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Spectral solar UV irradiance data for cycle 21

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Abstract. The Nimbus 7 Solar Backscatter Ultraviolet (SBUV) instrument, which began taking data in November 1978, was the first instrument to make solar UV irradiance measurements covering both the minimum and maximum activity levels of a solar cycle. The currently archived irradiance data set was processed with an instrument characterization which fails to completely account for sensor degradation in the later part of the data record, thus limiting the accuracy of estimated long-term solar activity variations and the scientific value of the data. In this paper, we describe an improved Nimbus 7 SBUV spectral irradiance data set, which utilizes a more accurate model for instrument sensitivity and treats other time-dependent problems in the archived data. Estimated long-term irradiance changes during solar cycle 21 are 8.3(±2.6)% at 205 nm, and 4.9(±1.8)% at 240 nm. The revised Nimbus 7 SBUV irradiance data are in good agreement with predictions of solar cycle variations from the Mg II index proxy model. These solar irradiance changes are also consistent with overlapping irradiance data from the declining phase of solar cycle 21 measured by the Solar Mesosphere Explorer (SME). The Nimbus 7 SBUV irradiance data represent the earliest component of a 20+ year continuous record of solar spectral UV activity.

1. Introduction

Knowledge of the spectral distribution of solar irradiance is important for atmospheric photochemistry. At ultraviolet (UV) wavelengths, irradiance variations become significant on both rotational (~27-day) and solar cycle (~11-year) timescales. The most striking and consistent evidence for correlations between solar UV activity and atmospheric response is found in stratospheric ozone data. Recent work on this topic includes the following papers: *Chandra and McPeters* [1994] for short and long timescales at 1-2 mbar; *Hood and Zhou* [1998] for 27-day variations in stratospheric ozone and temperature; *Bjarnason and Rögnvaldsson* [1997] for equatorial total ozone using Total Ozone Mapping Spectrometer (TOMS) data; *Jackman et al.* [1996] for 2-D model results; and *Chandra et al.* [1999] for tropospheric ozone. Long-term data sets capable of characterizing solar UV irradiance variations on both rotational and solar cycle timescales have been collected for more than 20 years, beginning with Nimbus 7 Solar Backscatter Ultraviolet (SBUV) data covering the wavelength region 160-400 nm from November 1978 to October 1986 [*Heath and Schlesinger*, 1986; *Schlesinger and Heath*, 1988]. Additional multiyear irradiance data sets include the Solar Mesosphere Explorer (SME), covering 115-302 nm from January 1982 to June 1988 [*Rottman*, 1988]; the NOAA 11 Solar Backscatter Ultraviolet, model 2 (SBUV/2) [*Cebula et al.*, 1998; *DeLand and Cebula*, 1998a], covering 160-400 nm from December 1988 to October 1994; the Upper Atmosphere Research Satellite (UARS) Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) [*Floyd et al.*, 1998] and the UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) [*Woods and Rottman*, 1998], both covering ~115-410 nm from September 1991 to the present; and the Global Ozone Monitoring Experiment (GOME) [*Weber et al.*, 1998], covering 240-790 nm from June 1996 to the present. *DeLand and Cebula* [1998a] provides further details about each of these instruments.

A critical element in the determination of solar cycle length irradiance changes from satellite instruments is the accuracy of the long-term instrument characterization. For Nimbus 7 SBUV the instrument sensitivity changed from November 1978 through December 1986 by ~25% at 340 nm and 50% at 255 nm. The time-dependent instrument characterization derived from the first 3 years of data was found to give substantial errors at shorter wavelengths ($\lambda < 250$ nm) when extrapolated to the end of the continuous scan solar data record in late 1986 [*Schlesinger et al.*, 1988]. Further details of the long-term instrument characterization are discussed in section 2.2. *Schlesinger and Cebula* [1992] (hereafter SC92) created a revised instrument characterization that greatly improved the Nimbus 7 SBUV data quality, reducing time-dependent uncertainties due to the instrument characterization to 2-3% at most wavelengths. However, SC92 did not produce an archival irradiance data set using the revised characterization. Our goal in this work is to improve the long-term calibration of SBUV to produce a data set suitable for studies of long-term solar variations, and create a publicly available irradiance data set that can be compared with other solar irradiance data sets. Section 2 describes the archived data and the baseline long-term instrument characterization, the revisions derived by SC92, and the steps we have taken to refine and improve the SC92 work. Section 3 shows our results, including comparisons with predictions from the Mg II index proxy model. Section 4 presents comparisons with overlapping data from SME during cycle 21. Finally, section 5 discusses our conclusions.

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2. Nimbus-7 SBUV Solar Irradiance Data and Instrument Characterization Corrections

2.1. Instrument Description

The Nimbus 7 SBUV instrument was described in detail by *Heath et al.* [1975]. It is a nadir-viewing Ebert-Fastie double monochromator with a 1.1 nm bandpass, designed to measure total column ozone and stratospheric ozone profiles using observations of backscattered Earth radiance between 255 and 340 nm. In normal discrete mode operations, SBUV made measurements at 12 discrete wavelengths during each 32 s scan. The determination of ozone values using the backscattered ultraviolet (buv) method also requires measurements of solar irradiance to calculate albedo values [e.g., *Bhartia et al.*, 1996]. The solar data are obtained as the spacecraft crosses the northern terminator into darkness by deploying a diffuser plate to direct solar radiation into the instrument. These measurements are thus full-disk solar observations. The measurements discussed in this paper were taken in the continuous scan mode, where SBUV scans in wavelength from 160 to 400 nm in ~0.2 nm steps. In normal operations, three consecutive scans were taken on a single orbit each day and averaged to create a daily irradiance spectrum. During selected intervals of 2-5 months duration, called 'accelerated deployment' periods, the observation frequency was increased to every orbit (13-14 orbits per day). Only daily average irradiance values are archived. A mercury lamp was viewed on a periodic schedule to track changes in the wavelength calibration. No direct monitoring of instrument throughput or diffuser reflectivity changes was available.

The Nimbus 7 satellite was launched in October 1978, and the irradiance data record begins on November 7, 1978. From 1978 to mid-1983 the SBUV instrument was usually operated on a 3 days on, 1 day off cycle to conserve power. From summer 1983 until the end of the data record, SBUV operated every day. The baseline data set for this paper, which is archived at the National Space Science Data Center (NSSDC), contains 8 years of daily average continuous scan solar irradiance data and runs through October 28, 1986 [*Schlesinger et al.*, 1988]. Additional continuous scan measurements were made through February 1987, but these data are not archived. The SBUV instrument began experiencing chopper nonsync errors in February 1987, and continuous scan irradiance measurements were terminated soon afterwards due to degraded data quality [*Gleason and McPeters*, 1995]. Discrete mode measurements continued through June 1990, although discrete solar data showed a factor of 7 increase in measurement noise compared with discrete data taken prior to the chopper nonsync period. After conducting special operations in summer 1990 to extend the lifetime of the TOMS instrument, Nimbus 7 SBUV data quality degraded further, and SBUV operations were terminated in June 1991.

2.2. Time-Dependent Characterization

An accurate characterization of long-term instrument response change is critical to determining solar activity changes on long time scales. The Nimbus 7 SBUV instrument did not carry an onboard calibration system to directly track changes in instrument throughput. The analysis of *Cebula et al.* [1988] therefore focused on albedo calibration changes for ozone processing, and considered observed solar irradiance measurements as an indicator of changes in instrument sensitivity. Changes in the measured solar output from an initial time t_0 were defined as the product of diffuser reflectivity degradation, instrument throughput (e.g., optics, electronics) changes, and true solar irradiance changes. *Cebula et al.* [1988] assumed that diffuser reflectivity changes could be further characterized as the product of separable exposure-dependent and time-dependent terms. With this assumption they defined the following equation for the measured solar output:

$$F(\lambda,t) = F(\lambda,0)\, P(t)\, e^{r(\lambda)E(t)}\, e^{s(\lambda)t}\, e^{-\gamma(\lambda)G(t)} \qquad (1)$$

$F(\lambda,t)$	measured solar irradiance output, mW/m²/nm;
$F(\lambda,0)$	measured irradiance at λ on first day of operation;
$P(t)$	photomultiplier tube (PMT) gain change;
$r(\lambda)$	exposure-dependent degradation coefficient, hr^{-1};
$E(t)$	solar diffuser exposure, hours;
$s(\lambda)$	time-dependent degradation coefficient, $days^{-1}$;
$\gamma(\lambda)$	solar activity scale factor;
$G(t)$	solar rotational modulation activity index.

The photomultiplier tube gain change $P(t)$ was characterized using the output from a reference photodiode. Solar activity was represented only for the purpose of deriving instrument sensitivity change by the term $e^{-\gamma(\lambda)G(t)}$, which was based on the Mg II index model developed by *Heath and Schlesinger* [1986]. This term is not applied in the creation of corrected solar irradiance values. The diffuser exposure rate $E(t)$ was significantly increased for three accelerated deployment periods during the six years of Nimbus 7 SBUV operation analyzed by *Cebula et al.* [1988]. Multiple linear regression fits using the logarithmic form of equation (1) then allowed values for $r(\lambda)$, $s(\lambda)$, and $\gamma(\lambda)$ to be determined. This analysis was performed at more than 30 wavelengths throughout the 160-400 nm wavelength region for each period of accelerated diffuser deployment. Regression results for the solar activity coefficient $\gamma(\lambda)$ were found to be negligible except at short wavelengths, consistent with the predictions of *Heath and Schlesinger* [1986]. *Cebula et al.* [1988] found that for data through 1984, changes in $r(\lambda)$ between regression fit intervals were not statistically significant, and adopted a time-independent parameterization. The time-dependent degradation coefficient $s(\lambda)$ was also assumed to remain constant between different accelerated deployment periods.

Figure 1a shows the Nimbus 7 SBUV time series at 205 nm from the archived data for the period 1978-1986. Short-term variations at the 2-6% peak-to-peak level represent rotational modulation. The magnitude of the change in Figure 1a (~30% from 1982 through 1986) is considerably larger than predicted solar cycle variations of 6-10% [e.g., *Lean*, 1991]. The continued decrease in 1985-1986, when solar activity was at a minimum level, strongly implies uncorrected instrument change in the data. Although smaller changes are observed at longer wavelengths (e.g. 5% decrease at 260 nm in Figure 1b), these changes are still a factor of 4 larger than predicted solar irradiance variations. The analysis of *Schlesinger et al.* [1988] demonstrated that the observed drift in irradiance values was consistent with time-dependent variations in $s(\lambda)$. *Schlesinger et al.* [1988] also found that the reference photodiode designed to monitor long-term changes in $P(t)$ was itself experiencing sensitivity changes. They chose to use a 1 nm average of irradiance data centered at 391.3 nm, corrected for goniometry (variations in the angular response of the solar diffuser plate) and diffuser degradation, to represent wave-

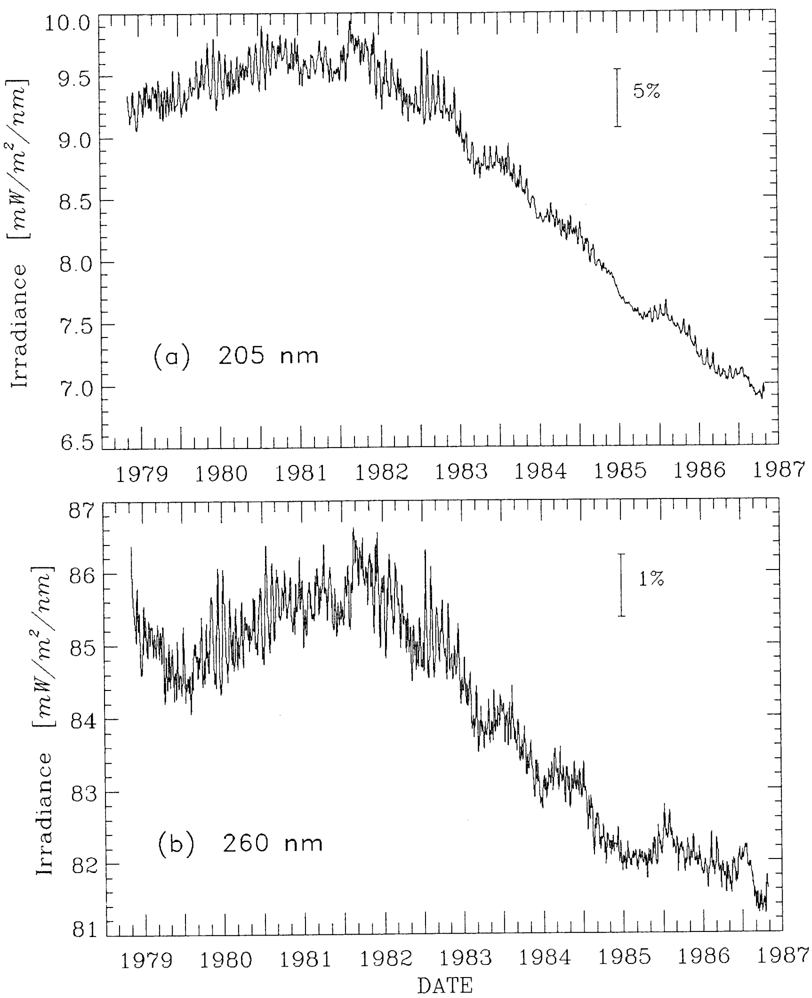

Figure 1. (a) Time series of archived Nimbus 7 Solar Backscatter Ultraviolet (SBUV) irradiance data at 205 nm. (b) Time series of archived Nimbus 7 SBUV irradiance data at 260 nm.

length-independent instrument sensitivity changes. Normalization of the Nimbus 7 SBUV data to F(391 nm, t) means that any errors in s(391 nm) will be incorporated into irradiances at other wavelengths. Any changes in $s(\lambda)$ for other wavelengths will therefore be made relative to s(391 nm).

Schlesinger and Cebula [1992] reviewed the Nimbus 7 SBUV instrument characterization using the full 8 year record of continuous scan irradiance data. They found significant differences between values of $s(\lambda)$ derived from the first two accelerated deployment periods in 1980 and 1981 and those determined from later periods in 1984 and 1986. For the calculation of absolute solar irradiances, a complete characterization of instrument response is required, but the apportionment between exposure-dependent and time-dependent terms is unimportant because corrections are needed for all instrument throughput changes. The coefficient $s(\lambda,t)$ therefore provides a representation of all time-dependent response changes. The operational form adopted by SC92 for $s(\lambda,t)$ is constant during the early and late portions of the SBUV data record, and varies linearly in between. Figure 2 illustrates the time dependence of $s(t)$ at 205 nm derived by SC92. The time dependent coefficients s_{12}, s_3, and s_4 derived from regression fits for each corresponding interval are also shown with their respective ±1 σ standard deviations. While this characterization represents an improvement over the formulation of *Cebula et al.* [1988], it does have some limitations. The revised model of SC92 is unable to evaluate changes in $s(\lambda,t)$ prior to the first accelerated deployment interval in 1980. The derived degradation rates become very small for wavelengths longward of 300 nm, and the corresponding uncertainties are proportionally larger. Sensitivity change coefficients for the 1986 accelerated deployment interval are more uncertain because of its shorter duration, leading to increased uncertainty in the sensitivity change correction for the 1985-1986 irradiance data.

Figure 3a shows the 205 nm time series constructed by SC92, with a 27-day running average also shown to better illustrate long-term changes. Solar activity variations at 205 nm predicted by the Mg II index proxy model [*DeLand and Cebula*, 1993] are shown for reference. While the Mg II model uses scaling factors derived from short-term solar variations to estimate long-term irradiance changes, comparisons with NOAA 11 SBUV/2 irradiance data indicate that the predicted irradiance changes are accurate to ~1% on solar cycle timescales as well [*DeLand and Cebula*, 1998a]. The revised Nimbus 7 data track the Mg II model predictions fairly well. The small differences in later years will be discussed further in section 2.5. Figure 3b shows a time series of SC92 irradiance data at 240 nm. Consistent with the predic-

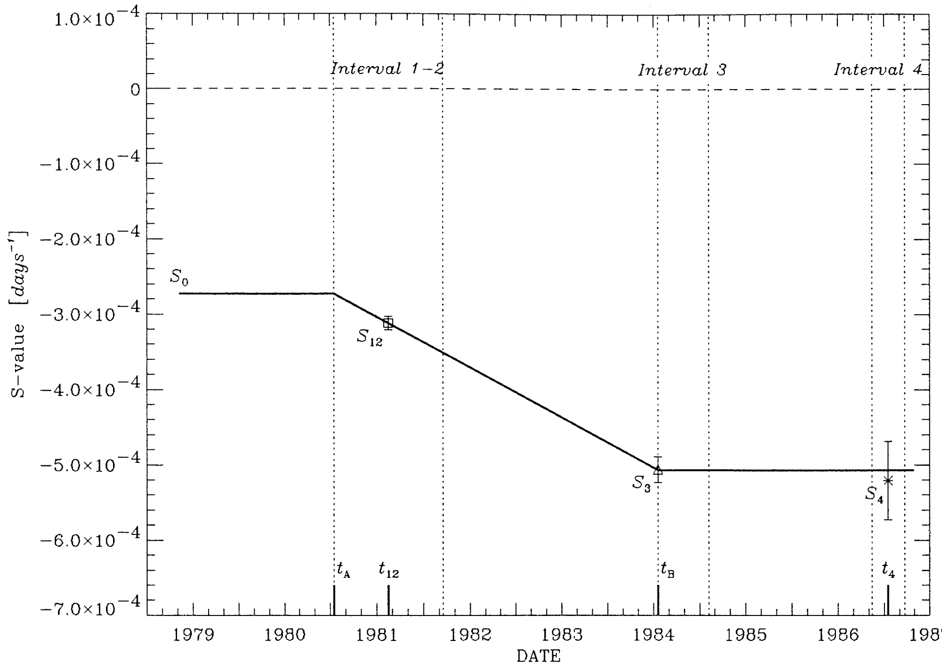

Figure 2. Time dependence of the instrument sensitivity change coefficient $s(t)$ at 205 nm. The time intervals are defined in SC92.

tions of the Mg II proxy model, solar activity variations are again observed, with an amplitude approximately one half that observed at 205 nm. Figure 3c shows the SC92 data time series at 325 nm, for which predicted solar activity is much less than 1% over a solar cycle. These data show long-term changes of 2-3%, increasing noticeably from 1984 onward, which we interpret as uncorrected instrument sensitivity change. The implication of 2-3% long-term drifts in the Nimbus-7 SBUV irradiance data adds substantial uncertainty to derived estimates of solar cycle irradiance changes for cycle 21. Our goal in this paper is to reduce these uncertainties through reasonable revisions of the long-term instrument characterization. Our investigation of possible adjustments to the SC92 instrument characterization focused on three areas: wavelength scale drift, periodic variations, and long-term sensitivity drift.

2.3. Wavelength Scale Drift

The Nimbus 7 SBUV wavelength drive used a mechanical cam to select the exact wavelength for each measurement. While different portions of the cam were used for discrete and continuous scan observations, the cam made a complete revolution for each scan in all operating modes. Thus the accumulated wear on the cam due to continuous use (more than 3,000,000 rotations over 8 years) represents a potential source of long-term drift in the wavelength calibration. *Cebula et al.* [1988] evaluated measurements from the onboard Hg lamp calibration system taken approximately twice/week. On the basis of data from May 1980 through December 1983, they derived a wavelength scale correction relation with a linear spectral and time dependence:

$$\Delta\lambda(\lambda,t) = 1.392\text{x}10^{-7}\,(\lambda_0\text{-}209)\,(d\text{-}2092) \qquad (2)$$

where d is day number (1 ≡ 1 January 1978). The nominal wavelength scale was referenced to measurements made in August-October 1983. Extrapolating this relationship through October 1986 leads to predicted wavelength scale changes of +0.078 nm at 400 nm and –0.016 nm at 170 nm. No wavelength scale drift correction was applied to the archived solar irradiance data.

We have reevaluated the SBUV wavelength scale drift by using measurements of absorption lines in the solar irradiance spectrum. These measurements provide better spectral distribution and temporal coverage than the Hg lamp data and are directly relevant to the solar irradiance product. Wavelength calibration analysis using solar spectra have been previously presented for NOAA 11 SBUV/2 [*DeLand and Cebula*, 1998a], SSBUV [*Cebula et al.*, 1995/96], and GOME [*Casper and Chance*, 1997]. We used 16 absorption features between 200 and 400 nm for this analysis. A set of consecutive points was identified on both the short and long wavelength sides of each feature which change approximately linearly in irradiance at the Nimbus 7 SBUV resolution. Regression fits were derived to each set of points, using daily average spectra, and the intersection of those fits calculated. The absolute position derived for each solar absorption line with an SBUV-type instrument may not equal the high resolution reference value due to broadening by the 1.1 nm bandpass. However, because only relative changes are of interest here, the variations over time give a good representation of long-term changes in the wavelength scale. *Cebula and DeLand* [1998] showed that NOAA 11 SBUV/2 wavelength drift could be characterized to 0.01 nm using this method. Figure 4 shows an example of the Nimbus 7 SBUV wavelength drift data for the Fe I line at 248.82 nm. These data demonstrate a steady linear time dependence, except for an unexplained dip of ~0.012 nm between July 1979 and July 1980. The dip is present in data at all wavelengths, with small variations in duration and amplitude. We omitted this period when deriving wavelength drift rates for each line to avoid biasing the regression fit. The time dependence slopes for all lines are shown in Figure 5. A

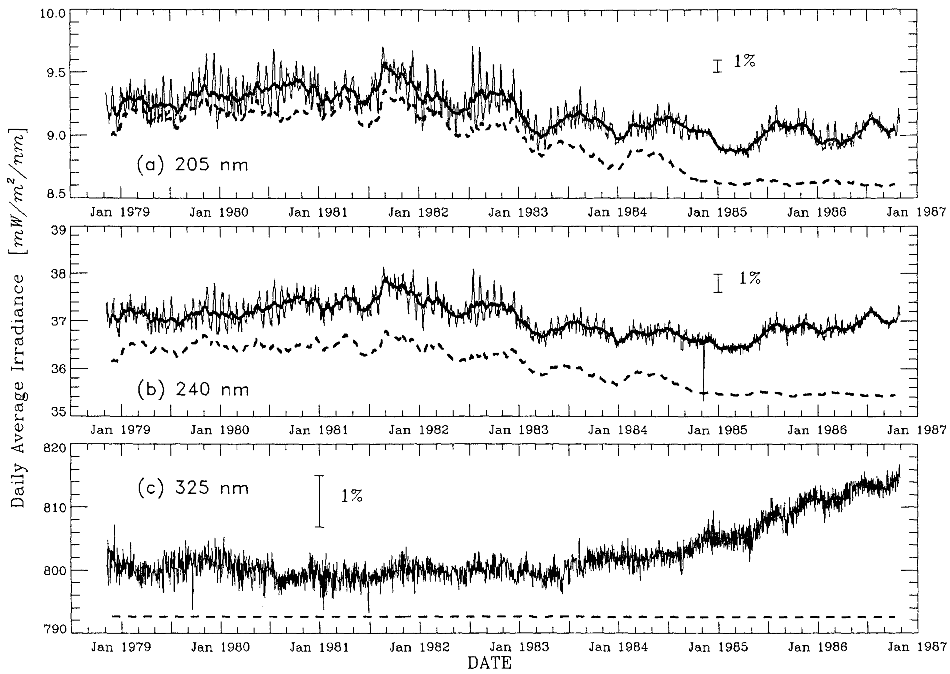

Figure 3. (a) Time series of Nimbus 7 SBUV solar irradiance data at 205 nm, reprocessed using the instrument characterization of SC92. The heavy solid line is a 27-day running average of the data. The dashed line is a 27-day average of the solar variations at 205 nm predicted by the Mg II index proxy model, normalized to the start of the irradiance data and offset by 3% for clarity. (b) Time series of Nimbus 7 SBUV solar irradiance data at 240 nm, reprocessed using the instrument characterization of SC92. The heavy solid and dashed lines have the same meaning as in Figure 3a. The predicted solar variation is offset by 3% for clarity. (c) Time series of Nimbus 7 SBUV solar irradiance data at 325 nm, reprocessed using the instrument characterization of SC92. The heavy solid line has the same meaning as in Figure 3a. The predicted solar variation is offset by 1% for clarity.

regression fit to these slopes as a function of wavelength gave a value of $8.35(\pm 8.54)\times10^{-9}$ nm/day/nm, implying no statistically significant spectral dependence to the wavelength drift. We therefore calculated an average time-dependent slope, with a value of $5.7(\pm 2.1)\times10^{-6}$ nm/day.

The total magnitude of the wavelength scale drift from November 1978 to October 1986 calculated using the wavelength-independent rate derived above is $\Delta\lambda = +0.017$ nm. This is considerably smaller than the drifts predicted by *Schlesinger et al.* [1988] at long wavelengths. The explanation lies in the fact that their analysis used onboard calibration data beginning in mid-1980, where the solar data show a short-term dip. Fitting data from mid-1980 to late 1983 thus gave time-dependent slopes that were too large. Regression calculations including the early dip in the $\Delta\lambda(t)$ data from the solar absorption lines give an average increase in $\Delta\lambda_{total}$ of approximately +0.003 nm, which is less than the estimated accuracy of the linear regression fit. However, because we believe that the dip represents a real aspect of the Nimbus 7 instrument behavior, we have modeled it as a linear decrease from May 1979 to September 1979, followed by a linear increase from October 1979 to June 1980. The maximum amplitude of −0.012 nm for the dip represents an average for all wavelengths. This approach provides a more spectrally consistent correction than using smoothed data from one or more lines. The revised time-dependent adjustment to the reference wavelength scale for each date is given by

$$\Delta\lambda(t) = m(t)\,(d\text{-}2092) \qquad (3)$$

$$m = 5.7\times10^{-6} \qquad d \le 485,\ d \ge 914$$
$$m = -7.3\times10^{-5} \qquad d = 486\text{-}638$$
$$m = 4.9\times10^{-5} \qquad d = 639\text{-}913.$$

Irradiance changes associated with the 8-year wavelength drift correction were estimated by applying a 0.017 nm nm shift to the initial SBUV irradiance spectrum and ratioing it to the unshifted spectrum. For the 1 nm binned spectrum, typical changes are of the order of ±0.4%, reaching ±1.2% at spectral locations associated with strong absorption lines such as Mg II and Ca II. The wavelength scale drift correction is a small but important component of the Nimbus 7 SBUV long-term instrument characterization.

2.4. Periodic Variation

The 205 nm time series shown in Figure 3a exhibits regular oscillations in the later part of the record, where solar activity is low. Removing solar variations predicted by the Mg II index model ("desolarize" the data), as discussed in section 2.2, leaves a residual time series with constant 2% peak-to-peak (p-p) fluctuations at approximately annual intervals throughout the data record (Figure 6a). The periodic variation is also observed at longer wavelengths with decreasing amplitude, reaching ~1% p-p at 230 nm (Figure 6b) and ~0.2% p-p at 260 nm (Figure 6c). Examination of desolarized time series at 10 nm intervals shows an approximately linear change in amplitude of the periodic variation over the wavelength range 190-260 nm (Figure 7).

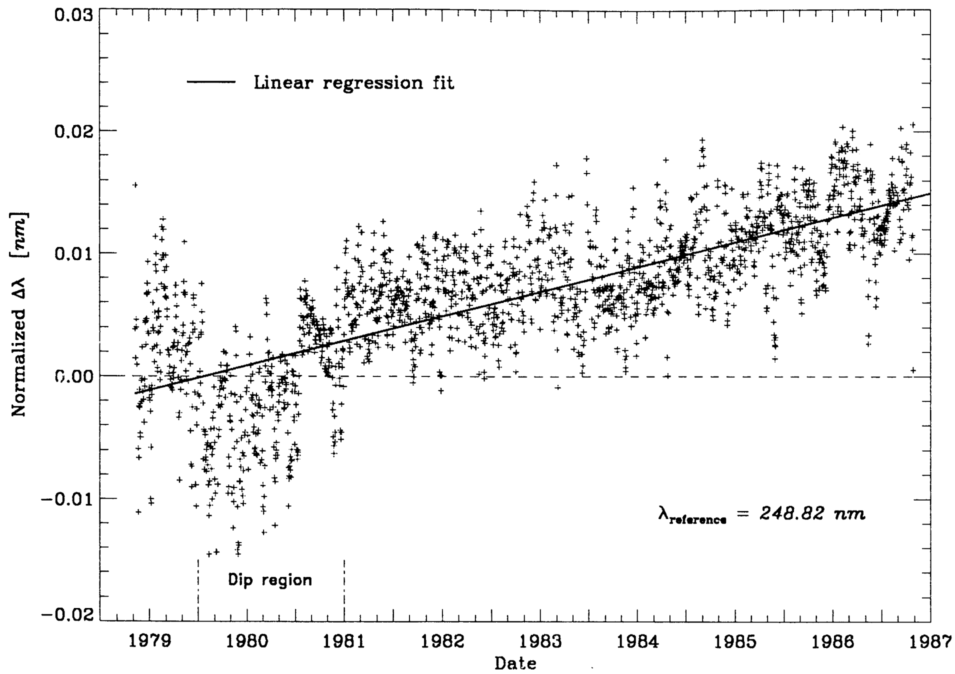

Figure 4. Nimbus 7 SBUV wavelength scale changes derived from measurements of the Fe I solar absorption line at 248.82 nm. The solid line is a linear regression fit, excluding the data between July 1979 and December 1980.

The length of the period suggests a problem in the processing algorithm related to annually varying quantities such as Sun-Earth distance, PMT temperature, or solar viewing angle (i.e., goniometry). The Sun-Earth distance correction is taken from *U.S. Government Printing Office* [1997], and is accurate to better than 0.02%. The extreme values of Sun-Earth distance in early January and July are not in phase with the broad minima and maxima shown in the irradiance residuals. Nimbus 7 SBUV did not exhibit any PMT temperature sensitivity in prelaunch calibration tests [*Schlesinger et al.*, 1988]. Although the SBUV/2 instruments do show a change in radiometric response with PMT temperature change, typical sensitivities are 0.2%/°C. Even if we assume the Nimbus 7 SBUV PMT gain had the same thermal sensitivity as that observed on the SBUV/2 instruments, because Nimbus-7 SBUV PMT temperatures only varied between 20-24°C, uncorrected re-

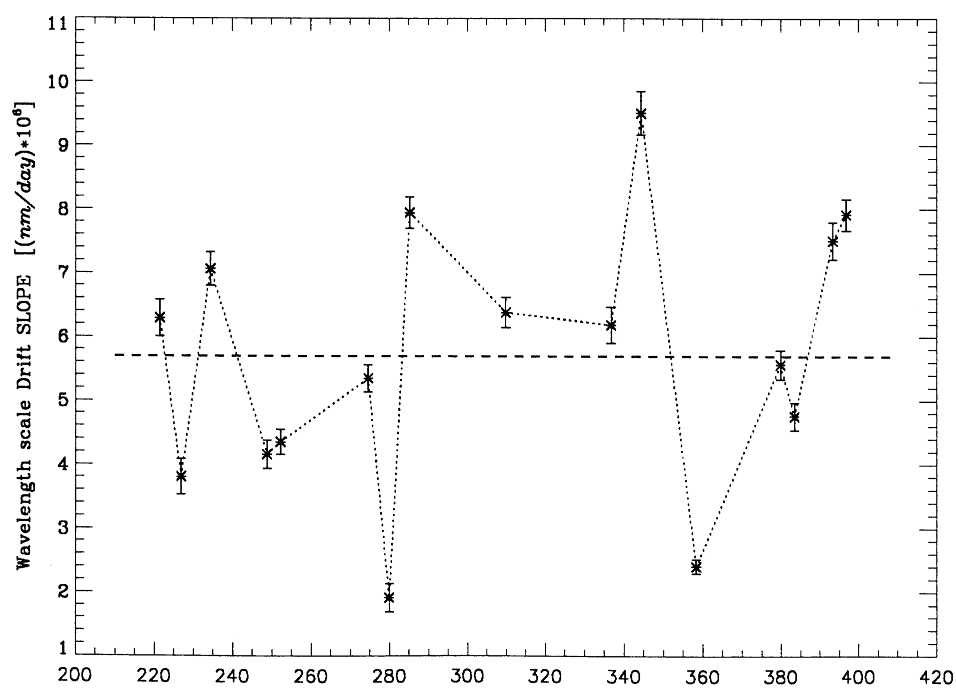

Figure 5. Spectral dependence of Nimbus 7 SBUV wavelength scale drift rates derived from solar absorption line data. Error bars are ± 2σ. The dashed line shows the average of all points.

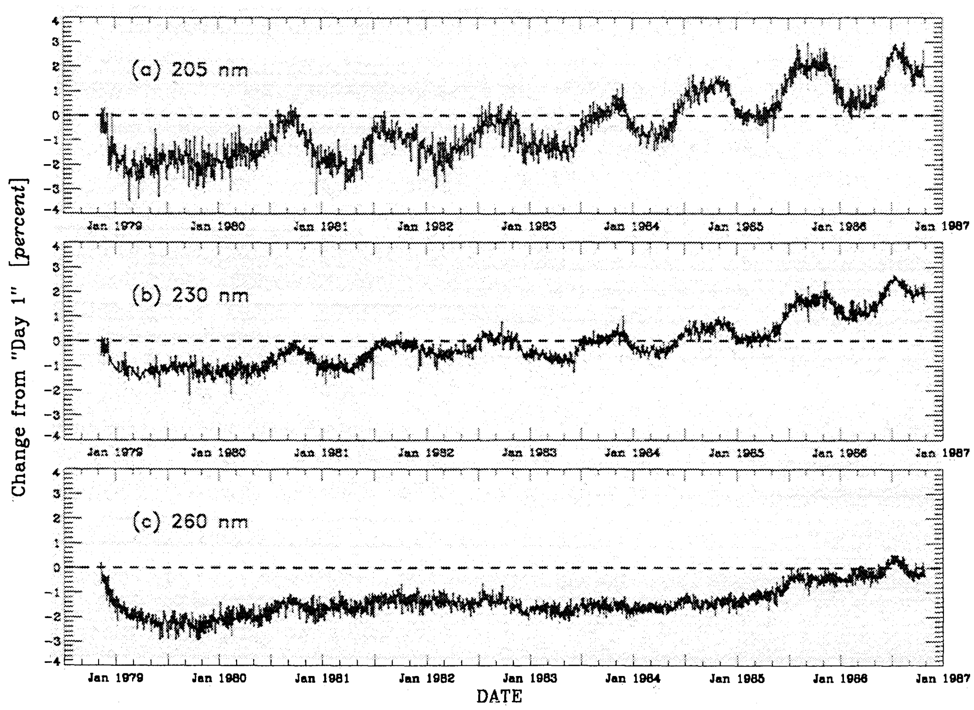

Figure 6. (a) Residual ("desolarized") time series of SC92 irradiance data at 205 nm, where the solar variations predicted by the Mg II index proxy model have been removed. (b) Desolarized SBUV irradiance data at 230 nm. (c) Desolarized SBUV irradiance data at 260 nm.

sponse variations would be less than half the magnitude required to produce the variations shown in Figure 6a. Again, the phase of PMT temperature variations is inconsistent with the residuals. Other instrument housekeeping parameters, such as voltages and motor currents, are extremely stable during the lifetime of the mission. While the Nimbus 7 SBUV operational goniometric correction has no spectral dependence, laboratory and inflight data from SBUV/2 instruments do show a wavelength-dependent diffuser bidirectional reflectance distribution function (BRDF). However, the annual variation of the solar azimuth angle is also out of phase with the irradiance variations and has a significant semiannual

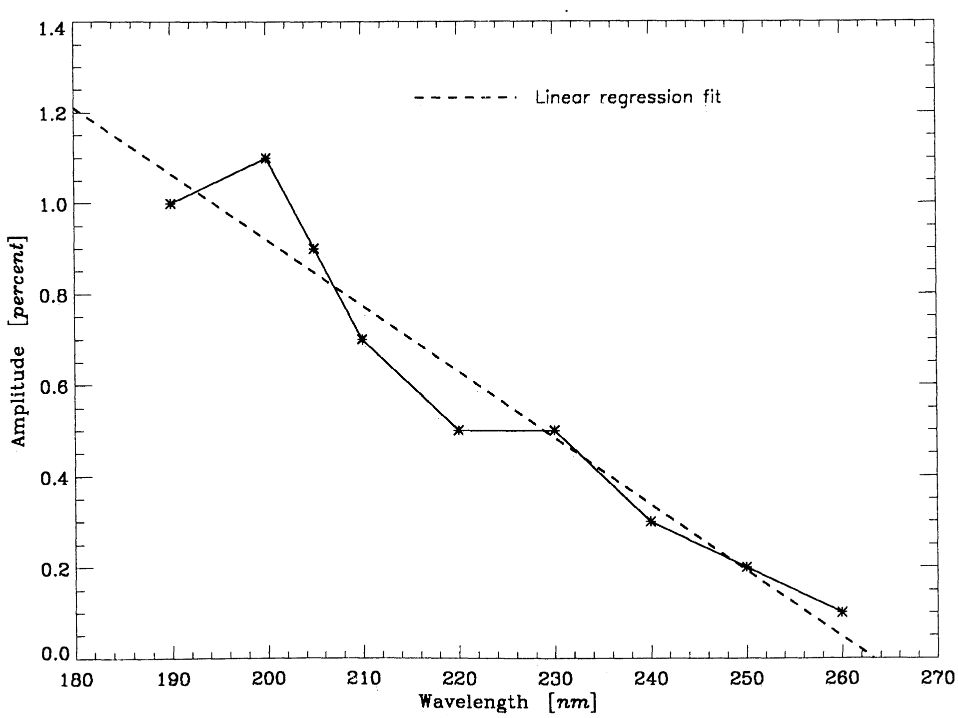

Figure 7. Spectral dependence of periodic term identified in Nimbus 7 SBUV desolarized residual time series between 190 and 260 nm.

structure that is not observed in Figure 6. Quasi-annual variations are not observed in other solar data sets during 1979-1986, including irradiance data from the mechanically similar NOAA 9 SBUV/2 instrument [*DeLand and Cebula*, 1998b]. Considering all of the information presented here, we conclude that the Nimbus 7 SBUV periodic irradiance variations are due to an unexplained instrumental effect.

Because we have been unable to develop a satisfactory physical model to explain the periodic irradiance variations shown in Figure 6, no correction has been applied to the final irradiances presented in section 3 of this paper. For the benefit of users who wish to evaluate the Nimbus 7 SBUV data without such artificial behavior, we have developed a characterization that can be applied to improve the appearance of the irradiance product. On the basis of a linear regression fit to the observed amplitudes shown in Figure 7, it is possible to derive a normalized amplitude for the periodic correction term given by

$$A(\lambda) = 3.93\text{x}10^{-2} - (1.45\text{x}10^{-4}\lambda) \qquad \lambda < 260 \text{ nm.} \quad (4)$$

A complete time-dependent periodic correction can then be written as

$$A(\lambda,t) = A(\lambda)\, cos\{2\pi[(d+110)/365.25]\} \qquad (5)$$

where d is the running day number as defined previously, and a phase shift of 110 days is used to align the function with the data. Applying this correction function to the SC92 205 nm irradiance data reduces the fluctuations in the desolarized residual to ~0.5% (Figure 8). The dip of ~2% in late 1979 is a consequence of applying equation (5) to the full data set, since the same time period in Figure 6 is essentially flat. Comparable results are obtained at other wavelengths.

2.5. Long-Term Sensitivity Drift

The irradiance time series residual at 205 nm shown in Figure 8 has a noticeable upturn in 1984-1986, similar to the 325 nm data shown in Figure 3c. This feature can be identified at many wavelengths, suggesting a systematic error in the value of the s_{34} sensitivity change coefficient. *Schlesinger and Ceand Cebula* [1992] examined the use of an $s(t)$ function which would explicitly include the s_4 values calculated for the 1986 accelerated deployment, rather than averaging them with the s_3 values derived for 1984. They calculated irradiance spectra for October 1986 using both $s_{34}(\lambda)$ and $s_4(\lambda)$. Ratios of these spectra were in the range 0.992-1.014 and exhibited no systematic trend. This result implies no significant difference between these functional forms but does not rule out an error in the $s_{34}(\lambda)$ values. When we examined numerous individual irradiance time series, we found that the adjustments to $s_{34}(\lambda)$ required to reduce long-term drift to ±1% ranged between $-1\text{x}10^{-5}$ day^{-1} and $+2\text{x}10^{-5}$ day^{-1}, with larger values derived at shorter wavelengths. For wavelengths shortward of 260 nm the long-term solar change term during the SBUV data record calculated by the Mg II proxy model begins to exceed 1%. This term must be removed before deriving a Δs_{34} value. Achieving a long-term drift value better than ±1% from direct analysis at short wavelengths by specifying Δs_{34} therefore becomes dependent on the solar model results. To avoid problems with circular reasoning, we concentrated on wavelengths longward of 300 nm, where solar cycle irradiance changes have been shown to be 0.3% or less, except in specific narrow regions [*Lean et al.*, 1997].

When we determined changes to $s_{34}(\lambda)$ that minimized the long-term drift at 10 nm steps in the 300-400 nm wavelength region, we found an average value of $\Delta s_{34} = 1.2(\pm 0.4)\text{ x}10^{-5}$ day^{-1}. The uncertainty represents the precision to which we can specify Δs_{34} for a given residual time series, rather than a

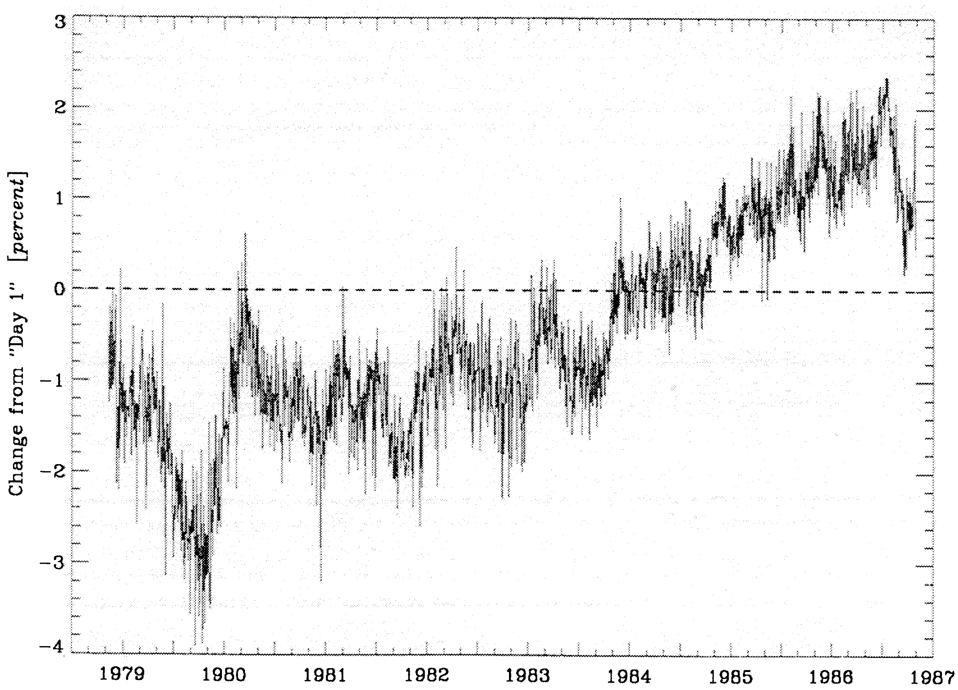

Figure 8. Residual time series of SC92 SBUV irradiance data at 205 nm. The solar variations predicted by the Mg II index proxy model have been removed.

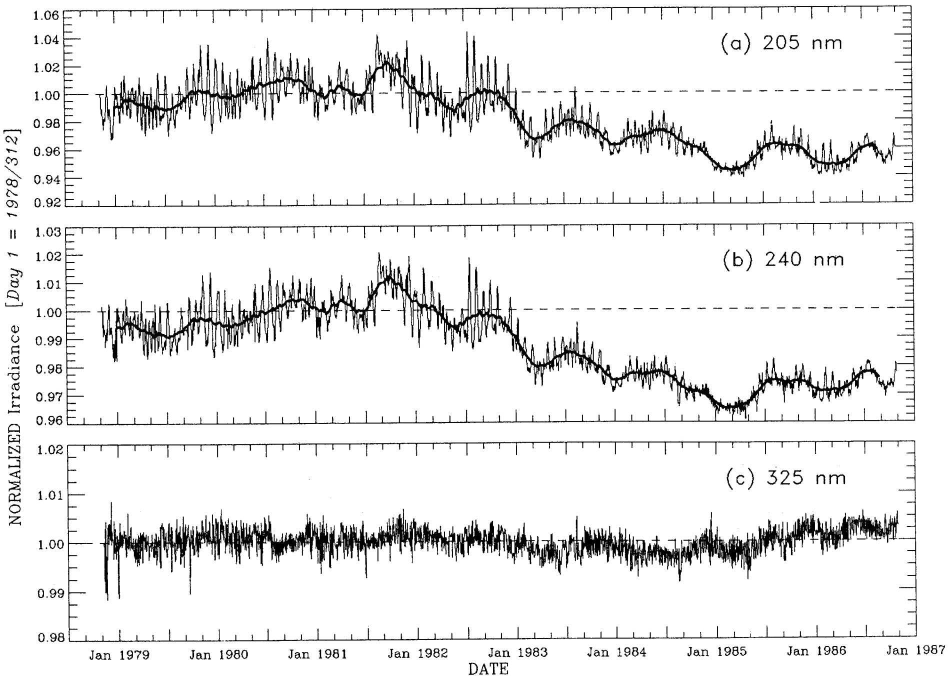

Figure 9. (a) Time series of Nimbus 7 SBUV solar irradiance data at 205 nm, reprocessed using the instrument characterization of SC92 and the adjustments described in this paper. The heavy solid line is a 81-day running average of the data. (b) Time series of Nimbus 7 SBUV solar irradiance data at 240 nm, reprocessed as in Figure 9a. (c) Time series of Nimbus 7 SBUV solar irradiance data at 325 nm, reprocessed as in Figure 9a.

statistical calculation. These changes are comparable to the 2 σ uncertainties for s_{34} listed in Table 4 of SC92 at $\lambda < 300$ nm, and approximately a factor of 2 larger at longer wavelengths. The uncertainties provided in SC92 were formal statistical errors for each wavelength, and did not include a possible systematic error in s_{34}. Thus the adjustment recommended here is reasonable within the uncertainties of the SC92 analysis. The sensitivity change Δs_{34} is applied to all wavelengths.

3. Revised Nimbus 7 SBUV Irradiance Data

3.1. Data Set Creation

For the creation of a revised Nimbus 7 SBUV solar irradiance data set, we first applied the time-dependent sensitivity change corrections of SC92 to the archived data, adjusting the $s_{34}(\lambda)$ values as discussed in section 2.5. We also applied the wavelength drift correction derived in section 2.3 (equation (3)). Figures 9a-9c show time series of the revised irradiance data at 205, 240, and 325 nm, where the time series have been normalized to the beginning of the Nimbus 7 data set to more readily assess solar cycle variations. The change in solar irradiance for solar cycle 21, as indicated by an 81-day running average, is ~8.3% at 205 nm and 4.9% at 240 nm. When evaluating these estimates, it should be noted that the smoothed maximum irradiance value in late 1981 and minimum irradiance value in early 1985 both coincide with extrema of the periodic variation, thus exaggerating the derived solar cycle amplitude. These solar cycle irradiance variations are consistent with predicted changes of 8.3(±0.3)% and 3.7(±0.2)% respectively, as derived from the Mg II index proxy model using a solar cycle amplitude of 7.6% for the 81-day smoothed Mg II index.

In order to assess the magnitude of remaining long-term drifts in the Nimbus 7 SBUV data, we used the method of *DeLand and Cebula* [1998a] as applied to NOAA 11 SBUV/2 data. Desolarized time series of Nimbus 7 SBUV data are shown in Figure 10 for 200-208 and 240-250 nm. The 200-208 nm data (Figure 10a) clearly show the 2% p-p periodic variation but no long-term drift at the 0.5% level. The 240-250 nm data decrease by ~2% during the first few months of operation, remain stable to better than 1% through 1984, then increase by ~1% in 1985-1986. These results are very similar to the long-term drift in desolarized NOAA 11 data for the same wavelength bands, as shown in Figure 4 of *DeLand and Cebula* [1998a]. For examination of the entire spectral range, irradiance time series were calculated in 5 nm bands between 170 and 400 nm, desolarized by removing predicted solar variations, then averaged in 10-day bins for clarity. We stress that these comparisons are not intended to draw conclusions about the validity of the Mg II model as a representation of solar change. Rather, they represent a validation tool for our estimates of the long-term accuracy of the Nimbus 7 irradiance data. Each time series is normalized to the average irradiance value during the first week of observations (November 7-14, 1978). Plate 1 shows that the majority of the data longward of 200 nm exhibit long-term changes of ±1% or less, with larger values of –2% at 250-270 nm and 340-360 nm, and +2% at 215-230 nm. Inspection of the data with narrower wavelength bins indicates that these problems are typically generated by spectrally small regions. The presence of the periodic variation is clearly evident at wavelengths shortward of 240 nm in Plate 1.

Shortward of ~185 nm, the Nimbus 7 SBUV data show a rapid increase during 1979 and early 1980. This suggests that the assumption of time-independent sensitivity change (s_0)

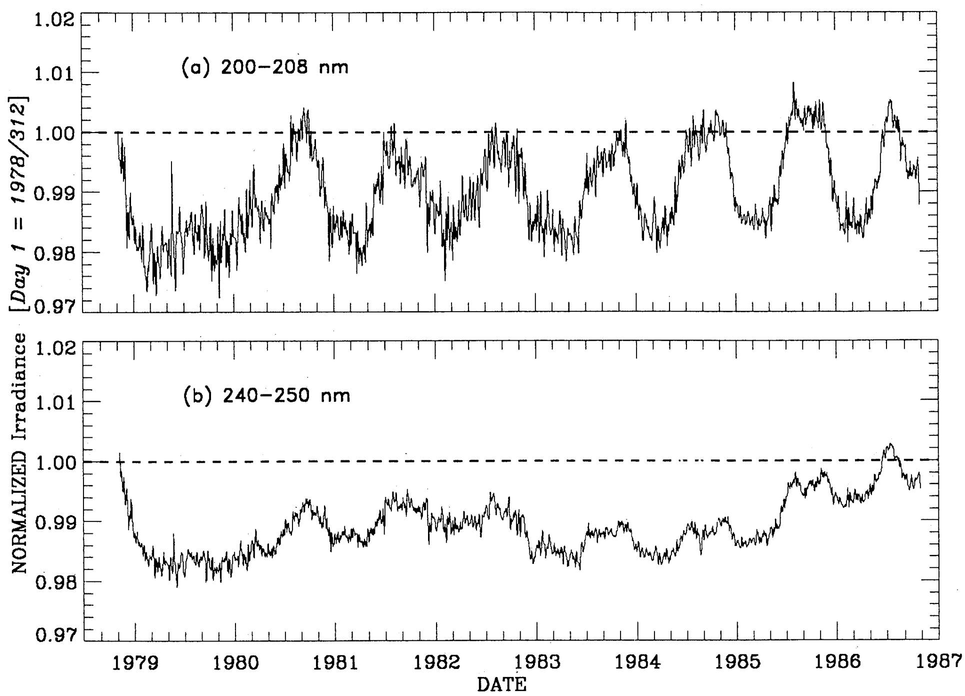

Figure 10. (a) Desolarized time series of Nimbus 7 SBUV irradiance data at 200-208 nm, with predicted solar variations removed. (b) Desolarized time series of Nimbus 7 SBUV irradiance data at 240-250 nm, with predicted solar variations removed.

during that period is incorrect at short wavelengths. Unfortunately, we have no data on which to base a correction in this spectral region without resorting to circular arguments. We therefore leave the instrument characterization unchanged and accept that an error likely exists in the irradiance data. From 1981 through 1986 the corrected Nimbus 7 data in the 170-185 nm region are consistent with the Mg II proxy estimate at the 3% level. Measurements of cycle 21 from Mg II index, sunspots, and other solar activity indexes show that the solar maximum period extends through the end of 1981. Thus, if the 1979-1980 data are neglected, Nimbus 7 SBUV data at $\lambda < 185$ nm can still be used to estimate solar cycle irradiance changes. We also recommend caution in using the 1979-1980 data for studies of short-term activity, because the anomalous

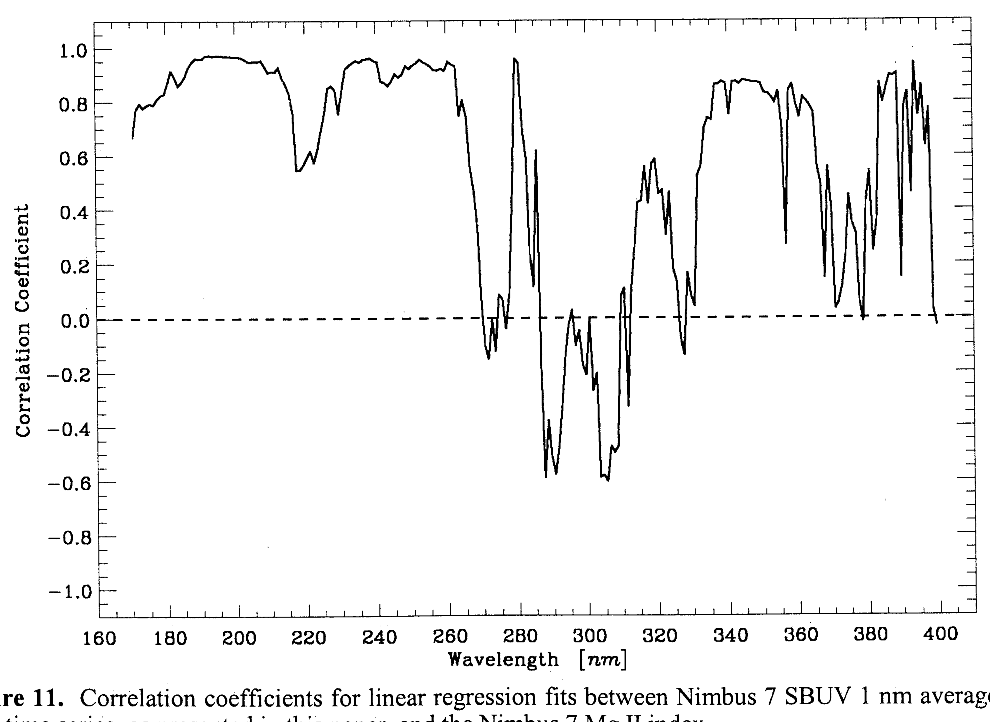

Figure 11. Correlation coefficients for linear regression fits between Nimbus 7 SBUV 1 nm average irradiance time series, as presented in this paper, and the Nimbus 7 Mg II index.

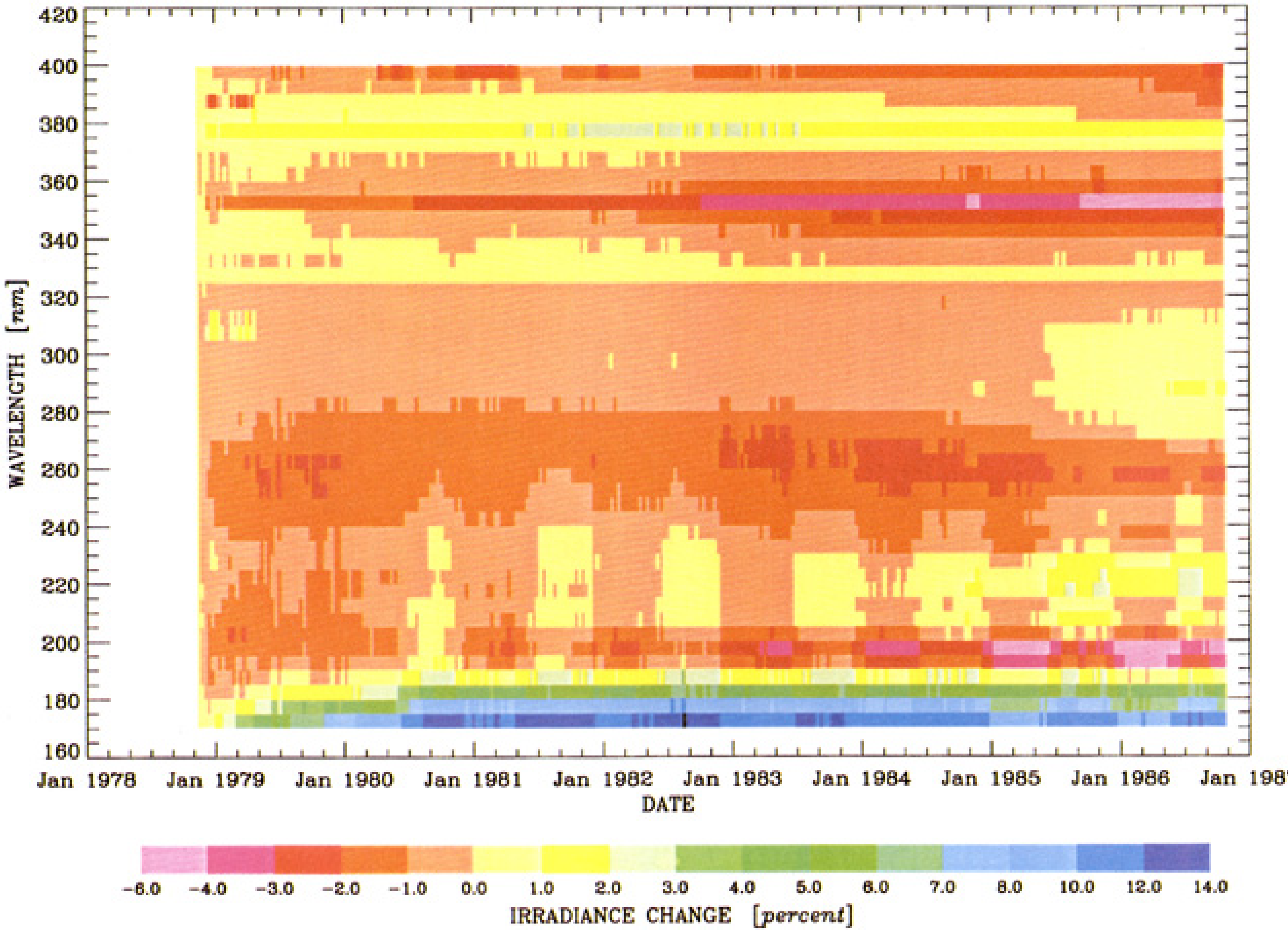

Plate 1. Nimbus 7 SBUV spectral change using desolarized data from November 1978 to October 1986. Data are binned in 5 nm, 10-day increments, and normalized to the average of November 7-14, 1978.

drift at 170 nm becomes significant on solar rotational (~27-day) timescales.

The influence of residual instrument characterization errors can be evaluated quantitatively by deriving linear regression fits between irradiance time series and the Nimbus 7 Mg II index. The correlation coefficients for regression fits with each 1 nm irradiance bin are shown in Figure 11. High values of ~0.90-0.97 are found between 185-215 nm and 230-262 nm, indicating that solar variability represents 80-94% of the variance in the irradiance data. Reduced correlation values at $\lambda < 185$ nm demonstrate the effect of the 1979-1980 calibration problems. The dip centered at 220 nm reflects the presence of uncorrected long-term drifts in this region, as shown by the green values during 1985-1986 in Plate 1. Correlation coefficients longward of ~286 nm are generally ±0.6 or less, consistent with the hypothesis that solar variations in this region are not well represented by a chromospheric proxy such as the Mg II index. The high correlations observed at 335-365 nm indicate a long-term drift in the same direction as the solar cycle Mg II index change. Repeating the regression analysis after applying the periodic variation correction derived in section 2.4 increases correlation values at $\lambda < 260$ nm by only 0.01-0.05. This demonstrates that the information content of the irradiance data is essentially unaffected by the anomalous variation.

3.2. Long-Term Uncertainty

The following terms represent components of the uncertainty in the long-term irradiance changes derived from Nimbus 7 SBUV irradiance data. Some discussions were previously presented in *Schlesinger et al.* [1988] and SC92 and are repeated here for convenience.

3.2.1. Periodic variation. Although we believe the periodic variations discussed in section 2.4 represent an artificial behavior, it is not clear whether the variations are an increase, decrease, or oscillation about the "true" irradiance. We therefore must consider the full amplitude as an uncertainty term, with a wavelength-dependent amplitude varying from 1.0% at 200 nm (2% peak-to-peak) to zero longward of 260 nm.

3.2.2. Instrument sensitivity (adjustment). In section 2.5, we derived an average sensitivity change coefficient adjustment of $\Delta s_{34} = 1.2(\pm 0.4) \times 10^{-5}$ day^{-1}. If we consider this term to represent our best estimate of diffuser changes, then the corresponding uncertainty in irradiance can be evaluated by calculating time series with higher and lower values of Δs_{34}. This analysis yields irradiance changes of 0.6%, which we adopt as our uncertainty for the instrument sensitivity adjustment. *Lean et al.* [1997] suggest a maximum amplitude for irradiance changes longward of 300 nm of 0.3% over a solar cycle, which would correspond to a decrease in irradiance during the Nimbus 7 SBUV time period, occurring primarily in 1982-1984. Figure 9c shows a change of approximately the correct magnitude and temporal location in the 325 nm data. However, the use of an empirically derived Δs_{34} correction and PMT gain change correction based on 391.3 nm data makes it difficult to cite this result as convincing evidence of real solar change.

3.2.3. Instrument sensitivity (interpolation). *Schlesinger et al.* [1988] note that the spline interpolation of $s(\lambda)$ to get values at all wavelengths has increased uncertainty at wavelengths between the nodal values used in the fit. They estimated the uncertainty of $s(\lambda)$ as 0.1% near a reference wavelength, increasing to 0.3% between such wavelengths.

3.2.4. PMT gain change. In SC92 (and *Schlesinger et al.* [1988]), the functional form of the term P(t) representing PMT gain change was the 391 nm irradiance time series, normalized to the beginning of the data record. The function applied to the first 6 years of SBUV data is shown in *Schlesinger et al.* [1988], with an overall range of approximately ±2%. Unpublished data for 1985-1986 show similar variations. This correction assumes no significant solar activity at 391 nm over a solar cycle, and also assumes that the PMT gain change is wavelength-independent. We assign an uncertainty of 0.2% to this term, based on the scatter in the irradiance data.

3.2.5. Goniometry. The Nimbus 7 orbit was maintained at the same Equator-crossing time through 1984, and drifted by less than 10 min through the end of the SBUV spectral irradiance record in October 1986. Examination of individual scan data suggests a possible goniometric effect during 1985-1986 correlated with orbital drift of no more than +1% in daily average irradiance values. However, this error is in the same sense as the Δs_{34} error discussed in section 2.5. Thus, if any goniometry error associated with orbit drift is wavelength-independent, it will be absorbed by the Δs_{34} correction. The residual long-term goniometry error in the irradiance data is therefore smaller than the diffuser uncertainty term. We have assigned an arbitrary value of 0.3% to the goniometry error term.

3.2.6. Interrange ratio. Because Nimbus 7 SBUV measured all gain ranges from the last dynode of the PMT, any changes in the ratios between gain ranges would have to occur in the instrument electronics. The estimated error of this as-

Table 1. Nimbus 7 SBUV Long-Term Uncertainty Values[a]

Term	205 nm	240 nm	300 nm	390 nm
Periodic Variation	2.0%	0.8%	0.0%	0.0%
Instrument sensitivity (adjustment)	1.2%	1.2%	1.2%	1.2%
Instrument sensitivity (interpolated)[b]	0.6%	0.2%	0.2%	0.2%
PMT gain change[b]	0.4%	0.4%	0.4%	0.4%
Interrange ratio[b]	0.6%	0.6%	0.6%	0.6%
Goniometry	0.6%	0.6%	0.6%	0.6%
Wavelength drift	0.4%	0.4%	0.4%	0.4%
Total (RMS)	2.6%	1.8%	1.6%	1.6%

[a]All terms are ±2 σ errors.
[b]From *Schlesinger et al.* [1988].

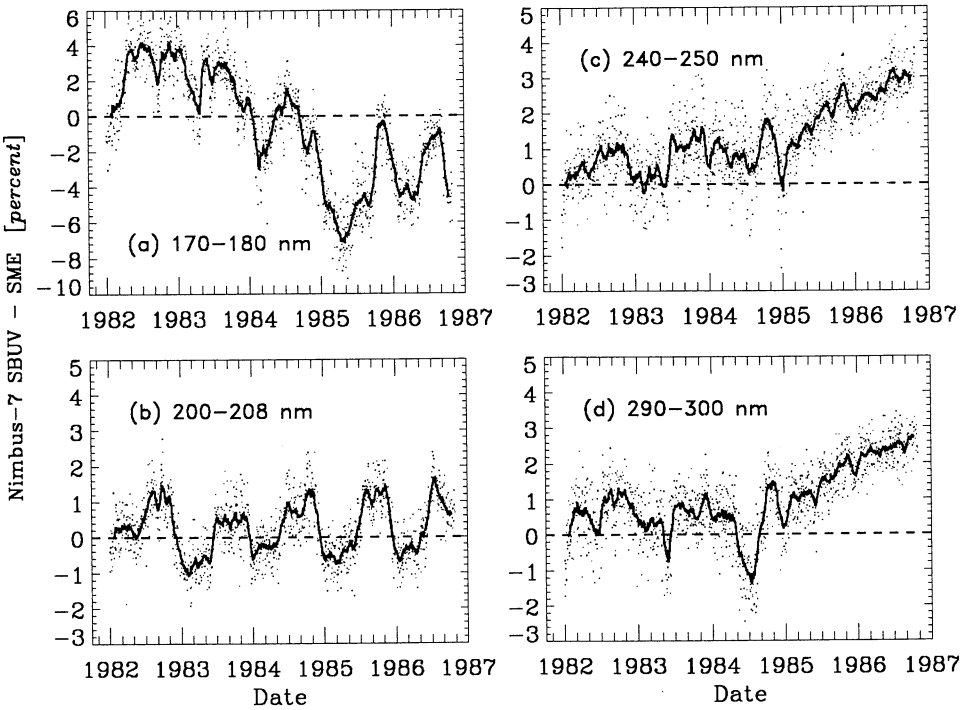

Figure 12. (a) Difference between Nimbus 7 SBUV and SME irradiance time series at 170-180 nm for the time period January 1982 to October 1986. Data represent daily values. The heavy solid line is a 27-day running average of the difference values. Each data set was normalized to the average irradiance value for January 1-3, 1982, prior to calculating differences. (b) Difference between Nimbus 7 SBUV and SME irradiance time series at 200-208 nm. (c) Difference between Nimbus 7 SBUV and SME irradiance time series at 240-250 nm. (d) Difference between Nimbus 7 SBUV and SME irradiance time series at 290-300 nm.

sumption is 0.3% during the first 5 years of operation [*Schlesinger et al.*, 1988].

3.2.7. Wavelength drift. *Cebula et al.* [1998] showed that for NOAA 11 SBUV/2, which has the same bandpass as Nimbus 7 SBUV, errors in 1 nm binned irradiance data due to a wavelength drift error of 0.02 nm were generally 1% or less, exceeding 2% only at strong absorption lines. The wavelength drift correction derived in section 2.3 gives an uncertainty of ~0.007 nm based on the average time-dependent slope. This corresponds to a maximum error of ±0.2% for 1 nm binned data, increasing to 0.4% near the Mg II and Ca II absorption features.

Table 1 lists the numerical values of the uncertainty terms discussed here for 205, 240, 300, and 390 nm. Calculating the RMS 2 σ uncertainty of these terms, we find that the Nimbus 7 SBUV estimated variation for solar cycle 21 at 205 nm is ΔF_{205} = 8.3(±2.6)%, based on the 81-day smoothed data shown in Figure 9a. For 240 nm the estimated solar cycle 21 variation is ΔF_{240} = 4.9(±1.8)%. The 2σ uncertainty values longward of 300 nm are considerably larger than any predicted solar changes. These results are comparable to NOAA 11 SBUV/2 at short wavelengths, and somewhat larger at long wavelengths [*Cebula et al.*, 1998]. Comparisons of UARS SUSIM and SOLSTICE irradiance data suggest that the long-term relative accuracy of these data is currently 1-2% and may approach 1% when the final instrument characterizations are available [*Rottman*, 1998]. The uncertainties quoted here for Nimbus 7 SBUV allow comparison of solar cycle irradiance variations to an accuracy of ~2%.

4. Comparisons with SME Irradiance Data

Measurements of solar UV activity which overlap part of the Nimbus 7 data record are available from the Solar Mesosphere Explorer (SME). This instrument is described by *Rottman et al.* [1982] and made measurements in the wavelength region 115-302 nm. Daily spectral irradiance data in 1 nm bins covering the period January 1982 to June 1988 are available from the National Space Science Data Center (NSSDC). *Schlesinger and Heath* [1988] presented comparisons between archived Nimbus 7 SBUV data, SME data and selected rocket measurements of solar UV irradiance. They focused on absolute irradiance differences between these data sets, and examined the impact of spectrally dependent noise on determination of solar activity magnitude from irradiance ratios. They concluded that 3-5% noise in the SME spectra available at that time prevented the determination of solar changes at λ > 170 nm from ratios using the archived data. *Rottman* [1988] reviewed an improved SME data set in light of previous estimates for solar UV and EUV variability. Their estimated irradiance variations for solar cycle 21 were approximately 50(±15)% at 121.5 nm (Lyman alpha), 8(±5)% at 170-180 nm, and 7(±5)% at 205 nm.

In this paper, we compare Nimbus 7 SBUV and SME solar irradiance time series for the overlap period from January 1982 to October 1986. This covers essentially the full range of solar activity for solar cycle 21. The SBUV data were first reduced to 1 nm binned daily average spectra for consistency with the archived SME product. Time series were then constructed in 10 nm bands, normalized to the average irradiance values on January 1-3, 1982, to remove differences in absolute irradiances, and smoothed with a 5-day binomial-weighted average. Solar cycle irradiance variation values refer to 27-day average time series in order to remove the impact of rotational modulations.

Figure 12a shows the difference between SBUV and SME time series for the wavelength band 170-180 nm. The long-term irradiance change between January-February 1982 and September 1986 derived from the individual time series data is ~10% for SBUV and 7% for SME, based on inspection of the 27-day averaged data. The Mg II index proxy model predicts a change of 9.4(±0.6)% over the same period. A relative drift of 10% between SBUV and SME can be seen during 1982-1984. Inspection of desolarized data suggests that the larger changes in late 1984 and late 1985 are primarily caused by SME data variations. Figure 12b shows the difference between SBUV and SME irradiance time series for the wavelength band 200-208 nm. The wavelength range was reduced for this figure to avoid complications from averaging across the sharp irradiance increase at the Al ionization edge. Long-term irradiance changes in this band are essentially identical for both instruments, with the dominant structure corresponding to the SBUV periodic variation. The 240-250 nm band (Figure 12c) and 290-300 nm band (Figure 12d) show very similar behavior. No long-term drift is observed during 1982-1984, followed by a 2-3% relative drift during 1985-1986. While it can be difficult to partition the trend results between different instruments, examination of Figure 10b suggests that most of the drift in Figure 12c is due to the SBUV data. The residual irradiance changes for each wavelength band shown in Figure 12 are well within the combined long-term uncertainty values quoted in this paper for Nimbus 7 SBUV and in the work of *Rottman* [1988] for SME.

5. Conclusion

In this paper, we have created an improved solar spectral irradiance product from the Nimbus 7 SBUV instrument for solar cycle 21. Implementation of the revised long-term characterization derived by *Schlesinger and Cebula* [1992] largely removed drifts of up to 30% that were present in the previously archived irradiance data. We have derived refinements to the SC92 instrument characterization for residual errors after 1984, and derived an improved wavelength drift correction from analysis of solar absorption lines. An anomalous periodic variation in the data at short wavelengths ($\lambda < 270$ nm) was modeled empirically, but has not been removed from the final irradiance product. The periodic variation has little effect on the information content of the irradiance data. The Nimbus 7 SBUV data produced with these adjustments show a long-term irradiance change of 8.3(±2.6)% at 205 nm and 4.9(±1.8)% at 240 nm for solar cycle 21, using 81-day averaged time series. These irradiance changes are in agreement with predicted long-term changes of 8.3% at 205 nm and 3.7% at 240 nm, respectively, using the Mg II index proxy model. The Nimbus 7 results are also in agreement with overlapping data from the SME satellite for solar cycle 21. The Nimbus 7 SBUV data presented here capture the full range of mid-UV solar variability for solar cycle 21 with a long-term accuracy of ~2%. These data can be used to constrain models of solar variability mechanisms and to provide realistic solar inputs for atmospheric models.

We have produced a data set of Nimbus 7 SBUV daily average spectral irradiances in 1 nm bins over the wavelength range 170-400 nm, extending from November 7, 1978, to October 25, 1986. These data are available by contacting the authors or on-line through our Web page at http://ventus.gsfc.nasa.gov/solar.html. We have also archived the revised Nimbus 7 spectral irradiance data at the National Geophysical Data Center (NGDC). Irradiance data at the nominal instrument sampling interval of 0.2 nm are available upon request. We are currently working towards the creation of a corrected spectral irradiance data set for NOAA 9 SBUV/2, which made measurements over a complete solar cycle (March 1985 to July 1997). Those data, combined with the Nimbus 7 SBUV and NOAA 11 SBUV/2 data sets, will allow us to assemble and examine a continuous 20+ year record of solar spectral UV irradiances from nearly identical instruments.

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