190$ nm. The spectral dependence of the changes shown in Figure 1 is very similar to the spectral shape observed for NOAA 9 SBUV/2 [*Cebula et al.*, 1994], Nimbus 7 SBUV [*Schlesinger and Cebula*, 1992], and UARS SUSIM [*Floyd et al.*, 1996]. Those shapes are dominated by instrument response changes, rather than actual solar variations. Predicted solar cycle irradiance changes for the spectral region shown in Figure 1 range from $\Delta F(\lambda,t) < 1\%$ longward of 300 nm to $\Delta F(\lambda,t) \approx 7$-9% at 205 nm, with potential rotational modulation variations of 6-7% at 200 nm [*Lean*, 1991]. Changes in NOAA 11 solar spectral data due to solar activity alone would be expected to increase in magnitude for $\lambda < 208$ nm (shortward of the Al ionization edge), rather than decreasing as shown in Figure 1. The change in NOAA 11 internally corrected solar data at 200 nm after 5 years is approximately double any predicted solar change, thus providing an indication of the magnitude of the NOAA 11 spectrometer throughput change during this period.

There is considerable structure in the spectral ratio curves of Figure 1 with a scale of 3-5 nm. This indicates the presence of uncorrected drift in the NOAA 11 wavelength scale. A wavelength scale shift of $\Delta\lambda = +0.1$ nm at the SBUV/2 resolution of 1.1 nm can produce spectral irradiance changes of 8-10% at major absorption features such as Mg II (280 nm), Mg I (285 nm), and Ca II *K* and *H* (393.4, 396.8 nm), although there is very little irradiance change over larger spectral regions. Long-term changes in the sweep mode wavelength scale of NOAA 11 SBUV/2 were monitored through observations of the positions of six emission lines in the Hg cali-

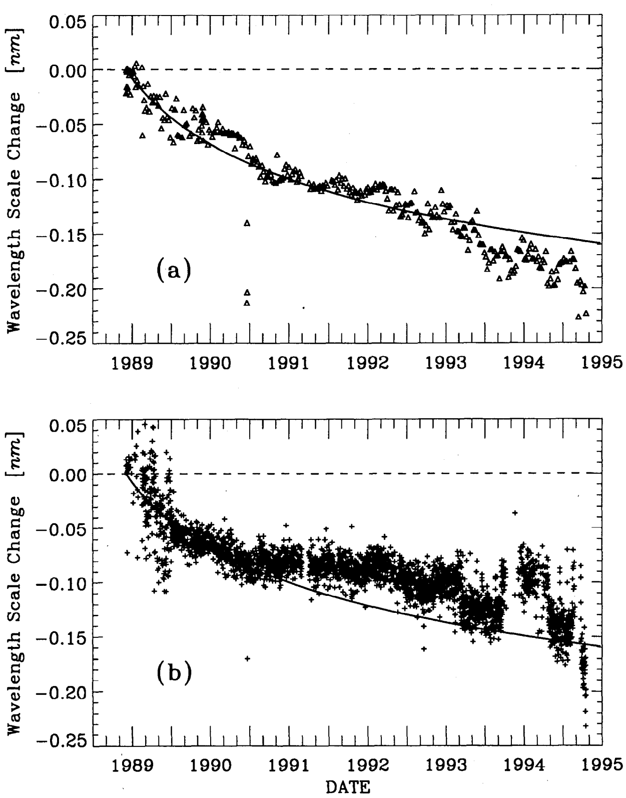

Figure 2. (a) NOAA 11 sweep mode wavelength scale drift time dependence, using data from the mercury calibration lamp emission line at 334 nm. A power law regression fit is also shown (solid line). (b) NOAA 11 wavelength scale drift using solar Ca II H absorption line data at 397 nm. The power law fit to the Hg lamp data from Figure 2a is also shown.

bration lamp spectrum (measurements made twice per week) and 12 absorption lines in the solar spectrum (daily spectra). For each data set, regression fits were made to the approximately linear portions of each line profile shortward and longward of the maximum (or minimum) intensity, and the location of the observed line center was determined from the intersection of the calculated fits. Although the absolute wavelength position thus determined for a given line may differ from reference standards due to instrument band-pass effects, the relative change in the calculated line position over time provides an excellent indication of wavelength scale stability. Applications of this technique to SSBUV are described by *Cebula et al.* [1995]. Data from both sources indicate an overall change of $\Delta\lambda \approx -0.15$ nm in the nominal NOAA 11 SBUV/2 sweep mode wavelength scale between December 1988 and October 1994 (Figure 2). The general time dependence of $\Delta\lambda(t)$ is adequately represented by a power law regression fit, although suggestions of additional temporal structure can be seen in solar data at selected wavelengths. This structure, which increases in severity during 1993-1994, may be related to increased temperature variations experienced by NOAA 11 as its orbit drifted toward the terminator. Because the complex temporal structure is not consistently reproduced between different spectral lines, adopting a wavelength drift correction based on temporally smoothed data was deemed inappropriate. Instead, we adopted a power law time dependence for the calculation of the NOAA 11 wavelength drift correction, using the average of the fits to the four Hg lamp lines with the best noise characteristics. The $\Delta\lambda(t)$ function we have derived is wavelength-independent to the accuracy of our data. Figure 3 shows the spectral ratios of Figure 1 after applying the wavelength drift correction for each date as determined by the power law fit. As expected, the majority of the small-scale structure is no longer present in the corrected spectral ratios. Prominent indicators of solar change, such as the Al I ionization edge at 208 nm, are still obscured by the strong spectral dependence of the uncorrected NOAA 11 throughput change.

Time series of NOAA 11 solar measurements corrected for wavelength scale drift, shown in Figure 4, reveal the temporal characteristics of long-term response change. All time series shown in this paper were constructed using a 4-nm band average to reduce measurement noise. The observed signal at 390 nm, where the influence of solar absorption lines is negligible and solar cycle variations are expected to be <1%, varies by ~1-2% from December 1988 to October 1994 (Figure 4a). An anomalous increase of 1.5%

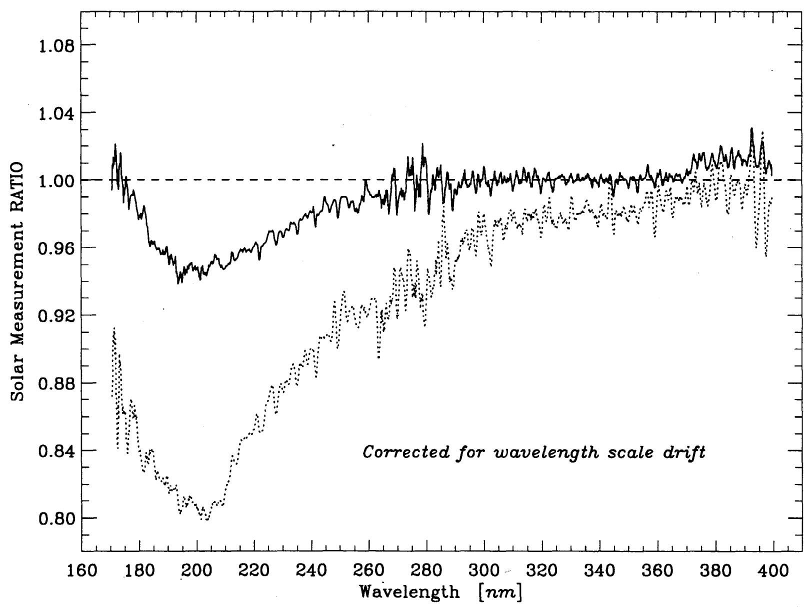

Figure 3. NOAA 11 spectral instrument sensitivity change between 170 and 400 nm at 1 year and 5 years from "day 1" (December 5, 1988), as in Figure 1. The 1989 and 1994 spectra were corrected for wavelength scale drift.

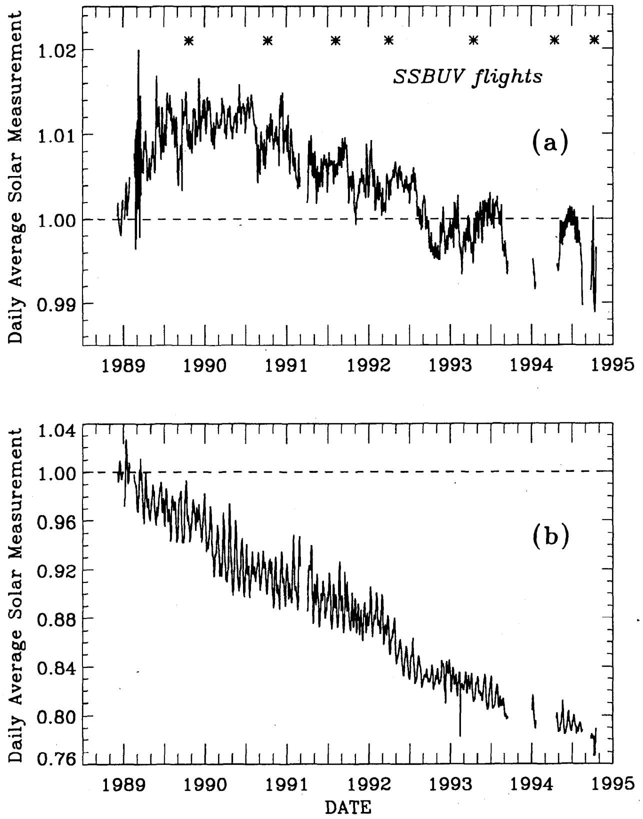

Figure 4. Time series of NOAA 11 SBUV/2 solar irradiance data at (a) 390 nm and (b) 205 nm, normalized to December 5, 1988. Each time series is a ±2 nm average. No correction for instrument sensitivity change was made. A 5-day binomial-weighted average was used to reduce day-to-day noise. Dates of SSBUV flights are marked in Figure 4a with asterisks.

in the NOAA 11 corrected solar data during February-September 1989 has been removed, based on evidence from NOAA 11 V6 profile ozone comparisons with Nimbus 7 SBUV data (see *Hilsenrath et al.* [1995] for discussion). The magnitude of the spectrometer throughput, or "sensitivity", change increases rapidly at shorter wavelengths, with a long-term decrease of more than 20% at 205 nm (Figure 4b). This wavelength region is particularly important because of its role in stratospheric photochemistry, where solar radiation dissociates O_2 molecules as part of the ozone production cycle [e.g., *Brasseur and Solomon*, 1986]. Short-term variations of 3-6% due to solar rotational modulation are evident throughout the 205 nm data, most prominently during the solar cycle 22 maximum period of 1989-1991. In order to successfully measure long-term solar variations using the NOAA 11 corrected data, the remaining sensitivity changes present in Figures 3 and 4 must be characterized both spectrally and temporally and removed. This can be done through comparisons with a well-calibrated external reference source.

The SSBUV instrument, the engineering model of the SBUV/2 instrument series, was configured to fly on the space shuttle. It uses a transmission diffuser rather than a reflecting plate for solar irradiance measurements but is otherwise optically identical to the satellite-based SBUV/2 instruments [*Hilsenrath et al.*, 1988]. The primary purpose of SSBUV is to support the international stratospheric ozone monitoring program in order to validate satellite ozone monitoring instruments' absolute calibrations, to maintain their long-term calibrations, and to provide in-flight calibration checks [*Frederick et al.*, 1990]. SSBUV also measures solar spectral irradiance over the wavelength range 160-405 nm, but its laboratory calibration is only valid between 200 and 405 nm because the measurement is performed in air. The SSBUV instrument calibration is thoroughly characterized by performing extensive laboratory absolute calibration measurements both preflight and postflight, as well as tracking relative changes during each flight via an on-board calibration system and vicarious calibration [*Cebula et al.*, 1989, 1998]. Additional discussion of the SSBUV calibration process is given by *Hilsenrath et al.* [1993, and references therein]. The SSBUV solar irradiance data underwent an extensive validation as part of the UARS/ATLAS validation effort, as described by *Cebula et al.* [1996] and *Woods et al.* [1996]. The first seven SSBUV flights occurred during the operational lifetime of the NOAA 11 SBUV/2 instrument, providing multiple coincident observations over a 5-year period. We have used these coincident data to develop spectral and temporal corrections for long-term NOAA 11 spectrometer sensitivity changes.

3. Spectral Correction Analysis

Table 2 lists the dates for which SSBUV made solar irradiance measurements during its first seven flights. These dates are shown by the asterisks in Figure 4a. On each of these dates, SSBUV observed the Sun during up to four ~35 min long solar observation periods, obtaining between three and eight spectral scans in each period. In order to improve signal-to-noise for the NOAA 11 data, which only obtained two scans during each daily spectral solar observation, we constructed averages of all NOAA 11 and SSBUV solar measurements for the dates of each SSBUV flight. A separate analysis has shown that if individual coincidence dates are used, rather than flight averages, the results derived in this paper are substantially unchanged. By using coincident NOAA 11 and SSBUV spectra, solar activity variations cancel when constructing spectral ratios. Exact coincident NOAA 11 data were unavailable for the time of the SSBUV 6 mission because of diffuser shadowing caused by orbital drift, and for the SSBUV 7 observation dates because the NOAA 11 diffuser deployment mechanism failed on October 19, 1994. We used NOAA 11 data from ~27 days after the SSBUV 6 observation dates and ~27 days before the SSBUV 7 dates for those coincidence ratios to minimize the possible impact of solar rotational variations. For both flights, the difference in the NOAA 9 discrete Mg II index [*DeLand and Cebula*, 1998] between the SSBUV flight dates and the NOAA 11 measurement dates used for the coincidence ratios was <1%. These solar activity differences were then estimated and corrected by using the average of the NOAA 11 Mg II index for each flight [*Cebula and DeLand*, 1998] and the spectral scale factors of *DeLand and Cebula* [1993]. This method provides an accurate representation of short-term solar irradiance variations [*Lean et al.*, 1992]. The maximum correction was <1% at 205 nm, and <0.5% longward of 250 nm.

Table 2. SSBUV Solar Irradiance Observation Dates

Flight	*Dates*
1	October 19, 20, 21, 1989
2	October 7, 8, 9, 1990
3	August 3, 4, 5, 6, 1991
4	March 29, 31, 1992
5	April 9, 11, 13, 15, 16, 1993
6	March 14, 15, 17, 1994
7	November 5, 7, 10, 13, 1994

The coincident measurement ratios contain any absolute irradiance differences between NOAA 11 and SSBUV, SSBUV calibration uncertainties, and long-term NOAA 11 sensitivity changes. An extensive discussion of SSBUV absolute calibration uncertainties is given by *Woods et al.* [1996]. The repeatability of the SSBUV irradiance measurements at wavelengths longward of 300 nm was estimated to be better than 1.5% by *Cebula et al.* [1994]. In order to simplify the interpretation of the NOAA 11/SSBUV coincident ratios, we normalized all of the SSBUV flight average irradiances to the SSBUV 2 flight average at 400 nm. Solar cycle variability at this wavelength is believed to be <1% [*Lean*, 1991]. The adjustments to the SSBUV data produced by this step were <±0.5% for all flights, consistent with previous estimates of SSBUV repeatability.

To characterize the spectral bias between these instruments, we constructed the ratio of the initial NOAA 11 inflight solar measurements on December 5, 1988 ("day 1"), to the average irradiance spectrum from the SSBUV 2 flight in October 1990. The SSBUV 1 data were not used for this step because of calibration difficulties which led to residual errors of ~1-2% for wavelengths shortward of 275 nm [*Cebula and Hilsenrath*, 1992, 1994; *Cebula et al.*, 1994]. Average solar activity variations between the observation dates in December 1988 and October 1990 were small (ΔMg II = 0.4%) and were corrected using the NOAA 11 Mg II index and spectral scale factors as discussed previously. The NOAA 11/SSBUV spectral bias is shown in Figure 5 and lies within the ±3% range over the wavelength interval 200-350 nm, increasing to +7% at 380 nm. For comparison, the ATLAS 1 SSBUV (SSBUV 4) spectrum agreed with the mean UARS solar spectrum to within ±2% over 200-405 nm on March 29, 1992 [*Woods et al.*, 1996]. The ATLAS 1 SSBUV data are also in excellent agreement with the ATLAS 1 mean spectrum (the mean solar irradiance from the SSBUV, SUSIM, and SOLSPEC instruments), with no offset and localized fluctuations of <±2% [*Cebula et al.*, 1996]. Considering the accuracy of the SSBUV absolute calibration demonstrated by these comparisons, we expect that the majority of the spectral bias in Figure 5 reflects errors in the NOAA 11 absolute calibration. The absolute calibration error budget for NOAA 11 SBUV/2 from all sources (see discussion of Table 3) is similar to the SSBUV error budget [*Woods et al.*, 1996], since the two instruments have essentially the same design except for the use of a transmission diffuser on SSBUV.

The NOAA 11 absolute radiometric calibration combines short-wavelength data taken in vacuum using an argon miniarc lamp as the irradiance source and long-wavelength data taken in air using deuterium lamps and a quartz-halogen arc as the spectral sources. The vacuum data are utilized shortward of ~220 nm and normalized to the air data to create the irradiance calibration. Comparisons of laboratory calibrations of other SBUV/2 instruments show regular fluctuations with scales of 30-40 nm in the ratios of instrument responsitivity measured in air to that measured in vacuum [*Fowler*, 1994], referred to here as "air-to-vacuum" differences. These differences, which arise from wavelength-dependent changes in instrument radiometric responsivity between air and vacuum, are similar to the fluctuations noted in Figure 5 for wavelengths longward of ~260 nm. Limited vacuum-based NOAA 11 prelaunch calibration data were taken for the entire spectral region 160-400 nm. However, these data were not intended to be used for determination of the NOAA 11 absolute radiometric calibration. We hope to examine these vacuum data in the future with the goal of eliminating errors in the NOAA 11 absolute calibration due to the air-to-vacuum differences, while at the same time preserving the overall accuracy of the current calibration. The NOAA 11/SSBUV spectral bias in Figure 5 is less than the initial data bias of +5-15% between Nimbus 7 SBUV and SSBUV, and is comparable to the NOAA 11 versus NOAA 9 "day 1" bias [*Cebula et al.*, 1991]. Separate comparisons with UARS SUSIM and SOLSTICE [*DeLand and Cebula*, this issue] indicate that the NOAA 11 irradiance calibration has a significant error at wavelengths below 190 nm, increasing to +20-25% at 170 nm. We hope to revisit the NOAA 11 absolute calibration to reconcile this discrepancy. For the present work, the difference between NOAA 11 and SSBUV is an improvement over the Nimbus-7 SBUV versus SSBUV comparison, and exceeds the

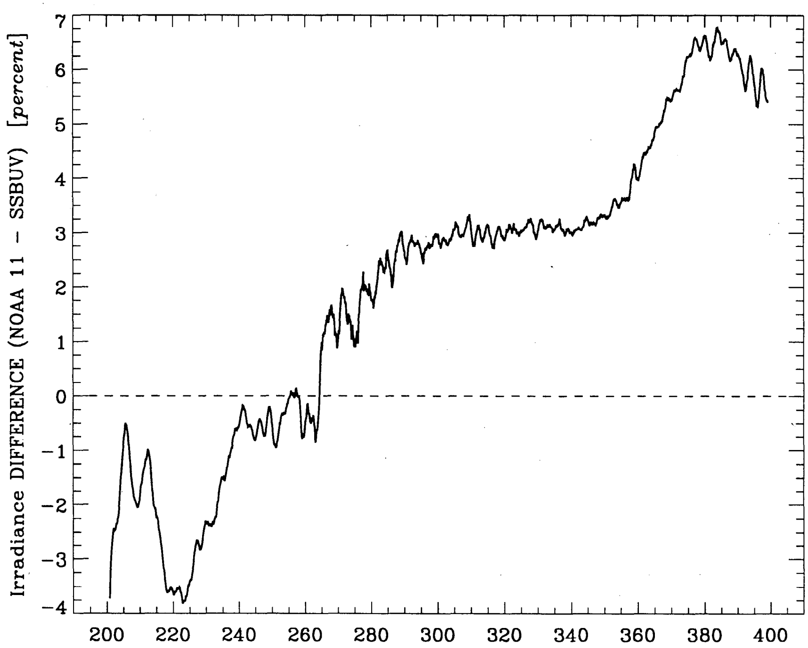

Figure 5. Irradiance difference between the NOAA 11 "day 1" solar spectrum (average of December 5, 7, 9, 1988) and the SSBUV 2 average spectrum (October 7-9, 1990). Estimated solar activity changes were removed. An 11-point running average was applied for smoothing.

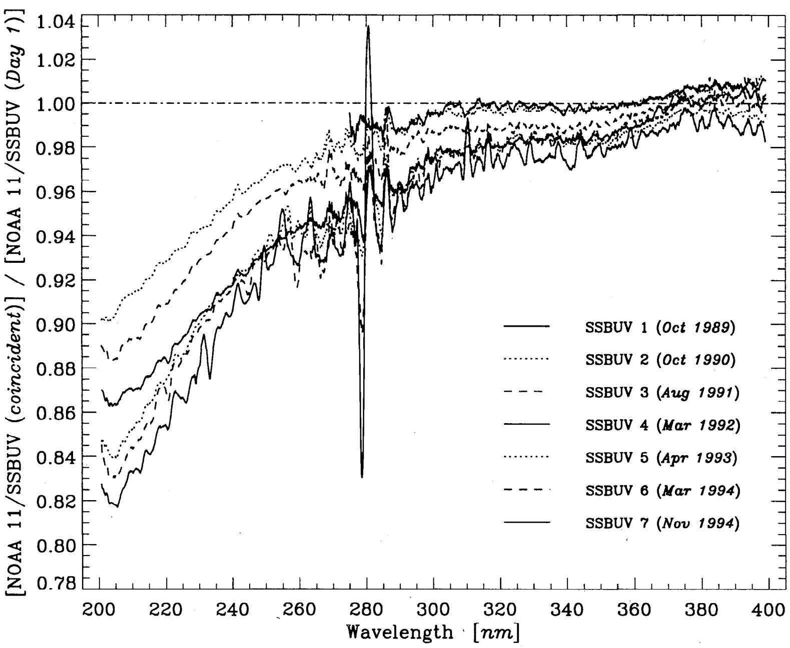

Figure 6. Ratios of coincident NOAA 11 SBUV/2 and SSBUV spectra for the first seven SSBUV flights, normalized to the initial irradiance ratio of Figure 5. An 11-point running average was applied.

2σ uncertainty of the NOAA 11 calibration only for $\lambda \geq 350$ nm. Since the goal of this work is to produce long-term corrections for the NOAA 11 irradiance data and to create a data set suitable for studies of solar variability, we have not adjusted the absolute calibration to correspond to an external reference. Users who require more accurate absolute solar irradiance data may wish to utilize data sources such as SSBUV, UARS SUSIM, or UARS SOLSTICE.

The NOAA 11/SSBUV coincident ratios for each SSBUV flight, normalized by the spectral bias correction discussed above, are shown in Figure 6. As discussed previously, SSBUV 1 data are not shown at $\lambda < 275$ nm. The general spectral shape noted in Figure 3 is evident in each of the coincident ratios. Residual small-scale structure ($\Delta\lambda < 10$ nm) is most likely an indication of small errors in the time-dependent NOAA 11 wavelength scale correction, as is the large "sawtooth" shape at 280 nm in the SSBUV 7 coincident ratio. Localized errors of this nature can be corrected for further use of individual spectra but are not important for the analysis performed in this paper. The determination of the exact NOAA 11 wavelength scale correction for specific dates is also subject to some uncertainty, as shown by the data scatter about the power law fit in Figure 2, which increases from 1993 on. In addition, the difficulties of matching wavelength scales, band-pass width, and band-pass shape between different instruments for solar irradiance comparisons have been discussed by *Cebula et al.* [1996] and *Woods et al.* [1996]. Although the NOAA 11 SBUV/2 and SSBUV instruments have very similar slit functions, even minor differences are amplified in the vicinity of strong solar absorption features such as the unresolved Mg II doublet at 280 nm. Since we do not feel that the small-scale structure in the spectral ratios shown in Figure 6 represents true NOAA 11 sensitivity change, we fit each spectral ratio to get a smooth representation for the spectral sensitivity change $\Delta F_{\mathrm{Inst}}(\lambda)$. A smoothing spline function called CLOESS, based on loess fitting methods described by *Cleveland and Grosse* [1991], was applied to the spectral ratios. With an appropriate choice of fit tension, the CLOESS function successfully reproduced only the ratio structure at scales greater than ~20 nm, which we believe to be indicative of true instrument sensitivity changes. The CLOESS spline fits to the NOAA 11/SSBUV coincident ratios corresponding to each of the SSBUV flights give RMS fit errors less than 0.3% for SSBUV flights 1-4, increasing to 0.4%, 0.7%, and 1.2% for flights 5-7, respectively. The increase for the later flights is predominately due to residual wavelength drift errors in the 270-290 nm region, as shown in Figure 6.

4. Temporal Correction Analysis

Given the spectral dependence of the NOAA 11 sensitivity changes represented by the wavelength-dependent spline fits, the temporal dependence at any wavelength can then be examined. Figure 7 shows the spectral spline fit values at various wavelengths, extracted for the dates of each SSBUV flight as a function of time. The overall time dependence is consistent with the physical expectation that the solarization of contaminants on optical surfaces by UV radiation produces a significant initial sensitivity change, which becomes less rapid with time. While an exponential function is often used to characterize such changes, the lack of SSBUV 1 data shortward of 275 nm makes it difficult to constrain such a fit in the spectral region where it is most relevant. We have used quadratic temporal fits to the NOAA 11/SSBUV coincident ratio ~~data~~ points derived from the CLOESS fits to determine the time-dependent NOAA 11 instrument sensitivity change at each wavelength. Using a higher-order polynomial or a spline fit, such as the CLOESS function discussed earlier, to derive a time dependence would clearly remove most of the residual error from these fits. However, this method then implies knowledge of the NOAA 11 temporal behavior between SSBUV flights, which is difficult to justify because of the sparse sampling of the coincident data (8-12 months) and also puts considerable weight on the validity of the 0.5-1.0% fluctuations between points shown in Figure 7. In addition, $\Delta F_{\mathrm{Inst}}(\lambda,t)$ would then have an extremely complicated, spectrally dependent time dependence. The uncorrected NOAA 11 time series, such as those shown in Figure 4, are generally free from abrupt changes in behavior on timescales of 6 months or less. The quadratic temporal fits to the coincident ratio data points are shown in Figure 7. An initial data point with a value of 1.0 has been added

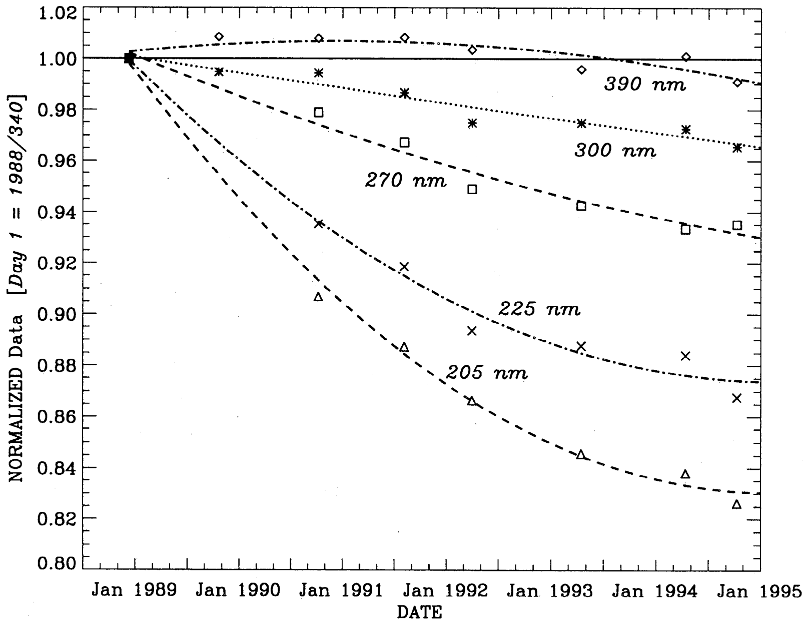

Figure 7. NOAA 11 instrument sensitivity changes for the dates of the first seven SSBUV flights, calculated from CLOESS spectral dependence spline fits at 205 nm (triangles), 225 nm (crosses), 270 nm (squares), 300 nm (asterisks), and 390 nm (diamonds). Quadratic fits to the temporal dependence at each wavelength are also plotted.

at the beginning of the NOAA 11 data record for each wavelength to help constrain the fits. The quadratic fits give residual errors of 0.5-0.8% between 200 and 260 nm, with errors generally <0.5% longward of 300 nm. The sensitivity change curves are nearly linear at 390 and 300 nm, where the overall throughput change is small relative to that observed at wavelengths shortward of 260 nm. A full spectral distribution of the quadratic fit 2σ error is presented in section 6.

5. Irradiance Data at 170-200 nm

Solar irradiance in the 170-200 nm wavelength region is an important component of the photochemistry of the upper stratosphere and lower mesosphere, primarily through O_2 absorption in the Schumann Runge bands [*Brasseur and Solomon*, 1986]. Although its radiometric sensitivity declines abruptly shortward of 190 nm, the NOAA 11 SBUV/2 instrument has a sufficiently high signal-to-noise ratio (~35:1) down to 170 nm that it can be used to track solar variations in this spectral region if time-dependent instrument degradation can be adequately characterized. However, the SSBUV absolute irradiance calibration is performed in air, so that molecular oxygen absorption prevents use of those data for wavelengths shortward of 200 nm. As shown in Figures 1 and 3, the NOAA 11 sensitivity change has a dramatically different spectral character shortward of 200 nm, preventing the simple extrapolation of the spectral ratio fits using the 200-400 nm data. In order to characterize $\Delta F_{Inst}(\lambda,t)$ at $\lambda < 200$ nm, we have chosen to make an initial estimate of NOAA 11 instrument throughput change by constructing time series similar to those shown in Figure 4, then removing the solar change predicted by the NOAA 11 Mg II index and scale factors, and then fitting the resulting data with a quadratic time dependence. This process was repeated at 5 nm intervals between 170 and 220 nm. The quadratic fit values at the SSBUV flight dates were then calculated and appended to the 200-400 nm coincident spectral ratio data shown in Figure 6. Finally, new CLOESS fits for each SSBUV flight were constructed. Examples of these results for SSBUV 2 and SSBUV 7 are shown in Figure 8.

We recognize that this process is circular, in that a predicted solar variation is removed from the irradiance data to estimate instrument sensitivity change, which is then removed so that the corrected irradiance data can be examined for solar variations. As shown in Figure 8, we have also used this procedure in the 200-220 nm spectral region, where we have directly determined long-term instrument changes using coincident data. The fitted time series values shown as symbols in Figure 8 lie within 2% of the coincident values in this spectral region, giving us some confidence that our method is not grossly in error. More importantly, the CLOESS fit to the combined data follows the more densely sampled irradiance ratios ($\Delta\lambda \approx 0.15$ nm) down to 200 nm before turning up to track the time series fit values. The CLOESS fit values at $\lambda > 200$ nm in Figure 8 agree with those calculated using 200-400 nm ratio fits alone to better than 0.1%. Nevertheless, we caution the user that because of the nature of the correction method derived in this section, the NOAA 11 irradiance values between 170 and 200 nm are more uncertain than those in the 200-400 nm region (see Table 3 and associated discussion). Derived estimates of solar long-term variability from these data at $\lambda < 200$ nm are largely determined by the solar change predicted by the Mg II index and scale factors and should be used with care. NOAA 11 measurements of short-term solar variations between 170-200 nm are not affected by this procedure and can be used with confidence.

6. Discussion of Results

The NOAA 11 SBUV/2 spectral scan solar irradiance data have been processed using the sensitivity change corrections derived in this paper. Equation (2) presents the formula used to derive the corrected irradiances:

$$I = C\ W\ f_{Degrade} \qquad (2)$$

$I(\lambda,t)$	absolute irradiance [mW m^{-2} nm^{-1}];
$C(\lambda,t)$	internally corrected solar data (from equation (1)) [mW m^{-2} nm^{-1}];
$W(t)$	wavelength scale drift correction;
$f_{Degrade}(\lambda,t)$	instrument throughput correction.

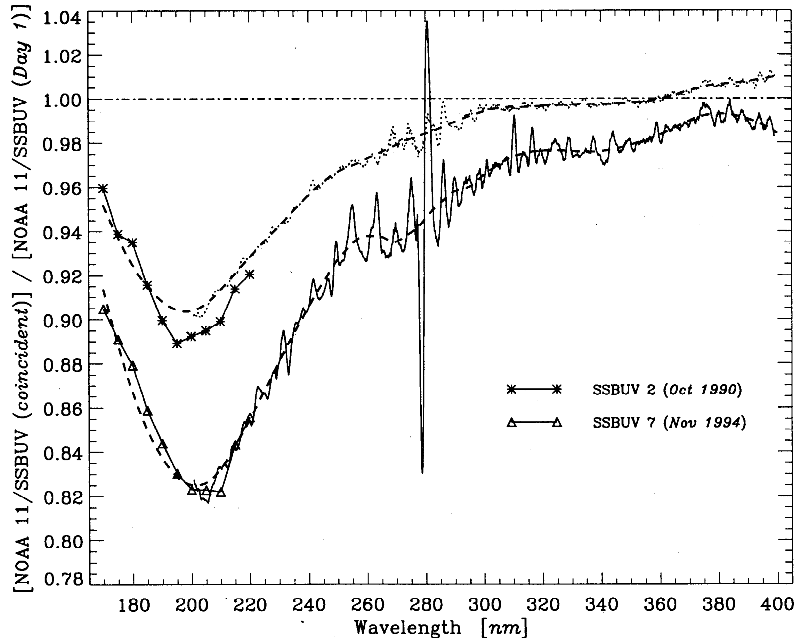

Figure 8. CLOESS spline fits (dashed lines) for NOAA 11 spectral instrument sensitivity change between 170 and 400 nm for SSBUV flights 2 and 7. The NOAA 11/SSBUV coincident ratio data (thin solid line) are identical to Figure 6. The sensitivity change points between 170 and 220 nm (triangles SSBUV 2; squares SSBUV 7) were determined from quadratic fits to solar time series, as discussed in the text.

The corrected irradiance time series at 390 nm shown in Figure 9a changes by approximately +1% during 1989 then changes by <1% during 1990-1994. Since we expect little or no solar variation near 400 nm, this result indicates the accuracy of our long-term correction. The corrected irradiance time series at 300 nm (Figure 9b) is almost identical to the 400-nm time series. The temporal shape of these curves suggests that the quadratic time dependence of the sensitivity change slightly overcorrects the irradiance data during 1989. However, as discussed in section 4, the limited sampling of the SSBUV flights makes it difficult to invoke a more complex time dependence for $\Delta F_{Inst}(\lambda,t)$ without some a priori knowledge of what the functional form "should" look like.

At shorter wavelengths, the time dependence of the NOAA 11 irradiance data looks considerably different from the internally corrected solar data shown in Figure 4b. As shown in Figure 10a, the 205 nm time series is fairly flat during 1989-1991, coincident with the maximum of solar cycle 22, and then drops sharply in April 1992. Solar rotational modulation amplitudes varying between 3 and 7% are clearly visible during this period. By the end of the NOAA 11 solar data record in October 1994, the 205 nm irradiance has decreased by ~7% from its maximum average level in mid-1991. This change is in good agreement with the NOAA 11 Mg II index time series of *Cebula and DeLand* [1998], which is shown in Figure 10b. Using the scale factors of *DeLand and Cebula* [1993] and the NOAA 11 Mg II index data, we can independently estimate the solar activity at 205 nm during 1989-1994. The average Mg II index scale factor for 203-207 nm is 1.04(±0.05) [see also *Chandra et al.*, 1995], which helps minimize possible errors in the comparison with the observed NOAA 11 irradiances. Figure 11 presents the difference between the observed variations at 205 nm and the predicted variations from the proxy model. The relative drift between these data sets is ~1% over the 5.5-year NOAA 11 data record. The excellent agreement between NOAA 11, NOAA 9, and UARS SUSIM Mg II index data presented by *Cebula and DeLand* [1998] implies that there is no long-

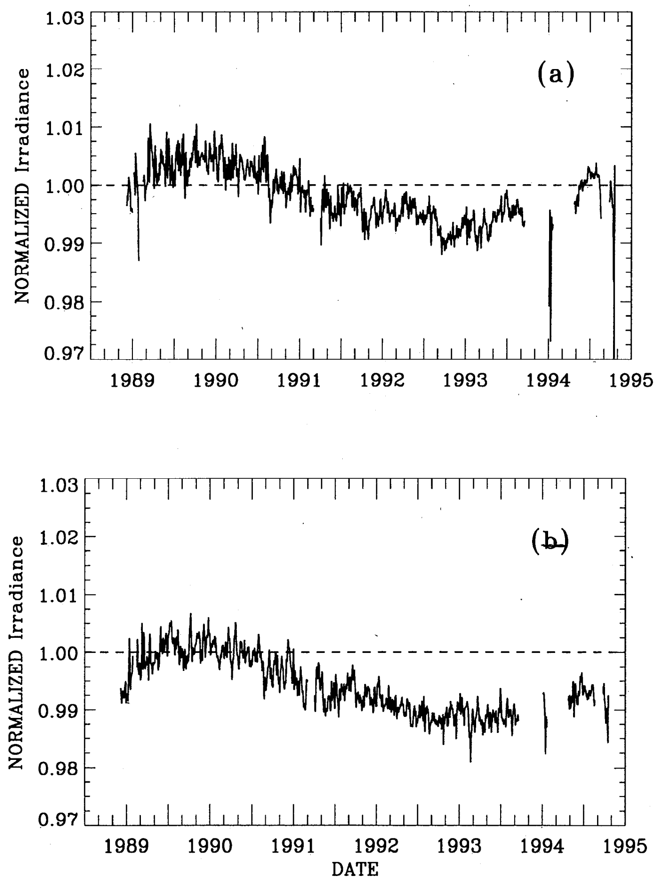

Figure 9. Time series of NOAA 11 SBUV/2 solar irradiance data at (a) 390 nm and (b) 300 nm, corrected for long-term instrument sensitivity change and normalized to December 5, 1988. Each time series is a ±2 nm average.

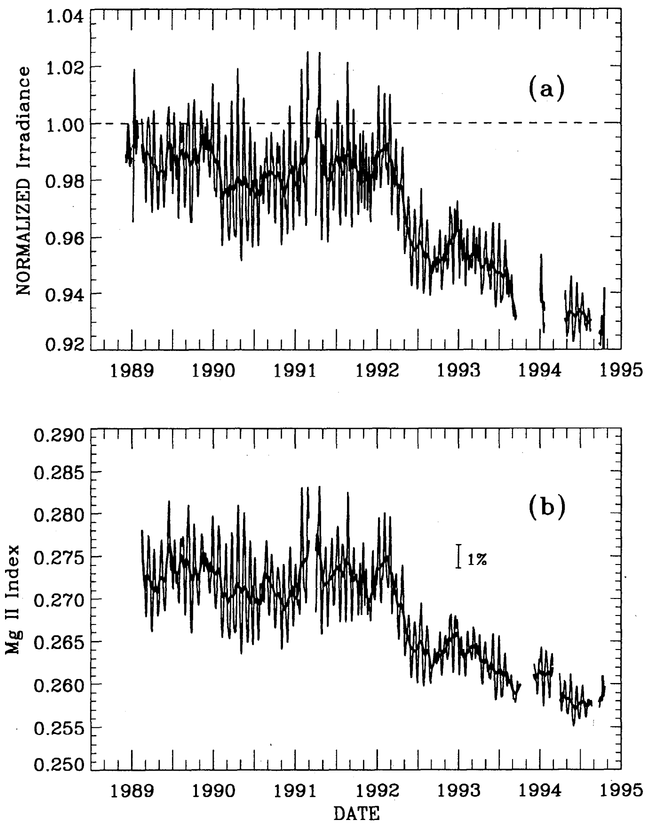

Figure 10. (a) NOAA 11 solar irradiance time series at 205 nm (±2 nm average), corrected for long-term instrument sensitivity change and normalized to December 5, 1988. (b) NOAA 11 "classical discrete" Mg II index time series [from *Cebula and DeLand*, 1998]. The heavy solid line in each panel is a 27-day running average of the data.

term drift in the NOAA 11 Mg II index data. Thus, Figure 11 suggests that the results of the Mg II proxy model and the NOAA 11 corrected irradiances agree to within ~1% over 5.5 years. Power spectral analysis of the data in Figure 11 shows no sign of significant periodicity near 27 days, indicating that the scaled Mg II index correctly represents the strength of 205 nm rotational variations at all levels of solar activity. *DeLand and Cebula* [this issue] further discuss the long-term spectral solar activity observed in the NOAA 11 irradiance data, as well as compare contemporaneous UARS SOLSTICE and SUSIM data.

The absolute accuracy of the NOAA 11 irradiance data is determined by uncertainties from both the prelaunch and inflight instrument characterizations. Table 3 presents a summary of the uncertainty budget for NOAA 11 SBUV/2 solar irradiance data. All entries represent ±2σ uncertainties in percent. The three wavelengths 180, 250, and 350 nm were chosen to be representative of the instrument's three electronic gain ranges, and error estimates at 205 nm are also included because of the importance of this wavelength for stratospheric ozone photochemistry. Numerical values in parentheses represent maximum errors within a given wavelength region. We have chosen to separate the uncertainty calculations into static and dynamic (time-dependent) equations in order to clearly distinguish the factors which primarily affect the absolute value of a single irradiance measurement from those which influence the long-term irradiance results. Equation (3) presents the calculation of the static uncertainties, following *Bevington* [1969]:

$$\sigma^2_{\mathrm{Static}} = \left(\frac{S\sigma_S + D\sigma_D}{S - D}\right)^2 + \sigma^2_{\mathrm{N}} + \sigma^2_{\mathrm{TCorr}} + \sigma^2_{\mathrm{R}} + \sigma^2_{\mathrm{A}} + \sigma^2_{\mathrm{W}} + \sigma^2_{\mathrm{AU}} \quad (3a)$$

where the uncertainty terms for the raw signal (σ_S) and the responsivity (σ_R) include the following components:

$$\sigma^2_{\mathrm{S}} = \sigma^2_{\mathrm{Scatt}} + \sigma^2_{\mathrm{Amp}} + \sigma^2_{\mathrm{SNR}} \quad (3b)$$

$$\sigma^2_{\mathrm{R}} = \sigma^2_{\mathrm{Lamp}} + \sigma^2_{\mathrm{Trans}} + \sigma^2_{\mathrm{Air}} \quad (3c)$$

The laboratory characterization section of Table 3 includes terms for radiometric calibration standards as well as prelaunch characterization results. The electronic amplification term (σ_{Amp}) represents the uncertainty in the electronic gain of the instrument.

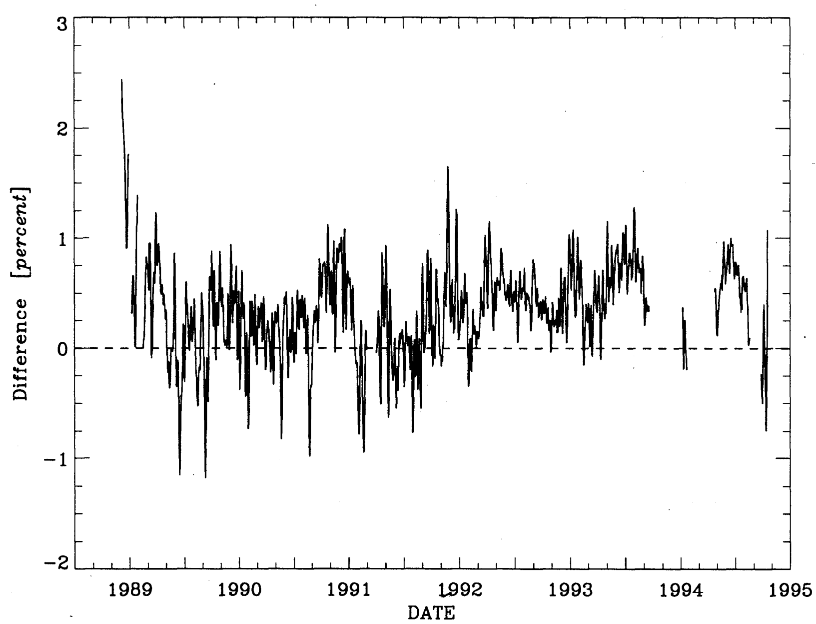

Figure 11. Time series plot of the difference in percent between the normalized NOAA 11 200-208 nm irradiance data and the solar activity variations predicted by the NOAA 11 Mg II index and scale factors.

Table 3. NOAA 11 SBUV/2 Uncertainty Budget

	180 nm	205 nm	250 nm	350 nm
	Static			
Laboratory characterization				
Scattered light (σ_{Scatt})	< 0.05	<0.05	< 0.05	< 0.05
Electronic amplification (σ_{Amp})	0.5	0.5	0.5	0.5
Signal-to-noise (SNR) (σ_{SNR})	2.0	0.45	0.08	0.05
Linearity (σ_N)	0.1	0.1	0.1	0.1 (0.6)
PMT temperature correction (σ_{TCorr})	0.2	0.2	0.2	—
NIST lamp calibration (σ_{Lamp})	5.0	5.0	1.9	1.1
Laboratory transfer (σ_{Trans})	3.0	3.0	2.0	2.0
Air-to-vacuum (σ_{Air})	7.0	7.0	5.0	2.0
Solar distance (σ_{AU})	< 0.02	< 0.02	< 0.02	< 0.02
Inflight characterization				
Electronic offset (σ_D)	0.2	<0.1	< 0.1	0.1 (0.5)
Goniometry (σ_A)	1.5	0.7	0.2	0.4
Wavelength scale correction (σ_W)	0.2 (0.4)	0.3 (0.7)	0.1 (0.8)	0.1
RMS total for static, %	9.6	9.2	5.8	3.1
	Dynamic			
Diffuser reflectivity (σ_{Diff})	0.2	0.2	0.2	0.2
Interrange ratio (σ_G)	1.0	1.0	1.0	—
Instrument sensitivity fits (σ_{Sens})	—	1.0	1.2	0.6
SSBUV repeatability (σ_{Repeat})	—	0.9	0.6	0.4
SSBUV normalization (σ_{Norm})	—	0.5	0.5	0.5
Short wavelength (σ_{SW})	2.0	—	—	—
RMS total for dynamic, %	2.3	1.8	1.8	0.9

All uncertainties are $\pm 2\sigma$ in percent. Values in parentheses represent maximum errors for local wavelength region.

Scattered light (σ_{Scatt}) is very low for the SBUV/2 design, and out-of-band rejection was found to be better than 10^5 in tests on the NOAA 9 SBUV/2 instrument. The signal-to-noise ratio (SNR) error values (σ_{SNR}) are based on engineering studies. They exceed 0.1% only at wavelengths shortward of 220 nm but reach 3% at 170 nm (Figure 12). The PMT temperature correction term (σ_{TCorr}), which is only applied to range 1 and range 2 data, combines the typical variability in the PMT temperature over a complete spectral scan and the uncertainty in the correction function for normal inflight temperatures. The linearity in each gain range is evaluated prelaunch, and any deviations (typically < 1%) are characterized with a functional fit for operational use. The values quoted in Table 3 for σ_N represent estimated error in the nonlinearity correction and exceed 0.1% only for low range 3 signals ($\lambda \approx$ 260-290 nm in the

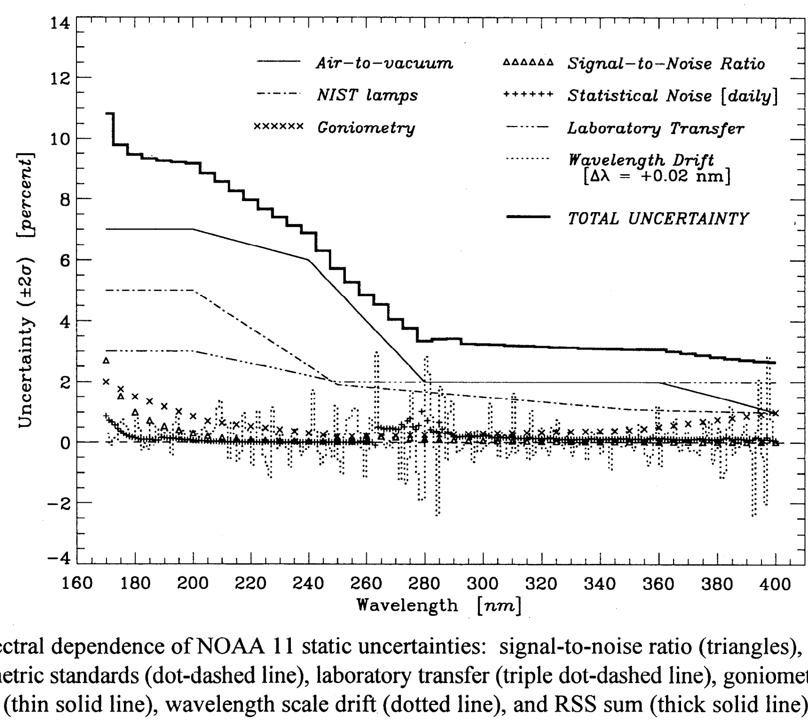

Figure 12. Spectral dependence of NOAA 11 static uncertainties: signal-to-noise ratio (triangles), electronic offset (pluses), radiometric standards (dot-dashed line), laboratory transfer (triple dot-dashed line), goniometry (crosses), air-to-vacuum bias (thin solid line), wavelength scale drift (dotted line), and RSS sum (thick solid line).

solar data). The values for the National Institute for Standards and Technology (NIST) lamps (σ_{Lamp}) and the laboratory transfer (σ_{Trans}) are the same as those presented for SSBUV by *Woods et al.* [1996]. The entries for air-to-vacuum bias (σ_{Air}) are taken from *Fowler* [1994, Figure 2] and are intended to represent the maximum value of the bias near each reference wavelength rather than a "point" value. Based on the difference with SSBUV shown in Figure 5, the actual NOAA 11 bias shortward of 250 nm is probably much smaller than the curve shown in Figure 12. We hope to quantify and eliminate most of the NOAA 11 air-to-vacuum bias in future processing. The uncertainty value for the solar distance correction (σ_{AU}) reflects a possible difference of up to 23.5 hours between the SBUV/2 solar measurement on a given date and the calculated correction defined at 0 hours UT [*U.S. Government Printing Office*, 1997].

The inflight characterization section in Table 3 represents quantities for which the final characterization used in irradiance data processing is based on inflight measurements, even though in some cases prelaunch studies were done. Detailed descriptions of the analysis procedures are given by *Steinfeld et al.* [1997]. The electronic offset (σ_D) is based on a combination of nightside Earth view data and measurements taken with the instrument aperture covered, with nominal values of ~64 counts in each range. The impact of the observationally determined offset standard deviation values ($\sigma_{R1} \approx 2.3$ counts, $\sigma_{R2} \approx 0.06$ counts, $\sigma_{R3} \approx 0.4$ counts) is spectrally dependent, as shown by the pluses in Figure 12. The accuracy of the goniometric correction for the solar ray incidence angle on the diffuser plate varies throughout the two scan measurement sequence and maps into the irradiance spectrum in a complex fashion. The accuracy values in Table 3 (σ_A) incorporate both an improved goniometric correction similar to that described by *Hilsenrath et al.* [1995] and an empirical scan bias correction for data taken shortward of 210 nm. The wavelength drift correction fits calculated in Figure 2 have an estimated uncertainty of $\Delta\lambda = \pm 0.02$ nm due to scatter in the data. This noise is present throughout the Hg lamp fits and represents a random error rather than a time-dependent drift. A shift in wavelength scale has a nonuniform effect on measured solar irradiances due to the pervasive absorption lines in the UV spectrum, as shown by the dotted line in Figure 12 calculated with 1-nm binned irradiance data. The uncertainty values listed in Table 3 for the wavelength scale correction (σ_W) represent 5-nm bands and significantly reduce the impact of wavelength scale drift in the vicinity of strong absorption lines such as Mg II, Mg I, and Ca II. Finally, the heavy solid line in Figure 12 represents the RSS total uncertainty at 5 nm intervals for all quantities in the laboratory and inflight sections of Table 3, as calculated by equation (3). We expect that future implementation of an improved air-to-vacuum correction will reduce the total $\pm 2\sigma$ uncertainty to ~6-7% in the 200-nm region.

The dynamic characterization section in Table 3 lists error estimates associated with long-term instrument characterization. Combining these terms is given as

$$\sigma^2_{time} = \sigma^2_{fDiffuser} + \sigma^2_G + \sigma^2_{fDegrade} \tag{4a}$$

where

$$\sigma^2_{Degrade} = \sigma^2_{Sens} + \sigma^2_{Repeat} + \sigma^2_{Norm} + \sigma^2_{SW} \tag{4b}$$

The wavelength-dependent diffuser reflectivity degradation rates derived by *Steinfeld et al.* [1997] range from –0.3(±0.2)%/yr at 400 nm to –1.7(±0.3)%/yr at 170 nm, corresponding to uncertainties of 1.0-1.5% when scaled to the ~5.5 year NOAA 11 operational lifetime for solar observations. However, if the NOAA 11 degradation correction is determined directly from SSBUV coincidence ratios without applying the NOAA 11 diffuser reflectivity correction, the resulting NOAA 11 irradiances differ by less than 0.1% from the data presented here. We therefore adopt 0.2% (2σ) as a value for diffuser reflectivity error (σ_{Diff}). The time dependence of the interrange ratio fit $IRR_{23}(t)$ determined by *Steinfeld et al.* [1997] is only relevant for range 1 and 2 data, because range 3 data are read directly off the cathode of the PMT and are therefore not subject to uncertainties arising from the characterization of time-dependent PMT gain changes. The uncertainty estimate (σ_G) for the derived $IRR_{23}(t)$ fit is ~0.5% (2σ). However, we use a larger value of 1.0% in Table 3 to reflect the data adjustment made in September-October 1994, as discussed below. The standard deviations of the quadratic fits for instrument sensitivity time dependence (σ_{Sens}) vary with wavelength, as shown in Figure 13

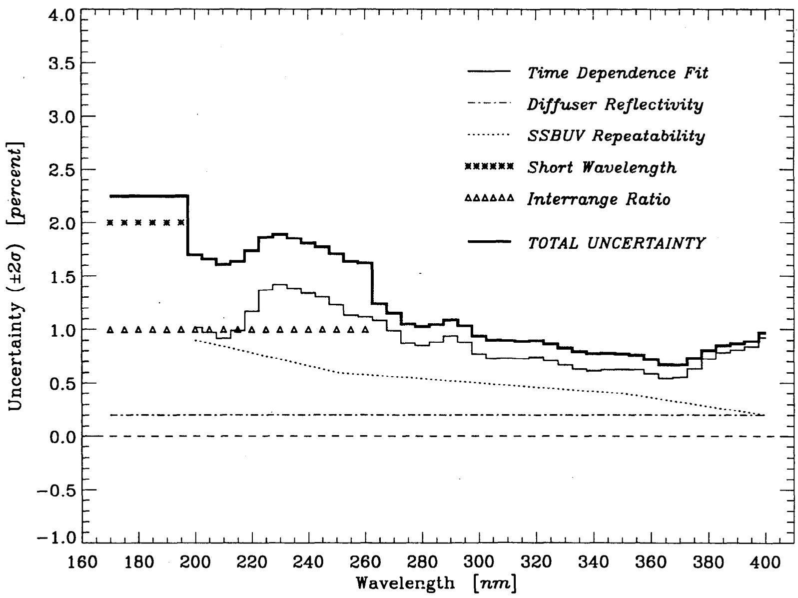

Figure 13. Spectral dependence of NOAA 11 dynamic uncertainties: sensitivity change fits (thin solid line), diffuser reflectivity correction (dot-dashed line), SSBUV repeatability (dotted line), short-wavelength sensitivity correction (asterisks), interrange ratio correction (triangles), and RSS sum (thick solid line).

(thin solid line) but are generally ~0.5%. There is no entry at 180 nm because the time dependence fit is influenced by the quadratic fit used to approximate instrument degradation in this spectral region. Our estimates for time-dependent NOAA 11 errors must also include the uncertainty in the SSBUV long-term results. Uncertainties in the long-term calibration of SSBUV do not translate directly into the NOAA 11 error budget because the SSBUV data from all flights were normalized at 400 nm before coincident spectral ratios were constructed, and also because the NOAA 11/SSBUV coincident ratios are fit temporally. A value of 0.5% (2σ) has been included to represent possible errors in the assumption of no solar variability at 400 nm introduced by the SSBUV normalization (σ_{Norm}), based on sunspot-induced solar irradiance variations summarized by *Lean* [1991]. The SSBUV "repeatability" uncertainty values (σ_{Repeat}) listed in Table 3 and shown in Figure 13 represent the spread in the flight-averaged irradiances after correction for solar variations and normalization at 400 nm. They include the results presented by *Cebula et al.* [1994] and data from SSBUV flights 5-7. For 180 nm, the "short wavelength" term (σ_{SW}) indicates an estimate of the accuracy of the quadratic fits used to characterize instrument throughput changes at wavelengths shortward of 200 nm. Combining these terms as shown in (4a) gives an RSS error estimate of approximately ±0.9% (2σ) for the accuracy of the NOAA 11 irradiance data at long wavelengths, and ±1.8% (2σ) at 205 nm for solar change over 5.5 years. The long-wavelength uncertainty value is consistent with the drift shown in the 390-nm and 300-nm time series of Figure 9. For shorter wavelengths with significant solar activity such as 205 nm, the drift in the "desolarized" data (e.g., Figure 11) is considerably better than the derived uncertainty limits.

The NOAA 11 solar spectral irradiance data set presented in this paper is generally quite well-behaved, but it does contain some specific spectral and temporal features that users should note.

1. The NOAA 11 instrument response at 180-200 nm degraded more rapidly than the quadratic fit function during the first year of observations, so that the reprocessed data in this wavelength region have a dip of ~2% during 1989 when solar activity is removed. In contrast, time series at all wavelengths greater than ~270 nm increase by ~1% during this same period, implying that the $\Delta F_{Inst}(\lambda,t)$ function is overcorrecting the observed data. As discussed in section 4, these results appear to be a consequence of the sparse data sampling used to derive the instrument sensitivity change time dependence correction and the simple functional form of that correction.

2. Time series constructed using relatively narrow band widths at regions with sharp irradiance gradients (e.g., 262-264, 392-394 nm) exhibit a drift of +2-4% during 1993-1994. This demonstrates a limitation of the wavelength scale drift correction adopted previously. While one of the solar absorption lines examined during the derivation of $\Delta\lambda(t)$ does show an upturn beginning in 1993, this result is not confirmed by measurements of neighboring lines. The data used to characterize the wavelength drift are not sufficiently convincing to justify a spectrally dependent wavelength scale correction. Thus certain narrow spectral regions may be subject to larger drifts than indicated by the uncertainty values in Table 3.

3. All solar data taken in the lowest two gain ranges ($\lambda \leq 270$ nm) during September-October 1994, after the end of a period of diffuser shadowing, were ~1% lower than the previous valid data in August 1994. The discrete solar data taken at the same time do not show a similar change. This offset in the irradiance data is at odds with the evidence from Earth view data, which were used to construct the interrange ratio time dependence for the NOAA 11 calibration and show no step at this time [*Steinfeld et al.*, 1997]. We have chosen to adjust the interrange ratio used in NOAA 11 solar irradiance processing by 1% for the September-October 1994 period in order to make the NOAA 11 solar irradiances self-consistent throughout the data set.

While none of these features are particularly large, we point them out as a caution to potential users of the NOAA 11 solar irradiance data, as an illustration of the challenges involved in attempting to characterize solar UV activity to 1% accuracy over a solar cycle.

7. Conclusions

The SBUV/2 instrument on the NOAA 11 satellite made spectral solar UV irradiance measurements from December 1988 to October 1994, covering the complete maximum and most of the declining phase of solar cycle 22. Although the SBUV/2 instruments carry an onboard calibration system capable of determining changes in the reflectivity of the solar diffuser plate (required for ozone monitoring), they do not incorporate an internal calibration system capable of monitoring long-term end-to-end instrument sensitivity changes. We have used comparisons with coincident solar observations from the SSBUV instrument to derive a complete sensitivity correction for the NOAA 11 solar irradiance data. A modified procedure was used to correct data in the 170-200 nm region which adds some uncertainty to the long-term variations in that region but does not affect short-term behavior. The NOAA 11 data are adequate for absolute irradiance comparisons, but other data with more extensive validations (e.g., SSBUV, SOLSTICE, SUSIM) are also available.

The estimated long-term accuracy of solar variations derived from the NOAA 11 data is ±0.9-2.3% (2σ), with better accuracy at longer wavelengths. *DeLand and Cebula* [this issue] examine these results in more detail, including extensive comparisons with concurrent data from UARS SUSIM and SOLSTICE. The corrected NOAA 11 irradiance data indicate a change of approximately 7.0(±1.8)% at 205 nm from the maximum smoothed data value for cycle 22 in mid-1991 to the end of the NOAA 11 data record in October 1994, when solar activity is approaching a minimum level. (The complete NOAA 11 solar irradiance data set, comprising daily average spectra from December 1988 to October 1994 over the wavelength range 170-400 nm, is available via anonymous FTP in the directory ssbuv.gsfc.nasa.gov/pub/solar/sbuv2/noaa11, or through the SBUV/2-SSBUV WWW site at http://ssbuv.gsfc.nasa.gov/solar.html). These data are gridded as 1-nm averaged values on 0.5-nm centers, for consistency with the UARS SOLSTICE and SUSIM level 3BS products currently available from the Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC). Given the success of the SSBUV-based correction technique for the NOAA 11 irradiance data, we plan to apply the same method to the NOAA 9 spectral irradiance data, which cover a complete solar cycle. The NOAA 9 satellite orbit drift over 13 years revealed significant errors in the prelaunch goniometric correction for extreme viewing conditions and produced rapid temperature fluctuations when the orbit approached the terminator that have impacted calibration results. These errors and the limited SSBUV overlap period (1989-1996 only) will make the NOAA 9 correction analysis more problematic.

Acknowledgments. Walter G. Planet and H. Dudley Bowman of NOAA/NESDIS provided the NOAA 11 SBUV/2 1B data. Andrew Au of Raytheon STX developed the IDL interface to the CLOESS spline fitting function. We wish to acknowledge the SSBUV Experiment Team, whose dedicated efforts provided the excellent long-term database which was used as our calibration reference. Helpful and instructive comments from two anonymous reviewers are appreciated. This work was supported by NASA grant NASW-4864.

References

Ahmad, Z., M. T. DeLand, R. P. Cebula, H. Weiss, C. G. Wellemeyer, W. G. Planet, J. H. Lienesch, H. D. Bowman, A. J. Miller, and R. M. Nagatani, Accuracy of total ozone retrieval from NOAA SBUV/2 measurements: Impact of instrument performance, *J. Geophys. Res.*, *99*, 22,975-22,984, 1994.

Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences*, 336 pp., McGraw-Hill, New York, 1969.

Brasseur, G., and S. Solomon, *Aeronomy of the Middle Atmosphere*, 2nd ed., 452 pp., D. Reidel, Norwell, Mass., 1986.

Brueckner, G. E., K. L. Edlow, L. E. Floyd, J. Lean, and M. E. VanHoosier, The Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) experiment on board the Upper Atmosphere Research Satellite (UARS), *J. Geophys. Res.*, *98*, 10,695-10,711, 1993.

Burrows, J. P., M. Weber, E. Hilsenrath, J. Gleason, S. Janz, R. P. Cebula, X.-Y. Gu, and K. Chance, Global Ozone Monitoring Experiment (GOME): Comparison of backscattered and O_3 (DOAS/BUV) retrievals, in *Atmospheric Ozone*, edited by R. D. Bojkov and G. Visconti, pp. 657-660, Parco Scientifico Tecnologico d'Abruzzo, Italy, 1998.

Cebula, R. P., and M. T. DeLand, Comparisons of the NOAA 11 SBUV/2, UARS SOLSTICE, and UARS SUSIM Mg II solar activity proxy indexes, *Sol. Phys.*, *177*, 117-132, 1998.

Cebula, R. P., and E. Hilsenrath, Ultraviolet solar irradiance measurements from the SSBUV-1 and SSBUV-2 missions, in *Proceedings of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22*, edited by R. F. Donnelly, pp. 250-264, NOAA Environ. Res. Lab., Space Environ. Lab., Boulder, Colo., 1992.

Cebula, R. P., and E. Hilsenrath, SSBUV middle ultraviolet solar spectral irradiance measurements, in *Ozone in the Stratosphere*, edited by R. D. Hudson, *NASA Conf. Publ., CP-3266*, 946-949, 1994.

Cebula, R. P., H. Park, and D. F. Heath, Characterization of the Nimbus-7 SBUV radiometer for the long-term monitoring of stratospheric ozone, *J. Atmos. Ocean. Tech.*, *5*, 215-227, 1988.

Cebula, R. P., E. Hilsenrath, and B. Guenther, Calibration of the shuttle borne solar backscatter ultraviolet spectrometer, *Proc. SPIE Int. Soc. Opt. Eng.*, *1109*, 205-218, 1989.

Cebula, R. P., M. T. DeLand, E. Hilsenrath, B. M. Schlesinger, R. D. Hudson, and D. F. Heath, Intercomparisons of the solar irradiance measurements from the Nimbus-7 SBUV, the NOAA-9 and NOAA 11 SBUV/2, and the STS-34 SSBUV instruments: A preliminary assessment, *J. Atmos. Terr. Phys.*, *53*, 993-997, 1991.

Cebula, R. P., M. T. DeLand, and B. M. Schlesinger, Estimates of solar ultraviolet variability using the solar backscatter ultraviolet (SBUV) 2 Mg II index from the NOAA 9 satellite, *J. Geophys. Res.*, *97*, 11,613-11,620, 1992.

Cebula, R. P., E. Hilsenrath, and M. T. DeLand, Middle ultraviolet solar spectral irradiance measurements, 1985-1992, from the SBUV/2 and SSBUV instruments, in *The Sun as a Variable Star*, edited by J. M. Pap et al., pp. 81-88, Cambridge Univ. Press, New York, 1994.

Cebula, R. P., E. Hilsenrath, P. W. DeCamp, K. Laamann, S. Janz, and K. McCullough, The SSBUV experiment wavelength scale and stability: 1988 to 1994, *Metrologia*, *32*, 633-636, 1995.

Cebula, R. P., G. O. Thullier, M. E. VanHoosier, E. Hilsenrath, M. Herse, G. E. Brueckner, and P. C. Simon, Observations of the solar irradiance in the 200-350 nm interval during the ATLAS-1 mission: A comparison among three sets of measurements-SSBUV, SOLSPEC, and SUSIM, *Geophys. Res. Lett.*, *23*, 2289-2292, 1996.

Cebula, R. P., L. K. Huang, and E. Hilsenrath, SSBUV sensitivity drift determined using solar spectral irradiance measurements, *Metrologia*, in press, 1998.

Chandra, S., J. L. Lean, O. R. White, D. K. Prinz, G. J. Rottman, and G. E. Brueckner, Solar UV irradiance variability during the declining phase of the solar cycle 22, *Geophys. Res. Lett.*, *22*, 2481-2484, 1995.

Cleveland, W. S., and E. Grosse, Computational methods for local regression, *Stat. and Comput.*, *1*, 47-62, 1991.

DeLand, M. T., and R. P. Cebula, Composite Mg II solar activity index for solar cycles 21 and 22, *J. Geophys. Res.*, *98*, 12,809-12,823, 1993.

DeLand, M. T., and R. P. Cebula, Solar UV activity at solar cycle 21 and 22 minimum from NOAA-9 SBUV/2 data, *Sol. Phys.*, *177*, 105-116, 1998.

DeLand, M. T., and R. P. Cebula, NOAA 11 solar backscatter ultraviolet, model 2, instrument (SBUV/2) instrument solar spectral irradiance measurements in 1989-1994, 2. Results and validation, *J. Geophys. Res.*, this issue.

DeLand, M. T., R. P. Cebula, and E. Hilsenrath, Solar UV contribution to stratospheric ozone variations 1989-1994, in *Atmospheric Ozone*, edited by R. D. Bojkov and G. Visconti, pp. 263-266, Parco Scientifico Tecnologico d'Abruzzo, Italy, 1998.

Floyd, L. E., L. C. Herring, D. K. Prinz, and G. E. Bruckner, Maintaining calibration during the long term space flight of the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM), *Proc. SPIE Int. Soc. Opt. Eng.*, *2831*, 36-47, 1996.

Fowler, W. F., Spectral sensitivity characteristic of the SBUV/2 instrument–Differences in air and vacuum, *Rep. Ball SER SBUV-WF-94-749*, Ball Aerospace, Boulder, Colo., Sept. 6, 1994.

Frederick, J. E., R. P. Cebula, and D. F. Heath, Instrument characterization for the detection of long-term changes in stratospheric ozone: An analysis of the SBUV/2 radiometer, *J. Atmos. Ocean Technol.*, *3*, 472-480, 1986.

Frederick, J. E., X. Niu, and E. Hilsenrath, An approach to the detection of long-term trends in upper stratospheric ozone from space, *J. Atmos. Ocean Technol.*, *7*, 734-740, 1990.

Heath, D. F., Observations of the intensity and variability of the near ultraviolet solar flux from the Nimbus 3 satellite, *J. Atmo. Sci.*, *26*, 1157-1160, 1969.

Heath, D. F., Space observations of the variability of solar irradiance in the near and far ultraviolet, *J. Geophys. Res.*, *78*, 2779-2792, 1973.

Heath, D. F., and B. M. Schlesinger, The Mg 280-nm doublet as a monitor of changes in solar ultraviolet irradiance, *J. Geophys. Res.*, *91*, 8672-8682, 1986.

Heath, D. F., A. J. Krueger, H. A. Roeder, and B. D. Henderson, The Solar Backscatter Ultraviolet and Total Ozone Mapping Spectrometer (SBUV/TOMS) for Nimbus G, *Opt. Eng.*, *14*, 323-331, 1975.

Herman, J. R., R. D. Hudson, and G. Serafino, Analysis of the 8-year trend in ozone depletion from empirical models of solar backscattered ultraviolet instrument degradation, *J. Geophys. Res.*, *95*, 7403-7416, 1990.

Hilsenrath, E., D. Williams, and J. Frederick, Calibration of long term data sets from operational satellites using the space shuttle, *Proc. SPIE Int. Soc. Opt. Eng.*, *924*, 215-222, 1988.

Hilsenrath, E., D. E. Williams, R. T. Caffrey, R. P. Cebula, and S. J. Hynes, Calibration and radiometric stability of the Shuttle Solar Backscatter Ultraviolet (SSBUV) experiment, *Metrologia*, *30*, 243-248, 1993.

Hilsenrath, E., R. P. Cebula, M. T. DeLand, K. Laamann, S. Taylor, C. Wellemeyer, and P. K. Bhartia, Calibration of the NOAA 11 SBUV/2 ozone data set from 1989 to 1993 using in-flight calibration data and SSBUV, *J. Geophys. Res.*, *100*, 1351-1366, 1995.

Labs, D., H. Neckel, P. C. Simon, and G. Thullier, Ultraviolet solar irradiance measurement from 200 to 358 nm during Spacelab 1 mission, *Sol. Phys.*, *107*, 203-219, 1987.

Lean, J., Solar ultraviolet irradiance variations: A review, *J. Geophys. Res.*, *92*, 839-868, 1987.

Lean, J., Variations in the Sun's radiative output, *Rev. Geophys.*, *29*, 505-535, 1991.

Lean, J., M. VanHoosier, G. Brueckner, D. Prinz, L. Floyd, and K. Edlow, SUSIM/UARS observations of the 120 to 300 nm flux variations during the maximum of the solar cycle: Inferences for the 11-year cycle, *Geophys. Res. Lett.*, *19*, 2203-2206, 1992.

Mount, G. H., and G. J. Rottman, The solar absolute spectral irradiance 1150-3173 Å: May 17, 1982, *J. Geophys. Res.*, *88*, 5403-5410, 1983.

Peeters, P., P. C. Simon, G. Rottman, and T. N. Woods, UARS SOLSTICE data as a calibration and validation for GOME, in *GOME Geophysical Validation Campaign: Final Results and Workshop Proceedings*, edited by P. Fletcher and F. Dodge, *Eur. Space Agency ESA WPP-108*, 75-83, 1996.

Prag, A. B., and F. A. Morse, Variations in the solar ultraviolet flux from July 13 to August 9, 1968, *J. Geophys. Res.*, *75*, 4613-4621, 1970.

Rottman, G. J., Observations of solar UV and EUV variability, *Adv. Space Res.*, *8*(7), 53-66, 1988.

Rottman, G. J., C. A. Barth, R. J. Thomas, G. H. Mount, G. M. Lawrence, D. W. Rusch, R. W. Sanders, G. E. Thomas, and J. London, Solar spectral irradiance, 120 to 190 nm, October 13, 1981 - January 3, 1982, *Geophys. Res. Lett.*, *9*, 587-590, 1982.

Rottman, G. J., T. N. Woods, and T. P. Sparn, Solar Stellar Irradiance Comparison Experiment: Instrument design and operation, *J. Geophys. Res.*, *98*, 10,667-10,678, 1993.

Schlesinger, B. M., and R. P. Cebula, Solar variation 1979-1987 estimated from an empirical model for changes with time in the sensitivity of the solar backscatter ultraviolet instrument, *J. Geophys. Res.*, *97*, 10,119-10,134, 1992.

Schlesinger, B. M., R. P. Cebula, D. F. Heath, M. T. DeLand, and R. D. Hudson, Ten years of solar change as monitored by SBUV and SBUV/2, in *Climate Impact of Solar Variability, NASA Conf. Publ. CP-3086*, 341-348, 1990.

Schmidtke, G., P. Seidl, and C. Wita, Airglow-solar spectrometer experiment (20-700 nm) aboard the San Marco D/L satellite, *Appl. Opt.*, *24*, 3206-3213, 1985.

Steinfeld, K., M. T. DeLand, R. P. Cebula, and S. L. Taylor, *NOAA 11 SBUV/2 (FM#4) version 6.1 calibration report, Tech. Rep. HSTX-3036-508-KS-97-015*, 159 pp., Hughes STX Corp., Lanham, Md., Aug. 18, 1997.

Thullier, G., M. Hersé, P. C. Simon, D. Labs, H. Mandel, and D. Gillotay, Observation of the UV solar spectral irradiance between 200 and 350 nm during the ATLAS 1 mission by the SOLSPEC spectrometer, *Sol. Phys.*, *171*, 283-302, 1997.

U. S. Government Printing Office, *Astronomical Almanac*, Washington, DC, 1997.

VanHoosier, M. E., J.-D. F. Bartoe, G. E. Brueckner, and D. K. Prinz, Absolute solar spectral irradiance 120-400 nm (results from the Solar Ultraviolet Spectral Irradiance Monitor-SUSIM-Experiment on board Spacelab 2), *Astrophys. Lett. Commun.*, *27*, 163-168, 1988.

Weber, M., J. P. Burrows, and R. P. Cebula, GOME Solar UV/VIS irradiance measurements in 1995 and 1996 - First results on proxy solar activity studies, *Sol. Phys.*, *177*, 63-77, 1998.

Wehrli, C., C. Frohlich, and J. Romero, Results of solar spectral irradiance measurements by SOVA2 on EURECA, *Adv. Space Res.*, *16*, (8)25-28, 1995.

Weiss, H., R. P. Cebula, K. Laamann, and R. D. Hudson, Evaluation of the NOAA 11 solar backscatter ultraviolet radiometer, mod 2 (SBUV/2): Inflight calibration, *Proc. SPIE Int. Soc. Opt. Eng.*, *1493*, 80-90, 1991.

Woods, T. N., G. J. Rottman, and G. J. Ucker, Solar Stellar Irradiance Comparison Experiment: Instrument calibration, *J. Geophys. Res.*, *98*, 10,679-10,694, 1993.

Woods, T. N., et al., Validation of the UARS solar ultraviolet irradiances: Comparisons with the ATLAS 1 and 2 measurements, *J. Geophys. Res.*, *101*, 9541-9569, 1996.

R.P. Cebula and M.T. DeLand, Raytheon STX Corporation, 4400 Forbes Blvd., Lanham, MD 20706. (e-mail: cebula@ssbuv.gsfc.nasa.gov; mdeland@stx.com)

E. Hilsenrath, Code 916, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: hilsenrath@ssbuv.gsfc.nasa.gov)

(Received October 8, 1997; revised April 6, 1998; accepted April 7, 1998.)