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Semi-Annual Report:

**Analysis of Solar Spectral Irradiance Measurements from
the SBUV/2-Series and the SSBUV Instruments**

Period of Performance: 31 August 1996 to 28 February 1997

24 March 1997

Contract Number:	NASW-4864
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1. SUMMARY OF ACTIVITY DURING CURRENT PERFORMANCE PERIOD

1.1 Development of the Long-term NOAA-11 SBUV/2 Solar Irradiance Data Set

During this period of performance, 1 September 1996 to 28 February 1997, we completed the long-term characterization of NOAA-11 SBUV/2 instrument sensitivity changes using coincident SSBUV observations. This characterization was combined with the updated instrument calibration data previously derived, and a complete reprocessing of the NOAA-11 SBUV/2 sweep mode solar irradiance data was performed. Initial analysis suggests that errors due to uncorrected long-term instrument drift have been reduced to 1-2% over the 5.5 year NOAA-11 data record. Assessments of long-term changes in near and middle UV solar spectral irradiance during the peak and declining phase of solar cycle 22 are now underway. Details of this work may be found in the attached preprints of papers given at the American Geophysical Union (AGU) Fall 1996 Meeting and XVIIIth Quadrennial Ozone Symposium.

1.2 Comparisons with Other Instruments

Preliminary comparisons between the NOAA-11 SBUV/2 solar irradiance data and contemporaneous data from the UARS SOLSTICE and UARS SUSIM instruments were performed during this performance period as part of the validation of the NOAA-11 data. The initial assessment of the NOAA-11 SBUV/2 data suggests that the precision and long-term accuracy of this data set meets or exceeds that of the Version 8 SOLSTICE and Version 16 SUSIM data sets. The attached copy of the paper given at the AGU Fall 1996 Meeting presents this work.

We have similarly begun comparisons of the SSBUV solar data set (discussed in the following section) with concurrent data from the two UARS instruments for the period for which UARS data are currently available, 1991-1994.

1.3 SSBUV Analysis

Solar spectral irradiances for January 1996 SSBUV-8 mission were derived. Prelaunch, in-flight, and postlaunch calibration data were first analyzed and a final radiometric calibration was determined. Outgassing and solar exposure corrections were derived, and the raw SSBUV-8 solar data were fully calibrated. The data were also wavelength adjusted to put them on a common wavelength scale with the solar irradiance data from the previous seven SSBUV missions. The now complete SSBUV solar irradiance data set covers the period October 1989 through January 1996. The SSBUV data are being compared to coincident UARS SOLSTICE and SUSIM solar irradiance data.



1.4 NOAA-9 SBUV/2 Analysis

The instrument calibration for NOAA-9 SBUV/2 was updated through May 1996 as part of the support for the NOAA ozone reprocessing activities. This instrument continues to operate as of March 1997, and has now compiled an unprecedented 12-year record of solar UV spectral irradiance data. Sensor aging related increases in the noise level of the NOAA-9 SBUV/2 solar spectral and Mg II data were noted. If further support becomes available, we hope to apply the techniques we have developed for correcting long-term instrument sensitivity changes to the NOAA-9 SBUV/2 irradiance data set.

1.5 Additional Activities

Dr. Cebula served as a session chairperson at the Fall 1996 American Geophysical Union Meeting on 18 December 1996. Dr. Cebula also served as a reviewer for papers submitted to the *Journal of Geophysical Research* and *Solar Physics*. Mr. DeLand served as a reviewer for a proposal submitted to NASA's Atmospheric Chemistry Modeling and Analysis Program.

1.6 Presentations and Publications

During this period of performance, a paper discussing a preliminary version of the corrected NOAA-11 irradiances was presented in September 1996 at the XVIIIth Quadrennial Ozone Symposium in L'Aquila, Italy. The written version of this paper was reviewed and accepted for publication in the proceedings of the Symposium. A preprint of this paper is attached. A more comprehensive paper describing the final correction procedures was given in December 1996 at the Fall 1996 AGU Meeting in San Francisco, CA. A copy of that paper is also attached.

A second Quadrennial Ozone Symposium paper, presenting a retrospective of all of the SSBUV data, was submitted and has been accepted for publication. We are presently finalizing the camera-ready version of this paper, and a preprint will be provided as soon as it is available.

Three papers describing research results, previously presented at the SOLERS22 Workshop in Sunspot, NM in June 1996, were submitted to *Solar Physics*. Two of these papers (NOAA-9 solar activity, NOAA-11 Mg II index) have been accepted for publication, and a third paper (GOME first results) is being revised to incorporate the reviewer's comments. Preprints of the two "in press" papers are attached.

Two additional oral presentations were given at the Fall 1996 AGU Meeting. In the first paper we presented SSBUV solar irradiance measurements, including those from the January 1996 SSBUV mission. The second paper presented the latest work on the final recalibration of the NOAA-11 SBUV/2 instrument for both solar and ozone observations, using both internal data and SSBUV comparisons.

A seminar on near and middle UV solar irradiance measurements and the SSBUV solar observations was given to Hughes STX Corporation's Center for Astronomy and Solar Physics on 26 February 1996. A copy of the view graphs from that presentation, which was an expanded version of the SSBUV Fall 1996 AGU paper, is attached.

Finally, a paper discussing extensive comparisons between the reprocessed NOAA-11 data, UARS SOLSTICE, and UARS SUSIM has been submitted for presentation at the Spring 1997 AGU Meeting.

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 Back Scattered Measurements and O₃ DOAS/BUV Retrievals", *Proceedings of the XVIIIth Quadrennial Ozone Symposium*, in press, 1997.

Cebula, R. P., "SSBUV Measurements of Solar Spectral Irradiance Variations, 1989-1996", Hughes STX Corporation, Center for Astronomy and Solar Physics (CASP) Seminar, 26 February 1997.

Cebula, R. P., and M. T. DeLand, "Mg II Index Comparisons: NOAA-11 SBUV/2, UARS SOLSTICE, and UARS SUSIM", *Solar Physics*, in press, 1997.

Cebula, R. P., and E. Hilsenrath, "SSBUV Measurements of Solar Spectral Irradiance Variations, 1989-1996", (abstract), *EOS Trans. Amer. Geophys. Union*, **77(46)**, Fall Meeting Suppl., F579, 1996.

DeLand, M. T., and R. P. Cebula, "Solar UV Activity at Solar Cycle 22 Minimum - Evidence for 13-day Periodic Variations", *Solar Physics*, in press, 1997.

DeLand, M. T., and R. P. Cebula, "SBUV/2 Long-Term Measurements of Solar Spectral Variability" (abstract), submitted to 1997 Spring Amer. Geophys. Union Meeting, 1997.

DeLand, M. T., R. P. Cebula, and E. Hilsenrath, "Solar UV Contribution to Stratospheric Ozone Variations 1989-1994", *Proceedings of the XVIIIth Quadrennial Ozone Symposium*, in press, 1997.

Hilsenrath, E., R. P. Cebula, M. C. Bories, J. J. Cerullo, P. W. DeCamp, L.-K. Huang, C. N. Hui, S. J. Janz, T. J. Kelly, K. R. McCullough, J. J. Medeiros, J. T. Riley, B. K. Rice, and C. D. Thorpe, "Contributions of the SSBUV Experiment to Long-Term Ozone Monitoring", *Proceedings of the XVIII Quadrennial Ozone Symposium*, in press, 1997.

Hilsenrath, E., R. P. Cebula, M. T. DeLand, K. Laamann, L. Moy, S. L. Taylor, and C. G. Welle-meyer, "Recalibration and Validation of the NOAA-9 and NOAA-11 SBUV/2 Ozone Data Sets Over the Period 1985-1996" (abstract), *EOS Trans. Amer. Geophys. Union*, **77(46)**, Fall Meeting Suppl., F62, 1996.

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", *Solar Physics*, submitted, 1997.

2. **WORK PLANNED: 1 MARCH 1997 THROUGH 31 AUGUST 1997**

During the next period of performance 1 March 1997 through 31 August 1997, the following activities are planned:

We will finish quality control efforts on the corrected NOAA-11 SBUV/2 spectral irradiance data, create a 1 nm averaged data set for direct comparison with UARS SOLSTICE and SUSIM solar irradiance data, and archive the data for FTP/WWW access on the SSBUV workstation. We intend to announce the availability of these data to the solar physics community via the *SolarNews* monthly newsletter.

The manuscript describing the creation of corrected NOAA-11 solar irradiance data set will be completed and submitted to the *Journal of Geophysical Research*.

We plan to perform extensive statistical analysis of the NOAA-11 solar irradiance data. These results will be compared to results from similar analyses of SOLSTICE and SUSIM data during the period in which all three instruments were operating simultaneously (September 1991 - October 1994). A summary of the results will be presented at the Spring 1997 AGU Meeting. A manuscript describing the complete results will be prepared and submitted to *Journal of Geophysical Research*.

We will validate the SSBUV data record for all eight missions. A paper describing the SSBUV solar irradiance data will be written and submitted to the *Journal of Geophysical Research* for publication. A SSBUV 1 nm averaged solar irradiance data set will be created and archived on the SSBUV workstation for FTP/WWW access. The availability of these data will be announced to the solar physics community via the *SolarNews* monthly newsletter.

COMPARISONS OF THE NOAA-11 SBUV/2, UARS SOLSTICE, AND UARS SUSIM MG II SOLAR ACTIVITY PROXY INDEXES

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ABSTRACT. A NOAA-11 SBUV/2 Mg II solar activity proxy index has been created for the period February 1989 through October 1994 from the daily discrete mode solar irradiance data using an algorithm that utilizes a thorough instrument characterization. This product represents a significant improvement over the previously released NOAA-11 SBUV/2 sweep mode-based Mg II data set. As measured by the NOAA-11 Mg II index, the amplitude of solar rotational activity declined from approximately 4-7% peak-to-peak near the maximum of solar cycle 22 in 1989-1991 to roughly 1% peak-to-peak by late 1994. Corresponding to this decrease, the 27-day averaged NOAA-11 Mg II index decreased by 5.8% over this period. The NOAA-11 Mg II data set is compared with coincident data sets from the UARS SOLSTICE and SUSIM instruments. The impact of differences in instrument resolution and observation platform are examined with respect to both the absolute value and temporal variations of the Mg II index. Periodograms of the three indexes demonstrate comparable solar variation tracking. Between October 1991 and October 1994 predominate power occurs near 27 days, with secondary maxima in the power spectra near 29 and 25 days. Overall, there is low power near 13.5 days during this period. Dynamic power spectral analysis reveals the quasi-periodic and quasi-stationary nature of the middle UV variations tracked by the Mg II index, and periods of significant power near 13.5 days in mid 1991 and late 1994 through mid 1995.

INTRODUCTION

Variations in middle ultraviolet (UV, approximately 200-350 nm) solar irradiance are the primary driver of stratospheric ozone variations. Recent work indicates a 1.5-2% solar cycle variation of global mean total ozone (Stolarski et al., 1991; Chandra and McPeters, 1994; Reinsel et al., 1994) as well as solar cycle-driven variations in lower stratospheric temperature and geopotential height (McCormack and Hood, 1996; Hood, 1997). Tracking solar change in the photochemically important region of the spectrum near 200 nm to an accuracy of approximately 1% over a solar cycle is required to thoroughly understand the role of solar variations on atmospheric change (L. Hood, private communication, 1997). While several measurement programs are underway to measure solar cycle length UV irradiance variations (*e.g.* Cebula et al., 1996; Woods et al., 1996; Weber et al., 1997), as a consequence of the difficulty of precisely tracking long-term instrument response changes, the 1% accuracy goal has yet to be met.

In lieu of direct solar UV measurements of sufficient accuracy, proxy indexes have been used to represent solar change. The core-to-wing irradiance ratio of the Mg II 280 nm absorption feature, commonly known as the Mg II index, is a valuable tool for tracking solar UV activity (*e.g.* Heath and Schlesinger, 1986; Donnelly, 1988, 1991; Cebula et al., 1992; DeLand and Cebula, 1993). A typical solar spectrum observed by the NOAA-11 SBUV/2 instrument near the Mg II feature is shown as the solid line in Figure 1. The use of an irradiance ratio cancels out most long-term instrument sensitivity changes which otherwise complicate

solar UV irradiance measurements, and the construction of a ratio with evenly spaced wings removes any spectrally dependent changes which are approximately linear over the small wavelength interval used ($\Delta\lambda \sim 7$ nm). Mg II index variations can be coupled with spectral scaling factors to estimate solar irradiance variability in the 170-400 nm wavelength region (Cebula et al., 1992; Lean et al., 1992; DeLand and Cebula, 1993), which is important for understanding stratospheric photochemistry.

The initial Mg II index data set from the Nimbus-7 SBUV instrument began in November 1978, using 1.1 nm resolution sweep mode solar data. In this mode the instrument scanned the solar spectrum from approximately 160 to 400 nm. These measurements were continued by the NOAA-9 and NOAA-11 SBUV/2 instruments, with sweep mode (scanning approximately 160 to 405 nm) data beginning in March 1985 and December 1988 respectively. A composite Mg II index data set combining these three data sets was produced for the period November 1978 to May 1993, and distributed to the user community (DeLand and Cebula, 1993). This data set was designed to provide consistency with the Heath and Schlesinger (1986) Nimbus-7 SBUV Mg II index by using the spectral scan Mg II data from NOAA-9 and NOAA-11. The SBUV/2 instruments also use a discrete operating mode to observe the Mg II feature at 12 selected wavelengths with improved signal-to-noise characteristics and superior long-term wavelength stability (Donnelly, 1988; DeLand and Cebula, 1994). The NOAA-11 discrete mode Mg II solar data, which are available from February 1989 to October 1994, have recently been processed with an updated absolute calibration and a thorough long-term instrument characterization.

In this paper we present the NOAA-11 discrete mode Mg II data set and compare it with the previously released sweep mode-based Mg II data set [the NOAA-9 SBUV/2 Mg II data set is presented in a companion paper (DeLand and Cebula, 1997)]. We also compare the NOAA-11 data with coincident Mg II data from the UARS SUSIM and UARS SOLSTICE instruments for the period September 1991 to October 1994. This provides an opportunity for a detailed examination of the impact of differences in both instrument resolution and observation platform on the absolute value and temporal variations of the Mg II index. The robustness of the solar variability information contained in the Mg II index is examined through statistical analysis of the three data sets. Our approach is complementary to that of de Toma et al. (1997), who focus on the degree to which the higher resolution SOLSTICE data reproduce the results of the lower resolution SBUV/2 instruments.

NOAA-11 Mg II CLASSICAL DISCRETE MODE PROXY INDEX

The initial NOAA-11 SBUV/2 Mg II proxy index used in DeLand and Cebula (1993) was based on sweep mode data in order to provide continuity with the Nimbus-7 SBUV and NOAA-9 SBUV/2 data sets also used in that paper. However, a Mg II proxy index based on SBUV/2 sweep mode data has a relatively poor signal to noise ratio (SNR) in comparison to the SNR of the Nimbus-7 SBUV Mg II index. This is because the SBUV/2 instruments measure the Mg II feature's wing irradiances at low count rate on the least sensitive radiometric range of the instrument, and electronic noise lowers the SNR (Schlesinger et al., 1990). In addition, the NOAA-11 instrument's sweep mode wavelength scale drifted by approximately 0.15 nm between 1989 and 1994, introducing an approximate 3% time-dependent drift in the sweep-mode Mg II index. Daily NOAA-11 discrete mode Mg II observations commenced in February 1989. An index constructed from these data has a much higher SNR than the sweep mode index, not only because of a factor of 12.5 increase in the integration time, but also because limiting the wavelength interval scanned to the Mg II feature's region increases the number of scans per day by a factor of 4-5 over the number obtained in the sweep mode (DeLand and Cebula, 1994). Further, the NOAA-11 SBUV/2 instrument's wavelength calibration stability was an order of magnitude better in discrete mode than in sweep mode (Ahmad et al., 1994). Using a subset of the discrete mode data and a less rigorous instrument characterization, Donnelly (1991) has constructed a modified discrete mode Mg II index from the NOAA-9 SBUV/2 instrument's data. That index was constructed to circumvent

some of the limitations of the preliminary instrument characterization, with the result that it was less sensitive to solar variations than is the sweep mode index. DeLand and Cebula (1994) suggested that an analogous *classical* discrete mode Mg II index, constructed from discrete mode measurements taken at essentially the same wavelengths as were used for the Nimbus-7 SBUV Mg II index, and employing a full instrument characterization, could combine the best features of the existing SBUV/2 proxy indexes.

The NOAA-11 SBUV/2 diffuser deployment mechanism failed on 16 October 1994, ending solar measurements, but permitting the continuation of daily ozone measurements. Following the launch of the NOAA-14 spacecraft on 30 December 1994, the NOAA-11 spacecraft was deactivated on 10 April 1995, terminating NOAA-11 SBUV/2 observations. The NASA Goddard Space Flight Center's Ozone Processing Team has recently completed a meticulous instrument characterization for the entire NOAA-11 SBUV/2 data record (Hilsenrath et al., 1996). Using that characterization, we have processed the discrete Mg II data set and produced a classical discrete mode NOAA-11 SBUV/2 Mg II index (hereafter $Mg II_{NOAA-11}$). The most significant revisions to the processing algorithm are updates to the instrument's goniometry, photomultiplier tube detector gain, and corrections for small discrete mode wavelength selection errors. The $Mg II_{NOAA-11}$ proxy index is presented in Figure 2a. The solar rotational activity, as determined by approximate 27-day variations in $Mg II_{NOAA-11}$, declined from roughly 4-7% peak-to-peak near the maximum of solar cycle 22 in 1989-1991 to approximately 1% peak-to-peak after mid 1994. Note that the strength of the rotational modulation varies significantly from one rotation to next. Shown as the heavy solid line in Figure 2a is a 27-day running average of $Mg II_{NOAA-11}$, which removes the rotational modulation and shows long-term variations. From this curve it is seen that the mean level of solar activity, as measured by $Mg II_{NOAA-11}$, decreased by approximately 5.8% over this period.

The percent difference between the composite sweep mode-based index (DeLand and Cebula, 1993) and $Mg II_{NOAA-11}$ is presented in Figure 3. During the period of overlap, 1989-1993, the composite index was based on NOAA-11 data. The day-to-day differences are predominately the result of noise in the sweep mode Mg II data, resulting from the SNR and sampling limitations previously discussed. In addition, absolute and time dependent differences are seen in Figure 3. The absolute difference is primarily the result of the procedure used to create the composite index. As discussed in DeLand and Cebula (1993), both the NOAA-11 SBUV/2 and the Nimbus-7 SBUV Mg II indexes were normalized to the NOAA-9 SBUV/2 Mg II index during their respective overlap periods. Due to small differences in the exact wavelengths used from one instrument to the next, as well as small but nontrivial inter-instrument differences in bandpass and slit function, the absolute value of each instrument's Mg II index and the instrument's sensitivity to solar change is unique (Hall and Anderson, 1988). Further, a long-term drift in the NOAA-9 instrument's wavelength calibration resulted in a 1% bias in its sweep mode Mg II index in 1989 relative to 1985. These effects explain the absolute difference between the composite index and $Mg II_{NOAA-11}$ shown in Figure 3. The minor drift between the sweep mode composite index and $Mg II_{NOAA-11}$ results from uncorrected drift in the NOAA-11 SBUV/2 instrument's sweep mode wavelength calibration (DeLand and Cebula, 1994), and, to a lesser extent, revisions to other components of the absolute and long-term instrument characterizations.

COMPARISON TO UARS SOLSTICE AND SUSIM MG II INDEXES

The later portion of the NOAA-11 SBUV/2 measurement period coincides with the availability of solar irradiance data from the SOLSTICE (Rottman et al., 1993) and SUSIM (Brueckner et al., 1993) instruments onboard the UARS satellite. Both UARS instruments began taking data in October 1991. The SUSIM V18 Mg II proxy index data set extends through December 1995, and is based on daily spectral measurements taken at 1.1 nm resolution (Floyd et al., 1997). The corresponding SOLSTICE V9 Mg II data set is constructed from spectral data taken at 0.24 nm resolution (de Toma et al., 1997; White et al., 1997). The two UARS

data sets, $Mg II_{SOLSTICE}$ and $Mg II_{SUSIM}$, are presented in Figures 2b and 2c, respectively. Comparisons of the two UARS $Mg II$ data sets to $Mg II_{NOAA-11}$ are presented in Figure 4. The $Mg II_{NOAA-11}$ and $Mg II_{SUSIM}$ indexes are based on solar irradiance measurements taken at similar spectral resolution and are constructed using similarly spaced (although not identical) core and wing samples. Hence, $Mg II_{NOAA-11}$ and $Mg II_{SUSIM}$ should have approximately the same absolute value as well as comparable sensitivity to solar variations. Figure 4a indicates that the ratio of the two $Mg II$ indexes is nearly unity. However, there is roughly a 1.5% relative drift between the two indexes during the first seven months of overlap. After the SUSIM data were interrupted for roughly 1.5 months due to problems with the UARS solar arrays, there is little additional drift from mid 1992 to the end of the overlap in the data record in October 1994. Although late 1991 and early 1992 is a period of significant rotational modulation, the mean level of solar activity did not change substantially during this seven month period. Further, from early 1993 to late 1994, when UV solar activity, as measured by the two $Mg II$ proxy indexes, decreased by 2.3%, the drift between the two indexes was less than 0.5%. Hence, the relative drift in the NOAA-11 and SUSIM indexes in late 1991 and early 1992 is most likely due to a systematic drift in one or both of the instruments' indexes rather than a difference in their response to solar variability. Since the comparison of the $Mg II_{NOAA-11}$ and $Mg II_{SOLSTICE}$ indexes presented in Figure 4b does not show a corresponding drift during this seven month period, we suspect there is an uncorrected systematic drift in the $Mg II_{SUSIM}$ during the initial phase of that instrument's operation. $Mg II_{SUSIM}$ exhibits a similar drift with respect to the NOAA-9 SBUV/2 $Mg II$ data set, $Mg II_{NOAA-9}$, presented by DeLand and Cebula (1997). There is no relative drift between $Mg II_{NOAA-9}$ and $Mg II_{NOAA-11}$.

The relationship between $Mg II_{SUSIM}$ and $Mg II_{NOAA-11}$ is further examined via the scatter plot and linear regression analysis presented in Figure 5a and Table 1. While there is an approximately linear relationship between the two indexes for the entire period, the data for first seven months, denoted by the "X's" in Fig. 5a, clearly show more dispersion and an absolute offset relative to the data for the rest of the overlap period. The linear correlation coefficient for the period October 1991-June 1992 is only 0.900, indicating that 20% of the variance in $Mg II_{SUSIM}$ is not explained by the linear relation with respect to $Mg II_{NOAA-11}$. The linear correlation coefficient for the rest of the data record, July 1992-October 1994, is 0.954. Therefore, for this period about 91% of the variance in $Mg II_{SUSIM}$ is explained by the linear relation with respect to $Mg II_{NOAA-11}$. The slope of the linear regression for the period July 1992 through October 1994 is 0.994, indicating that, as predicted, the two instruments have very similar responses to solar change. Note that the correlation coefficient is slightly greater for the entire period, October 1991-October 1994 ($r=0.963$) than it is for the July 1992-October 1994 period, despite the inclusion of the early data with increased dispersion. This is a consequence of the regression procedure; whereas the latter period encompasses only about one-half the dynamic range of the solar cycle, the full dynamic range of the solar cycle is included in the former period. A similar, although significantly smaller effect is seen in the regression between $Mg II_{SOLSTICE}$ and $Mg II_{NOAA-11}$ discussed below. It is therefore beneficial and important to maximize the dynamic range of the data sets used in the linear regression analysis, provided that significant drifts have been removed. If the cause of the drift in $Mg II_{SUSIM}$ can be identified and corrected, the relationship between $Mg II_{SUSIM}$ and $Mg II_{NOAA-11}$ should be redetermined using the entire dynamic range of the solar cycle. Doing so will yield a more accurate and precise relationship than is currently achievable.

Interpretation of the comparison between $Mg II_{SOLSTICE}$ and $Mg II_{NOAA-11}$, presented in Figure 4b, is more complicated than is the comparison between $Mg II_{NOAA-11}$ and $Mg II_{SUSIM}$ as a result of differences in instrument resolution and processing algorithms. Figure 2 shows that the absolute value of $Mg II_{SOLSTICE}$ is approximately a factor of two smaller than are the absolute values of $Mg II_{NOAA-11}$ and $Mg II_{SUSIM}$. A typical scan of SOLSTICE ~0.24 nm resolution solar spectral irradiance data in the vicinity of the $Mg II$ absorption feature, shown as the dashed curve in Figure 1, is useful in understanding these differences. The higher spectral resolution data reveal significantly more spectral structure in the absorption feature than do the lower spectral

resolution data. As observed by SOLSTICE the Mg II *h* and *k* emission lines are visible as distinct emission peaks in the core of the broad absorption feature. In contrast, these central emission peaks are not visible at the 1.1 nm resolution of the SBUV/2 and SUSIM instruments. Because of the higher resolution, the core of the Mg II feature as observed by SOLSTICE contains no contribution from the photospheric wing wavelengths (as opposed to the Mg II feature at 1.1 nm resolution, where the core contains a non-negligible photospheric content). Since the core of the Mg II feature as observed by SOLSTICE originates higher in the solar atmosphere at a correspondingly higher temperature than does the core of the feature when observed by NOAA-11, $Mg II_{SOLSTICE}$ and $Mg II_{NOAA-11}$ have different sensitivities to solar irradiance variations. Thus, except for the non-linear behavior observed in early 1992, the change in the relative percent difference between the two indexes presented in Figure 4b is physical rather than instrumental in origin. Note that the temporal dependence of this feature is quite distinct from the drift between $Mg II_{SUSIM}$ and $Mg II_{NOAA-11}$ shown in Figure 4a. We thus suspect this feature may result from a transitory feature in $Mg II_{SOLSTICE}$. A scatter plot of $Mg II_{SOLSTICE}$ versus $Mg II_{NOAA-11}$ (Figure 5b) and linear regression analysis results (Table 1) show that the two indexes are well correlated ($r=0.984$) and scale approximately linearly. In contrast to the comparison between $Mg II_{SUSIM}$ and $Mg II_{NOAA-11}$ presented previously, note that the linear regression coefficients for the October 1991-June 1992 ($r=0.958$) and July 1992-October 1994 ($r=0.963$) periods are nearly identical. The slope of this regression fit is 1.40, which is almost identical to the result obtained by de Toma et al. (1997) in their analysis of these data sets ($Mg II_{NOAA-11} = 0.153 + 0.696 * Mg II_{SOLSTICE}$; Equation 8). As determined from the extreme values of Figure 5b, the SOLSTICE index has approximately a factor of 2.2 greater response to rotational and solar cycle change than do the lower resolution indexes (SBUV/2 and SUSIM). This enhanced sensitivity, which is a consequence of SOLSTICE's higher spectral resolution, results in the change noted in Figure 4b. de Toma et al. (1997) also degraded the SOLSTICE irradiance data to the nominal SBUV/2 resolution and recomputed Mg II index values. They found a slope of 0.927 when these data were regressed against $Mg II_{NOAA-11}$. This indicates that, as observed in the Mg II feature, the higher resolution SOLSTICE irradiance data are more responsive to chromospheric activity, even when degraded to comparable resolution, than are the lower resolution SBUV/2 irradiance data. White et al. (1997) compared the effects of degrading the SOLSTICE data to the nominal SBUV/2 and SUSIM resolution. Consistent with the current work, White et al. (1997) found that the sensitivity of higher resolution data to both solar rotational and long-term modulation is approximately twice the sensitivity of the index when observed at 1.1 nm resolution. Scale factors derived from SBUV/2 data (DeLand and Cebula, 1993) must therefore be rescaled for use with $Mg II_{SOLSTICE}$.

POWER SPECTRAL ANALYSIS

Using the technique described by Horne and Baliunas (1986) and Lean and Brueckner (1989), we have constructed periodograms of $Mg II_{NOAA-11}$, $Mg II_{SOLSTICE}$, and $Mg II_{SUSIM}$ for the period of coincident measurements, October 1991 to October 1994, to examine the power spectra of the three data sets. The periodograms, shown in Figure 6, demonstrate comparable solar variation tracking between the three indexes, consistent with the high correlation coefficients observed previously. For this period the predominant power occurs with a period near 27 days, with secondary maxima in the power spectra near 29 and 25 days. Overall, there is relatively low power near 13.5 days during the interval of coincident data. This indicates that, during this period, solar UV variability was dominated by a single active region at a time.

Shown in Figure 7 is the result of a dynamic power spectral analysis of the three Mg II data sets. The analysis was performed by fixing the periodogram data window at a width of 256 days and stepping through the data sets in 64-day increments, following the work of Bouwer (1992). This analysis reveals the complex quasi-periodic and quasi-stationary nature of middle UV solar variations. Note the significant changes in power

surrounding the dominant 27-day periodicity, which explains the presence of the secondary maxima noted in Figure 6 near 29 and 25 days. Strong approximate 35-day and 30-day periodicities were observed by the NOAA-11 instrument during late 1989 and mid 1990, respectively. $Mg II_{NOAA-11}$ also exhibits a period of approximate 13.5-day solar variability from the middle of 1991 through early 1992, with the peak in the power occurring shortly after the UARS launch. This variability indicates the emergence of active regions on opposing faces of the Sun simultaneously. The very end of this episode of approximate 13.5-day periodicity is just barely visible at the beginning of the $Mg II_{SOLSTICE}$ data set. A period of relatively weak 13.5-day periodicity was observed by all three instruments in Spring 1993. This period gives rise to the small peak near 13.5 days seen in Figure 6.

An extended period of significant, approximate 13.5 day periodicity commenced in September 1994, shortly before the termination of the NOAA-11 SBUV/2 solar measurements. The analysis technique employed here, coupled with the termination of the NOAA-11 data set in mid October 1994, prohibits revelation of this change in solar activity in the dynamic power spectra of $Mg II_{NOAA-11}$. The $Mg II_{SUSIM}$ and $Mg II_{SOLSTICE}$ dynamic power spectra (Figures 7b and 7c, respectively) reveal the presence of this periodicity. As demonstrated in the periodogram analysis presented in Figure 6 of DeLand and Cebula (1997), the NOAA-9 SBUV/2 instrument also observed persistent approximate 13.5-day solar variability from September 1994 through March 1995. These observations are significant because this period of strong 13.5 day periodicity was observed near solar cycle 22 minimum. During the only other solar minimum period monitored to date in the UV, 1985-1986, very little 13.5 day activity was observed (Heath and Schlesinger, 1986). These observations, and the differences in activity seen during the maximum of solar cycle 22 versus that seen during cycle 21 maximum, suggest that each solar cycle is unique and that we are not yet at the point where one can simply use the middle UV solar data sets we presently have to extrapolate to the future.

CONCLUSIONS

A classical discrete mode $Mg II$ index, $Mg II_{NOAA-11}$, has been created from the entire six-year NOAA-11 SBUV/2 data set. This product has better signal-to-noise characteristics and long term accuracy than the sweep mode NOAA-11 $Mg II$ data set previously published by DeLand and Cebula (1993). Comparisons of $Mg II_{NOAA-11}$ with $Mg II_{SOLSTICE}$ and $Mg II_{SUSIM}$ indicates that each instrument is capable of accurately tracking both short- and long-term solar variations. There is an approximate 1.5% relative drift between $Mg II_{SUSIM}$ and $Mg II_{NOAA-11}$ during the first seven months of SUSIM operations which needs to be understood. No corresponding drift is seen between $Mg II_{NOAA-11}$ and either $Mg II_{SOLSTICE}$ or $Mg II_{NOAA-9}$. $Mg II_{SOLSTICE}$ and $Mg II_{NOAA-11}$ exhibit good linear correlation ($r=0.984$) even though the SOLSTICE index has roughly a factor of 2.2 greater response to solar variations relative to the SBUV/2 index and $Mg II_{SOLSTICE}$ exhibits a transitory feature with respect to $Mg II_{NOAA-11}$ in early 1992, during the first year of SOLSTICE operation. The $Mg II_{NOAA-11}$ data are available from the authors (cebula@ssbuv.gsfc.nasa.gov). The $Mg II_{NOAA-9}$ data are also available from the authors for the period June 1986 through May 1996. In the near future these two data sets will be combined with the Nimbus-7 SBUV $Mg II$ data to create a single $Mg II$ proxy index covering the period November 1978 through May 1996.

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FIGURE CAPTIONS

Fig. 1. The Mg II doublet at 280 nm as observed by the NOAA-11 SBUV/2 instrument at 1.1 nm resolution (solid line) and the UARS SOLSTICE instrument at 0.24 nm resolution (dashed line). Positions of the 7 wavelengths used to construct the SBUV/2 classical discrete mode Mg II index, $Mg II_{NOAA-11}$, are indicated by the arrows. The wavelengths used to construct $Mg II_{SUSIM}$ (not shown) are very similar to those used to construct $Mg II_{NOAA-11}$. Positions of the wavelengths used to construct $Mg II_{SOLSTICE}$ are indicated by the small boxes.

Fig. 2. Time series of Mg II proxy index products from three instruments: (a) the NOAA-11 SBUV/2 classical discrete mode Mg II index, $Mg II_{NOAA-11}$; (b) the UARS SUSIM V18 Mg II index, $Mg II_{SUSIM}$; (c) the UARS SOLSTICE V9 Mg II index, $Mg II_{SOLSTICE}$. The heavy line in (a) is a 27-day running mean of $Mg II_{NOAA-11}$.

Fig. 3. Percent difference between the SBUV-SBUV/2 composite Mg II index (DeLand and Cebula, 1993) and $Mg II_{NOAA-11}$. For the period shown here the composite index was based on NOAA-11 SBUV/2 sweep mode data.

Fig. 4. Percent differences between the time series of the two UARS Mg II indexes and $Mg II_{NOAA-11}$ for the period of common measurements, October 1991 through October 1994: (a) $Mg II_{SUSIM}$; (b) $Mg II_{SOLSTICE}$. The crosses in panel (a) correspond to data taken during the first seven months of SUSIM operations and the squares to data taken after this period. The SUSIM to SBUV/2 comparison is normalized by the absolute ratio of the two indexes. As discussed in the text, the change shown in (b) is physical in origin.

Fig. 5. Comparisons of the two UARS Mg II indexes to $Mg II_{NOAA-11}$: (a) $Mg II_{SUSIM}$, and (b) $Mg II_{SOLSTICE}$. The crosses in panel (a) correspond to data taken during the first seven months of SUSIM operations and the squares to data taken after this period. The lines are the result of least square linear regression fits. In panel (a) the dashed line is a fit to the period October 1991-October 1994 and the solid line is the fit to the period July 1992-October 1994. The solid line in panel (b) is the result of fitting the entire period of coincident

measurements, October 1991-October 1994.

Fig. 6. Periodogram analysis of the three Mg II data sets for the period October 1991 through October 1994: (a) $\text{Mg II}_{\text{NOAA-11}}$; (b) $\text{Mg II}_{\text{SUSIM}}$; (c) $\text{Mg II}_{\text{SOLSTICE}}$. The dashed line indicates the false alarm probability (FAP) level of 0.1%; features with power above this FAP are statistically significant at the 99.9% confidence level (Horne and Baliunas, 1986).

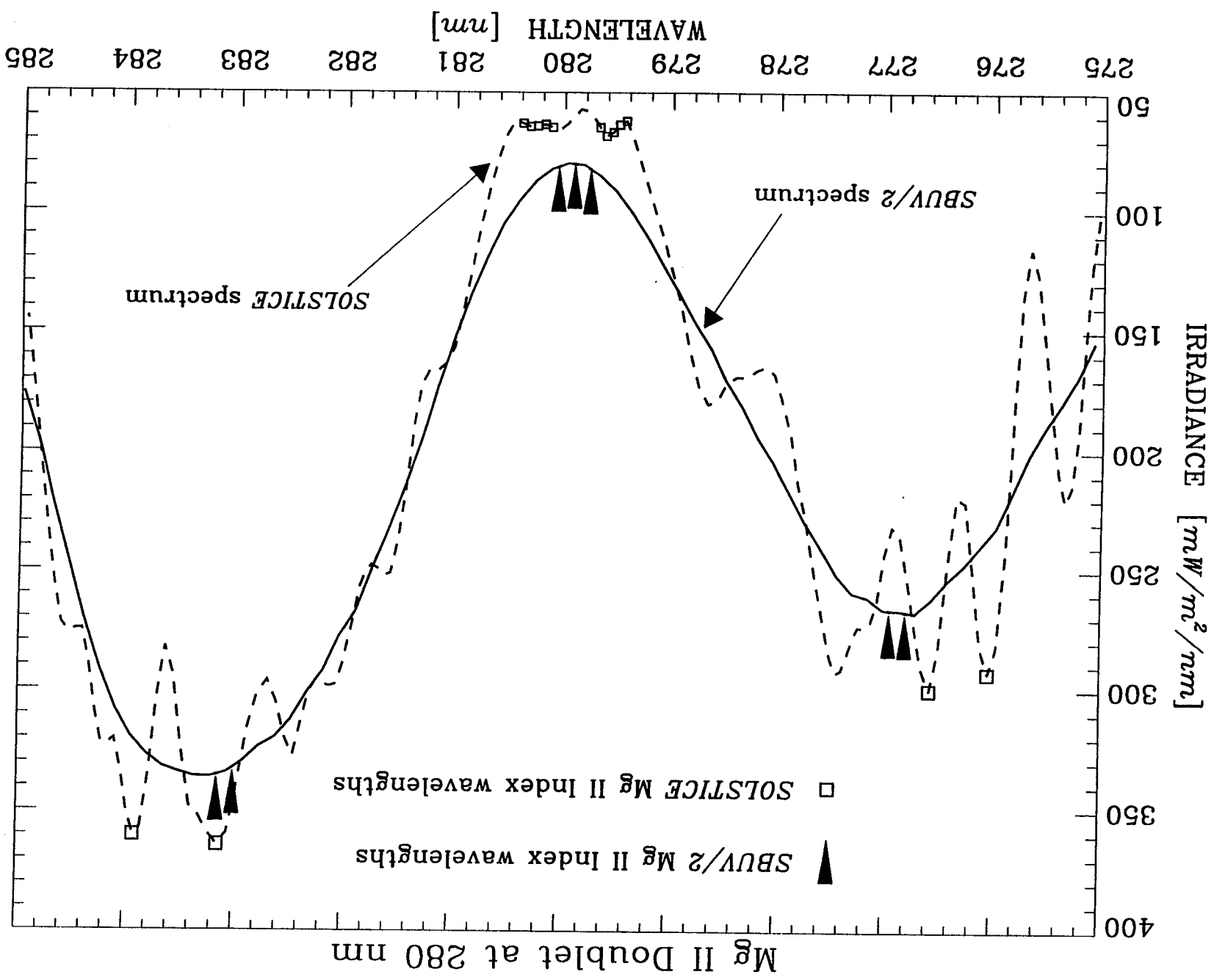
Fig. 7. Dynamic power spectral analysis of the three Mg II data sets: (a) $\text{Mg II}_{\text{NOAA-11}}$; (b) $\text{Mg II}_{\text{SUSIM}}$; (c) $\text{Mg II}_{\text{SOLSTICE}}$. Contour levels represent periodogram power in increments of 15, corresponding to the vertical scale of Fig. 6. All contour levels shown are statistically significant at the 99.9% level.

Table 1

**Slope and Linear Correlation Coefficients Derived from Least Squares Linear Regression
Comparisons of Mg II_{SOLSTICE} and Mg II_{SUSIM} with Mg II_{NOAA-11}**

DATA SET	SLOPE	LINEAR CORRELATION COEFFICIENT
All SUSIM: Oct 1991 - Oct 1994	0.852	0.963
SUSIM: Oct 1991 - June 1992	0.855	0.900
SUSIM: July 1992 - Oct 1994	0.994	0.954
All SOLSTICE: Oct 1991 - Oct 1994	1.40	0.984
SOLSTICE: Oct 1991 - June 1992	1.31	0.958
SOLSTICE: July 1992 - Oct 1994	1.41	0.963

Figure 1



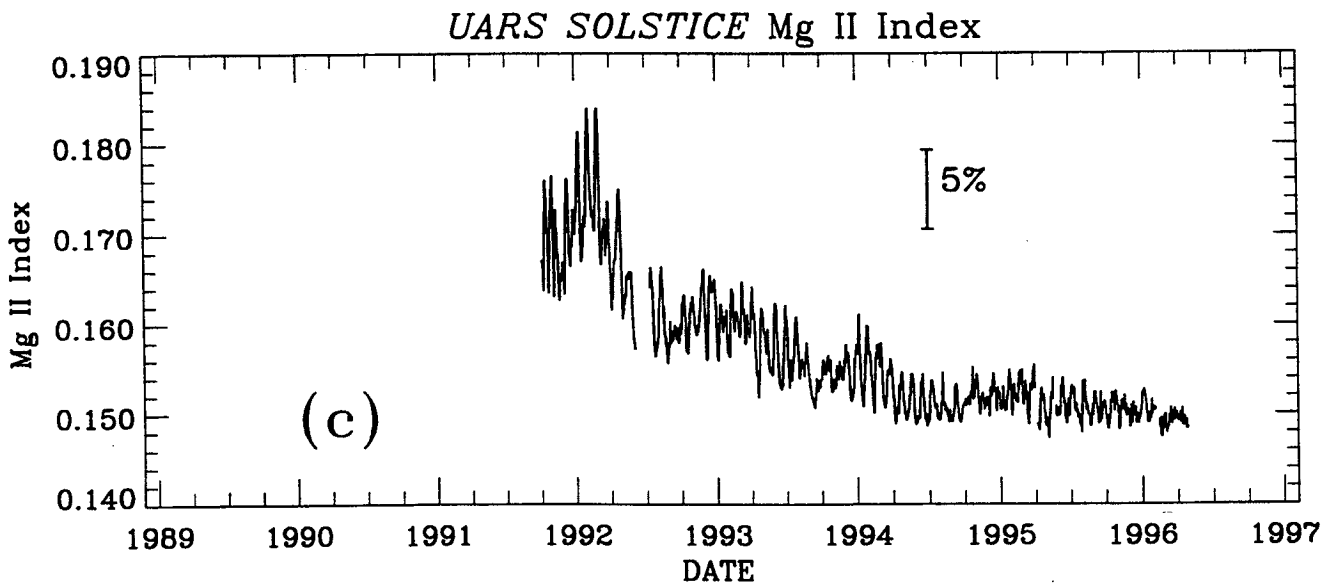
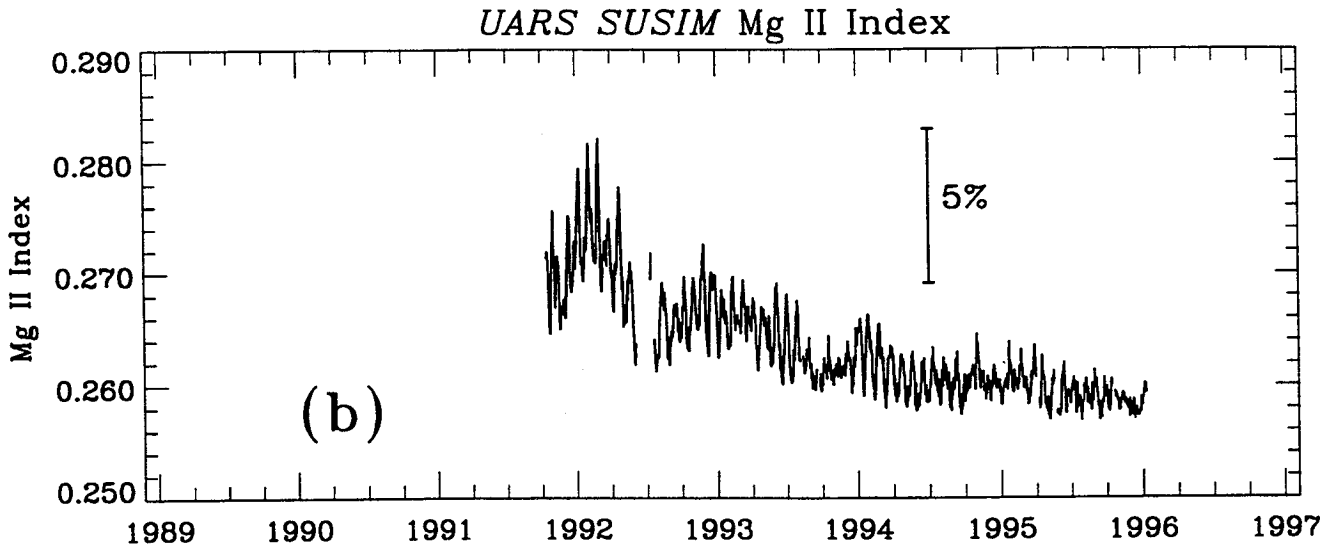
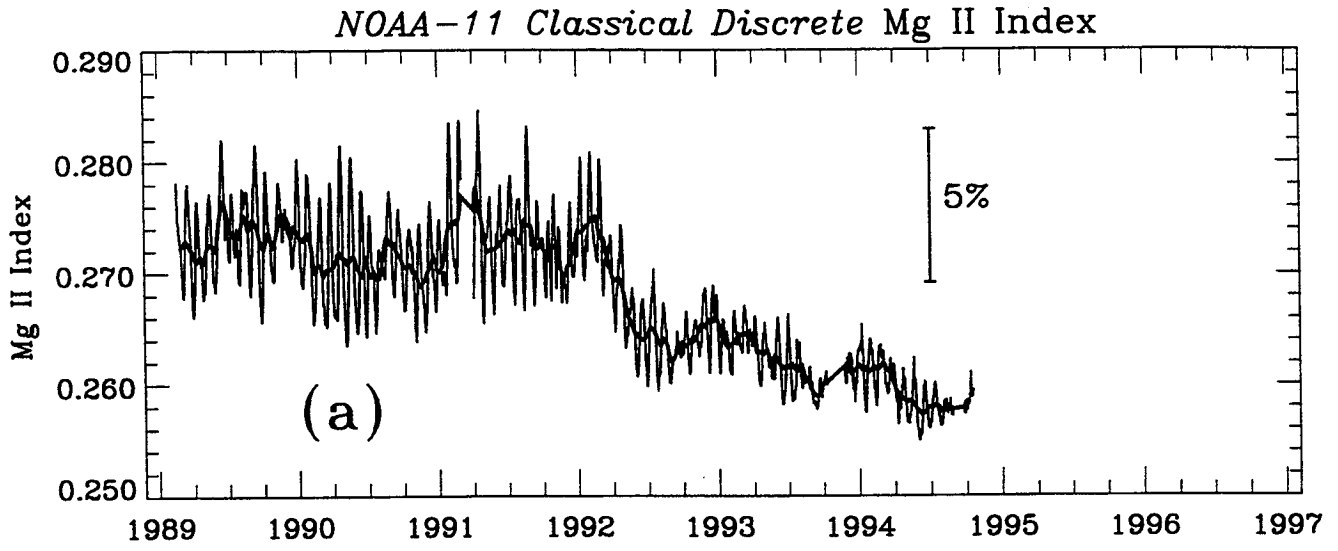
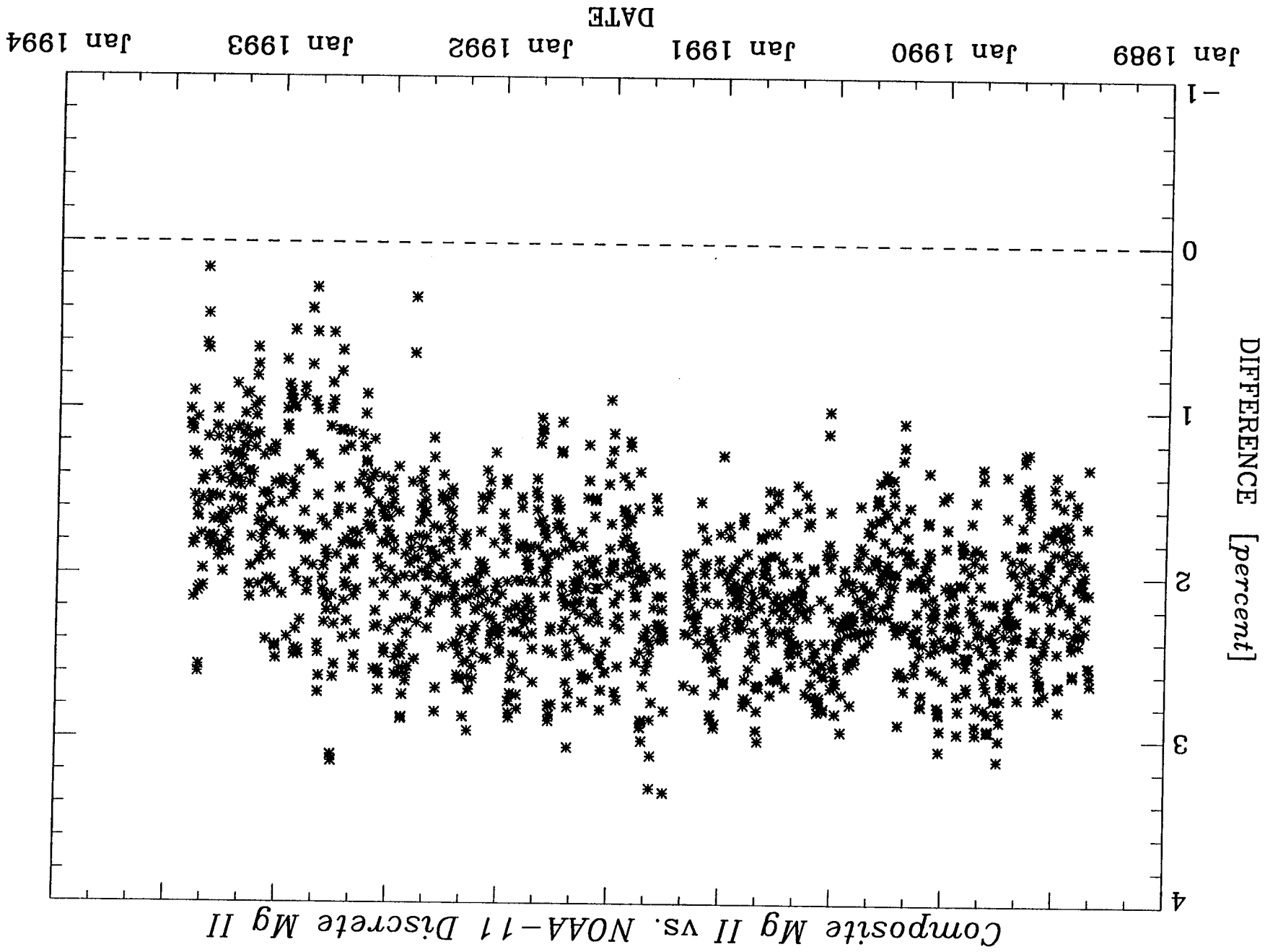


Figure 3

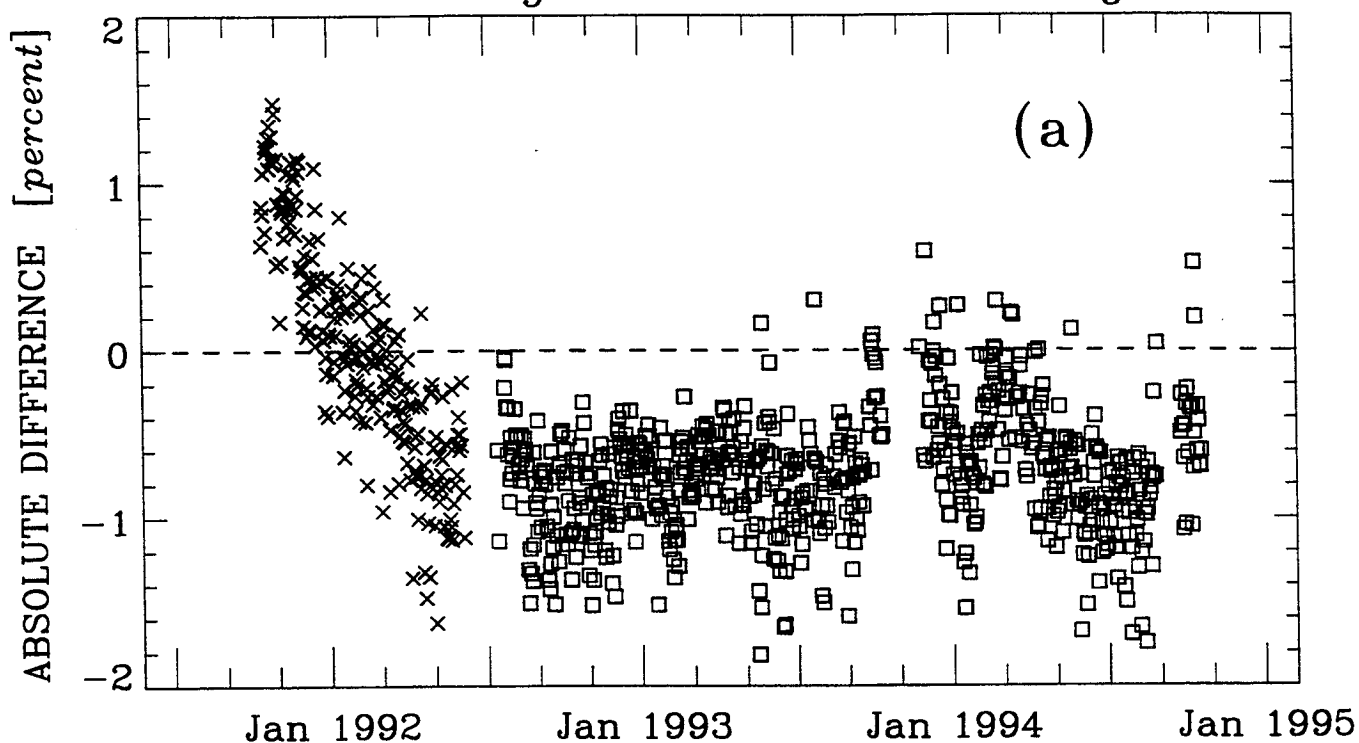
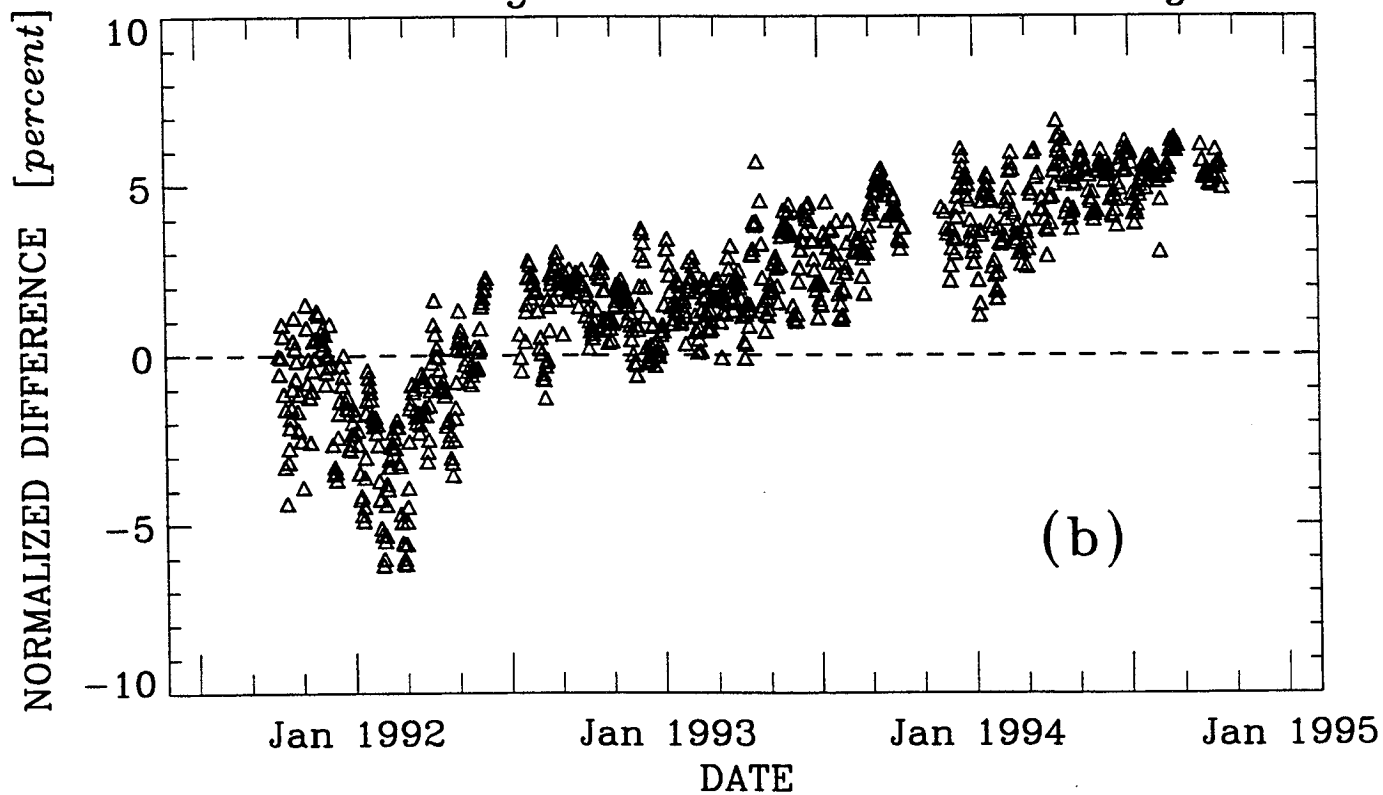


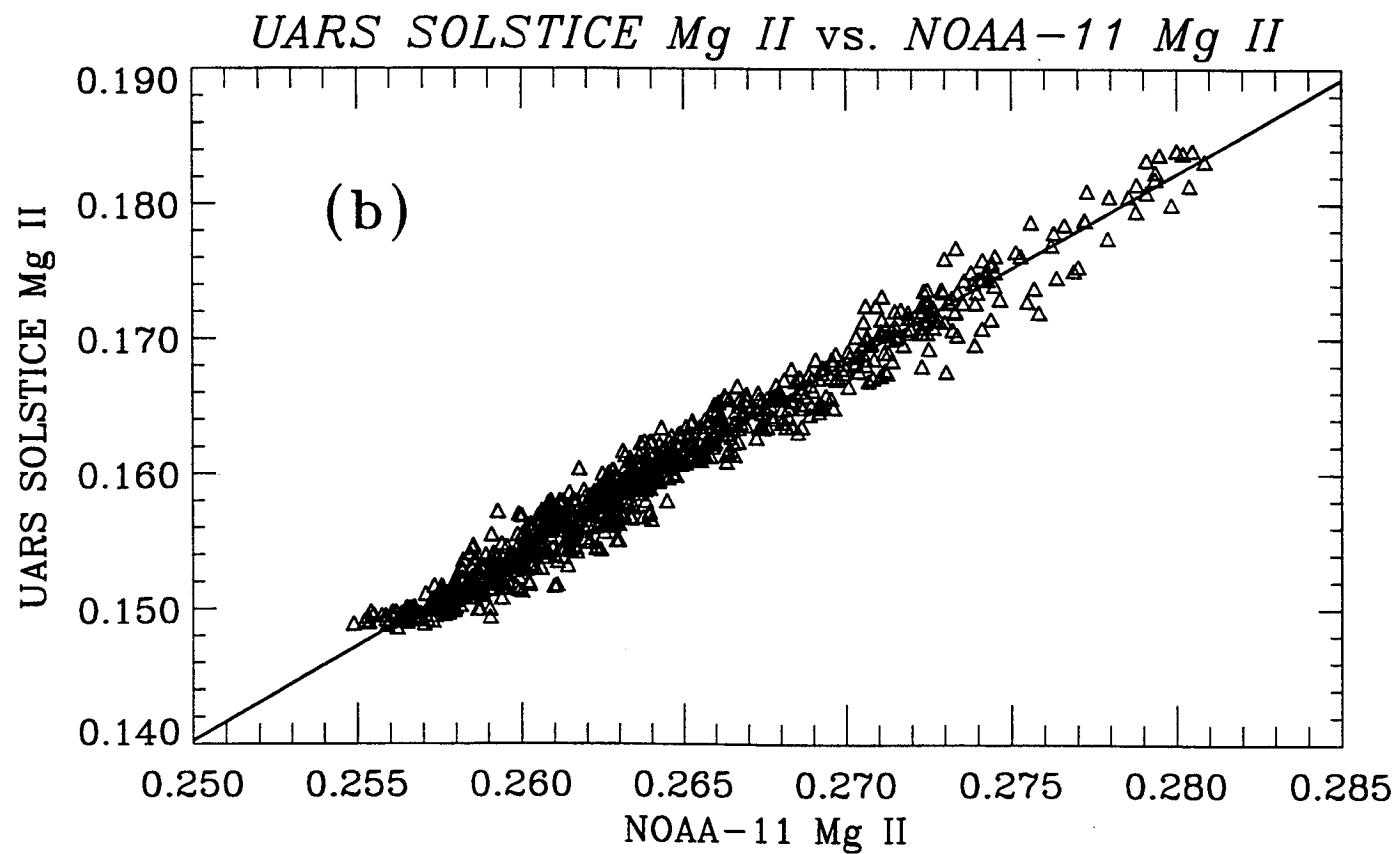
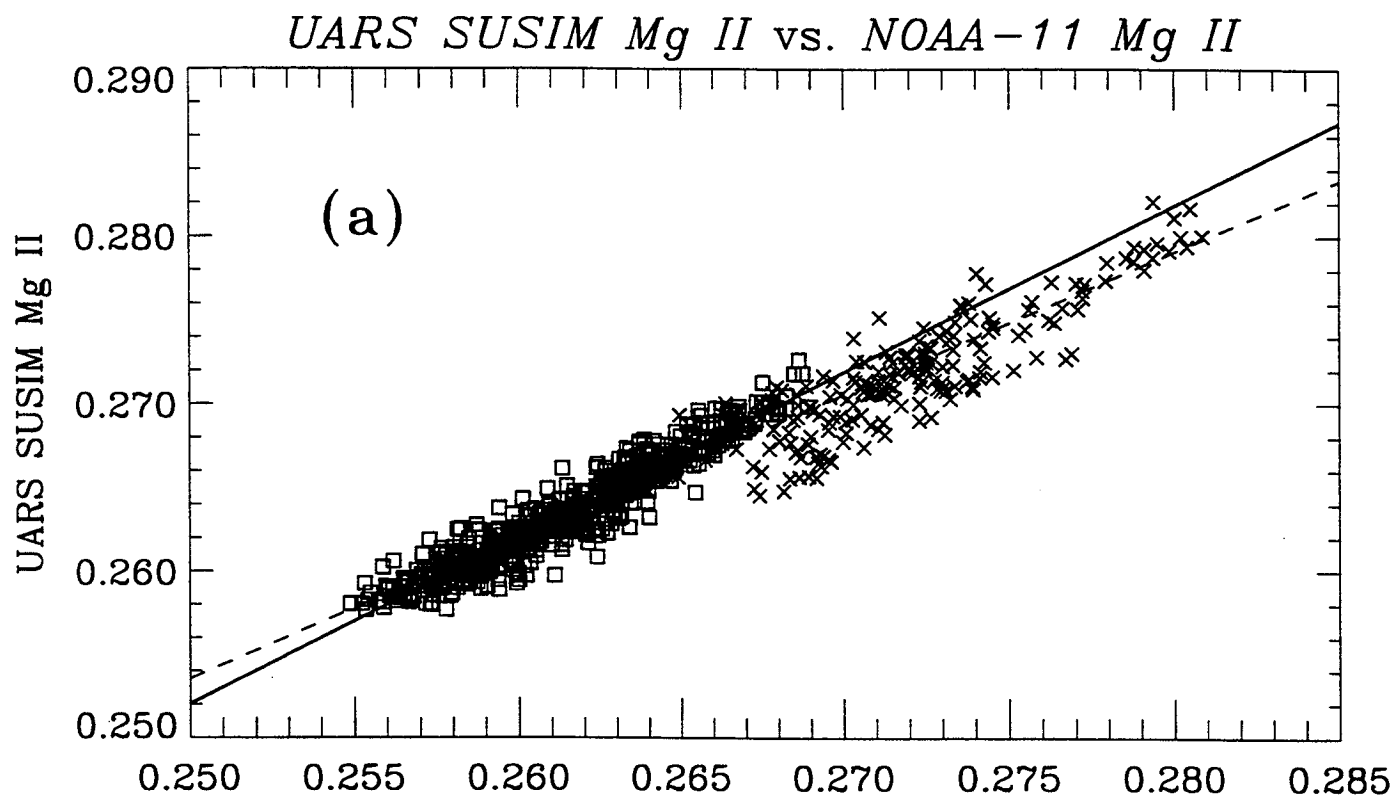
Composite Mg II vs. NOAA-11 Discrete Mg II

DIFFERENCE [percent]

DATE

Jan 1989 Jan 1990 Jan 1991 Jan 1992 Jan 1993 Jan 1994

NOAA-11 Mg II vs. UARS SUSIM Mg II*NOAA-11 Mg II vs. UARS SOLSTICE Mg II*



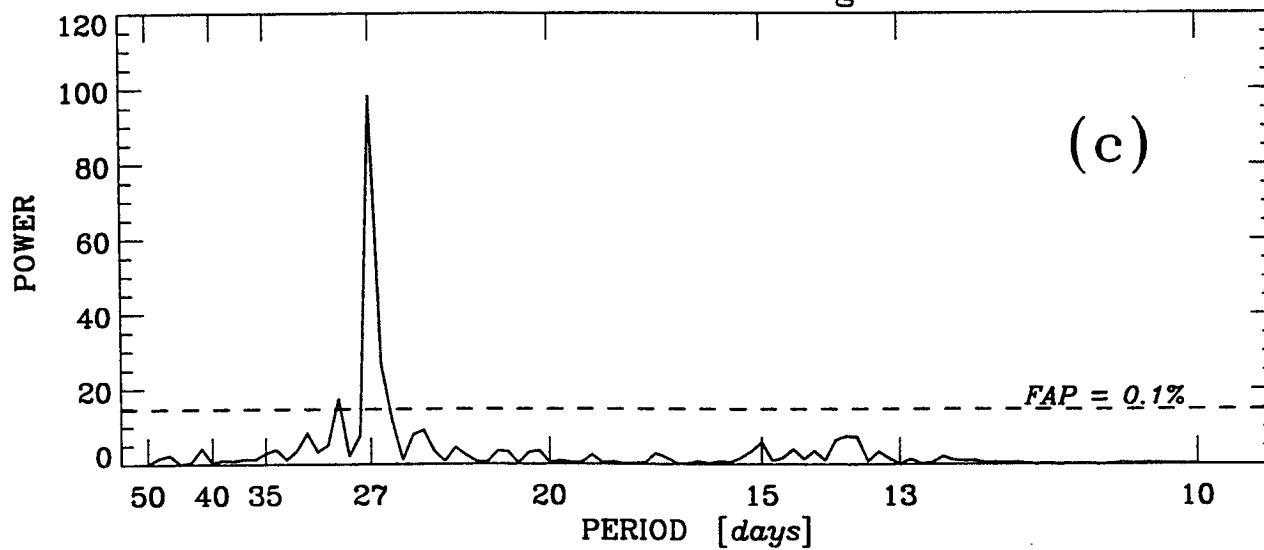
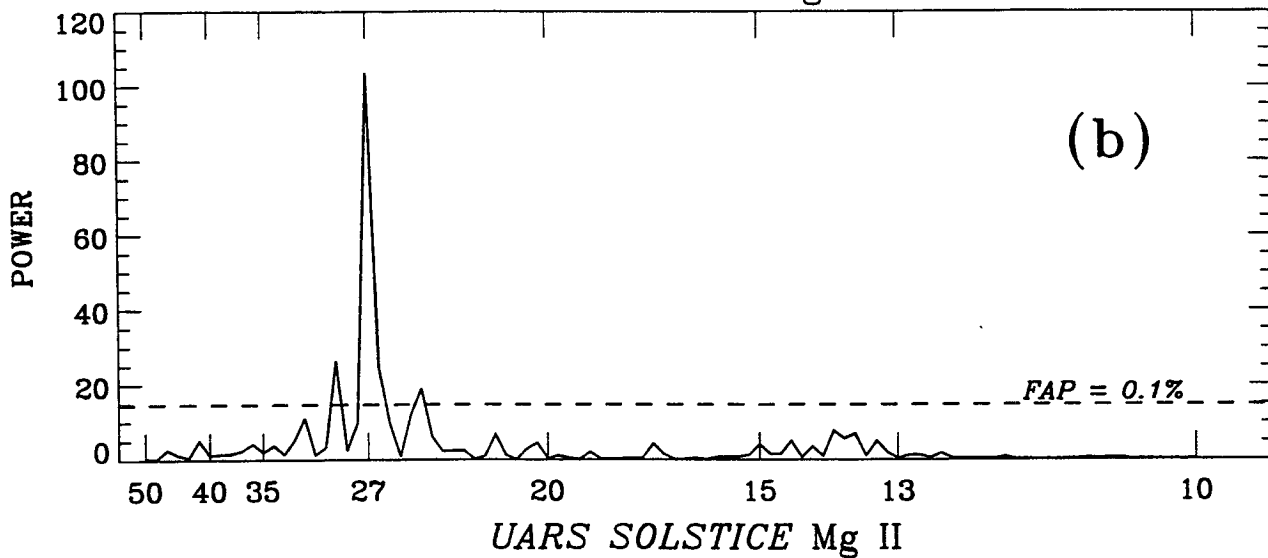
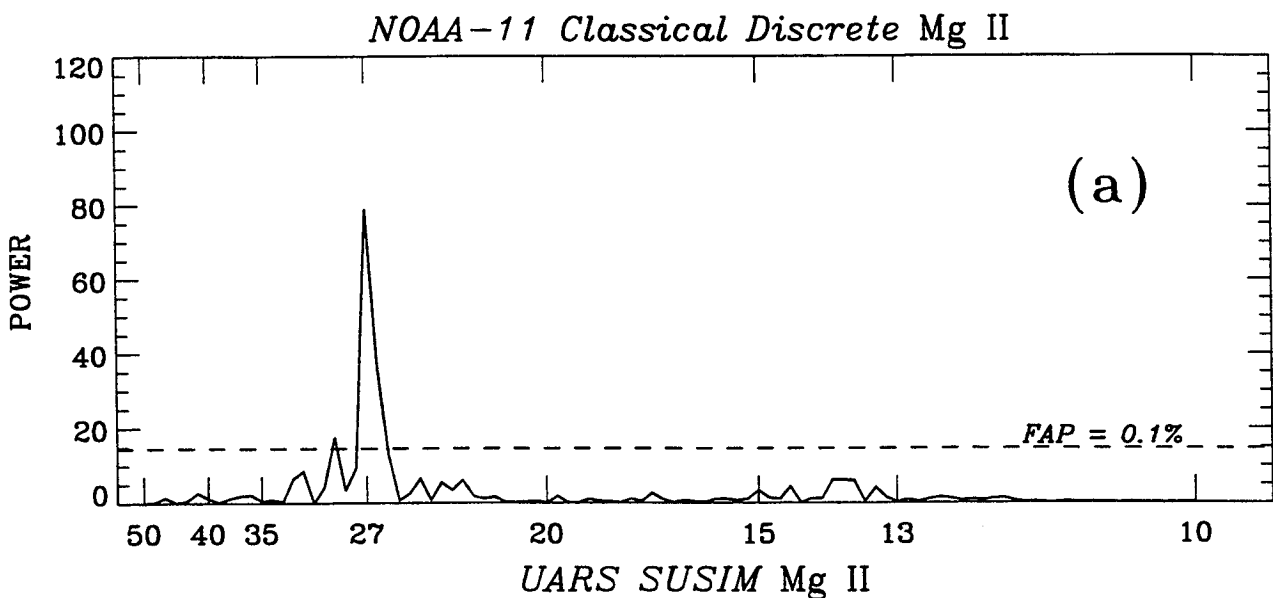


Figure 7(a)

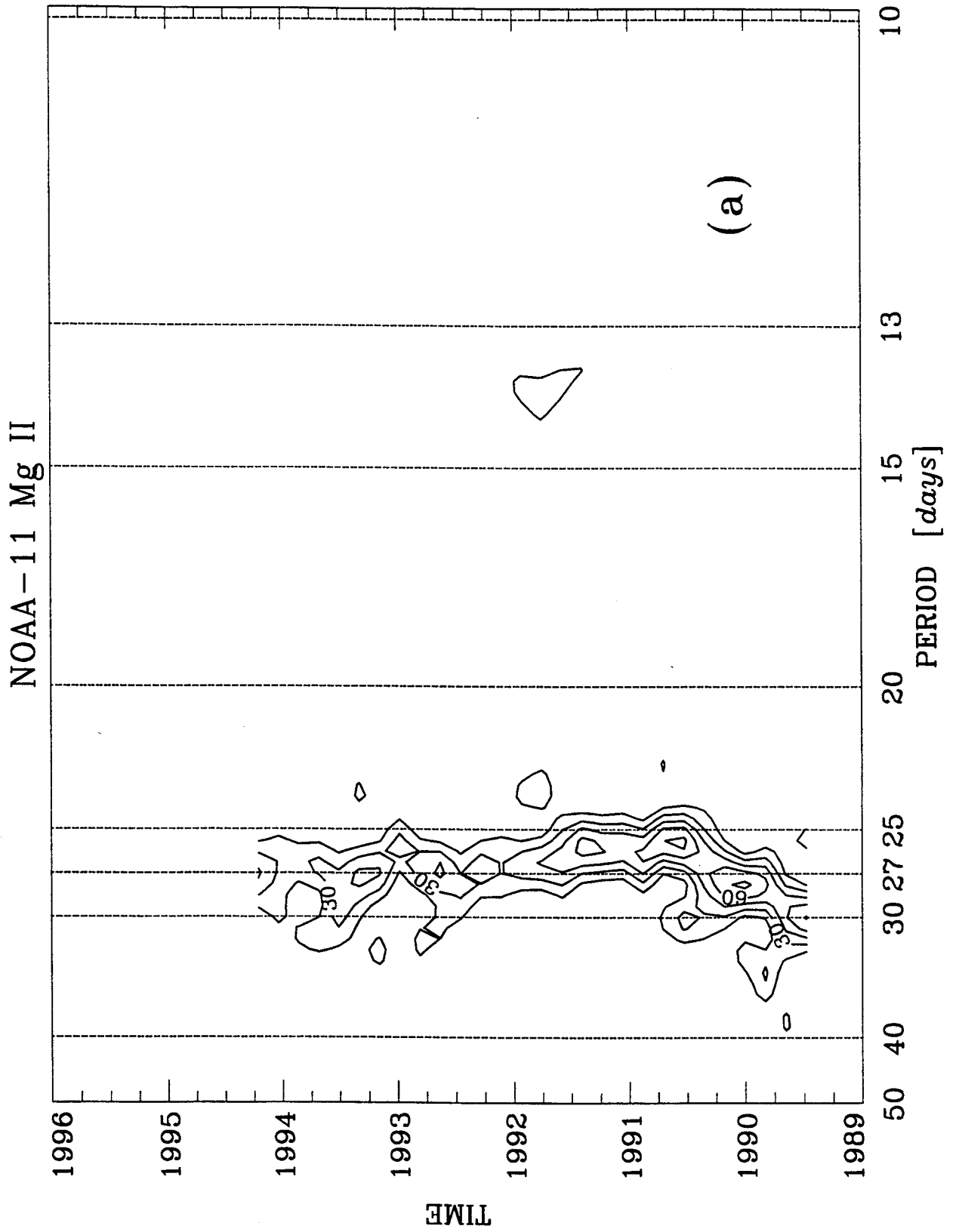


Figure 7(b)

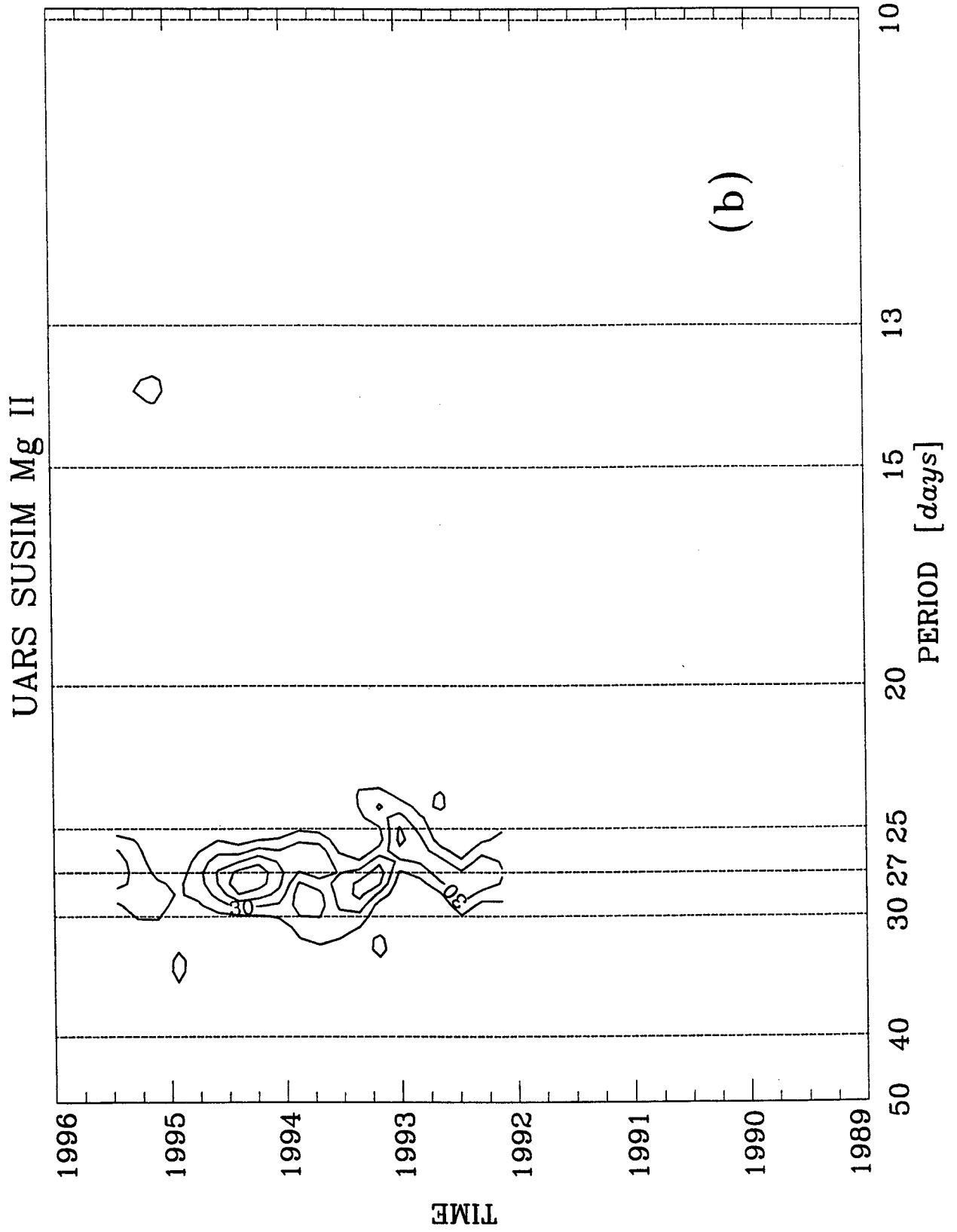
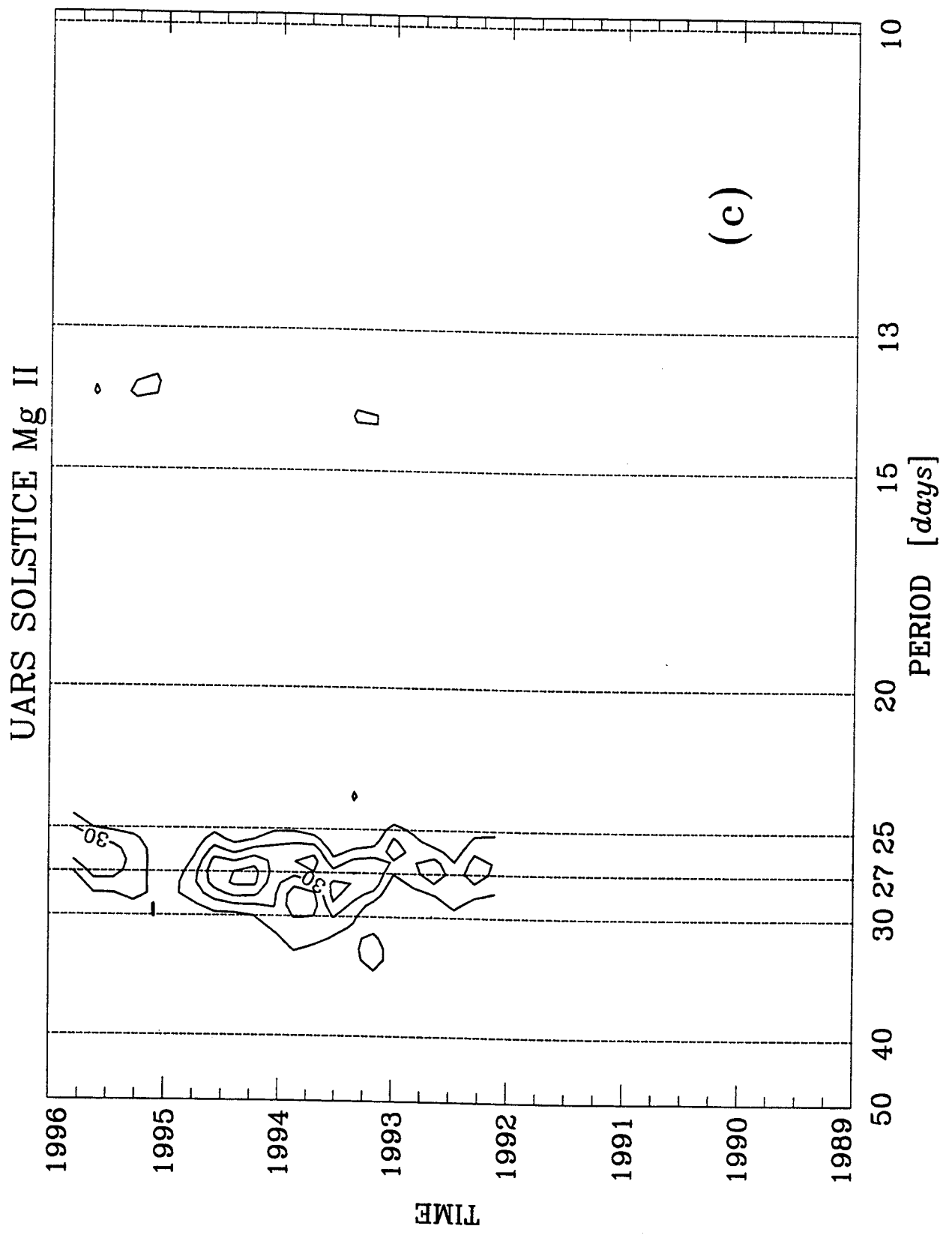


Figure 7(c)



Solar UV Activity at Solar Cycle 21 and 22 Minimum from NOAA-9 SBUV/2 Data

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ABSTRACT. Although solar ultraviolet (UV) irradiance measurements have been made regularly from satellite instruments for almost 20 years, only one complete solar cycle minimum has been observed during this period. Solar activity is currently moving through the minimum phase between Cycles 22 and 23, so it is of interest to compare recent data taken from the NOAA-9 SBUV/2 instrument with data taken by the same instrument during the previous solar minimum in 1985-1986. NOAA-9 SBUV/2 is the first instrument to make continuous solar UV measurements for a complete solar cycle. Direct irradiance measurements (*e.g.* 205 nm) from NOAA-9 are currently useful for examining short-term variations, but have not been corrected for long-term instrument sensitivity changes. We use the Mg II proxy index to illustrate variability on solar cycle time scales, and to provide complementary information on short-term variability. Comparisons with contemporaneous data from Nimbus-7 SBUV (1985-1986) and UARS SUSIM (1994-1995) are used to validate the results obtained from the NOAA-9 data. Current short-term UV activity differs from the Cycle 21-22 minimum. Continuous 13-day periodicity was observed from September 1994 to March 1995, a condition which has only been seen previously for shorter intervals during rising or maximum activity levels. The 205 nm irradiance and Mg II index are expected to track very closely on short timescales, but show differences in behavior during the minimum between Cycles 22 and 23.

1. INTRODUCTION

The first long-term record of solar spectral activity in the mid-ultraviolet wavelength region was obtained by the Nimbus-7 SBUV (Solar Backscatter Ultraviolet) instrument, which obtained solar data in the wavelength range 160-400 nm from November 1978 to February 1987 (Heath, Repoff, and Donnelly, 1984; Donnelly *et al.*, 1985; Schlesinger and Cebula, 1992). These data are currently archived at the National Space Science Data Center (NSSDC). This instrument was launched just prior to the beginning of the extended maximum activity period of solar cycle 21 in 1979, and continued to gather data through the solar activity minimum between Cycles 21 and 22 in 1985-1986. Additional coverage from the declining phase of Cycle 21 through the rise of Cycle 22 (January 1982 - April 1989) was provided by the Solar Mesosphere Explorer (SME) experiment (Rottman, 1988).

Beginning in 1985, the SBUV/2 series of instruments have been launched by NOAA on TIROS satellites to provide follow-on data to Nimbus-7 SBUV. These instruments continue the solar spectral measurements begun by Nimbus-7, and make additional daily high-quality measurements of the Mg II absorption line at 280 nm. Data are currently available from the NOAA-9 instrument from March 1985 to the present (*e.g.* Donnelly, 1988; Schlesinger *et al.*, 1990; Donnelly, 1991; Cebula, DeLand, and Schlesinger, 1992) and the NOAA-11 instrument from December 1988 to October 1994 (*e.g.* DeLand and Cebula, 1993; Hilsenrath *et al.*, 1995; Cebula and DeLand, 1997). The NOAA-14 SBUV/2 instrument was launched in December 1994 and began taking solar data in February 1995, but grating drive problems have limited the usefulness of these data. Daily solar UV data have also been taken since September 1991 by the SOLSTICE (Rottman *et al.*, 1993) and SUSIM (Brueckner *et al.*, 1993) instruments on the UARS satellite, and since June 1995 by the GOME instrument

(Weber, Burrows, and Cebula, 1997).

While the available record of continuous solar middle UV data now spans 18 years, we are entering only the second solar minimum with regular coverage. Previous studies have examined variations in solar activity between descending, minimum, ascending, and maximum solar cycle phases by comparing different proxy indexes (e.g. Pap, Tobiska, and Bouwer, 1990; Bouwer, 1992; DeLand and Cebula, 1993; Guhathakutra and Pap, 1994). NOAA-9 SBUV/2 is the first instrument to make continuous measurements over a complete solar cycle, and thus allow direct comparisons of activity levels from two separate solar minima. In this paper we examine NOAA-9 irradiance and proxy index data for the Cycle 21-22 minimum period of 1985-1986 and the Cycle 22-23 minimum period beginning in Fall 1994. The magnitude and periodicity of short-term variations during these intervals are examined. Comparisons with Nimbus-7 SBUV Mg II index data during 1985-1986 and UARS SUSIM Mg II index data during 1994-1995 are used to supplement the NOAA-9 data, and illustrate the differences between the behavior of the Mg II index and the 205 nm irradiance.

2. NOAA-9 SOLAR IRRADIANCE DATA

The NOAA-9 SBUV/2 instrument was launched on 12 December 1984, and made its first solar measurements on 14 March 1985. It is a 1/4-m Ebert-Fastie double monochromator (Frederick, Cebula, and Heath, 1986), whose primary purpose is to measure terrestrial ozone profiles using backscattered UV radiation at 12 discrete wavelengths between 252-340 nm. Two spectral scan ("sweep") solar measurements over the 160-406 nm wavelength region are made on a single orbit each day, with ~0.15 nm sampling and 1.1 nm resolution. Step scan solar measurements at the same 12 wavelengths used for ozone measurements are also made once per week. A time series of the solar output at 205 nm from March 1985 to May 1996 as measured by NOAA-9 with no correction for long-term changes in instrument sensitivity is shown in Figure 1(a). The NOAA-9 SBUV/2 instrument has no internal calibration system for monitoring such changes, which vary from less than -0.5%/year at 400 nm to approximately -5%/year at 200 nm (Cebula and DeLand, 1992). These changes are more rapid than the predicted solar cycle irradiance changes at the same wavelengths (e.g. Lean, 1991), and are generally monotonic in time rather than cyclic. Thus, while the short-term solar rotational modulation variations are clear in Figure 1(a), the magnitude of the solar cycle variations cannot, at this time, be accurately quantified from these data. We are currently developing a characterization of the NOAA-9 long-term instrument sensitivity changes, and will present the corrected irradiance data in a future paper.

The Mg II index, first developed for Nimbus-7 SBUV by Heath and Schlesinger (1986) and extended to NOAA-9 SBUV/2 (e.g. Donnelly, 1988; Cebula, DeLand, and Schlesinger, 1992), uses the core-to-wing irradiance ratio of the 280 nm Mg II absorption line to eliminate most long-term instrument change effects and provide a convenient measure of solar mid-UV activity. The core of the Mg II line is generated in the chromosphere, while the wing wavelengths are representative of the upper photosphere. Because the SBUV/2 measurements are made at 1.1 nm resolution, there is a slight blending of photospheric radiation into the Mg II product. Previous comparisons of short-term variations have shown that the Mg II index and 205 nm irradiance (which is generated in the upper photosphere) should have almost identical response amplitudes (Heath and Schlesinger, 1986; DeLand and Cebula, 1993), so that the Mg II index is an accurate proxy for 205 nm variations. The NOAA-9 Mg II index developed from spectral scan data is significantly impacted by noise due to the electronic design of the instrument, and also experiences substantial wavelength scale drift with time. While these limitations were anticipated prior to launch (Schlesinger *et al.*, 1990), the spectral scan data were initially analyzed to provide continuity with the Nimbus-7 Mg II product.

In May 1986, daily step scan ("discrete") measurements were initiated at 12 positions across the Mg II absorption

line. As discussed by Donnelly (1988) and DeLand and Cebula (1994), these data are inherently superior to the sweep mode data for constructing an Mg II index. DeLand and Cebula (1994) used the discrete data to produce a "classical discrete" Mg II index with nearly identical absolute values to the Mg II index derived from the spectral scan data, and greatly improved noise and wavelength drift characteristics. DeLand and Cebula (1994) also compared the "classical discrete" Mg II index to the Mg II product of Donnelly (1991), and found similar representations of solar activity using both NOAA-9 and NOAA-11 data. de Toma *et al.* (1997) find that the NOAA and NASA Mg II index algorithms give very similar results when applied to NOAA-9 data. The time series of the NOAA-9 "classical discrete" Mg II index is shown in Figure 1(b). Rotational modulation is present at peak-to-peak amplitudes of 2-7% throughout most of the solar cycle. The solar cycle amplitude is approximately 8% from the Cycle 21-22 minimum in 1985-1986 to the Cycle 22 maximum in 1989-1991. Comparisons with the NOAA-11 "classical discrete" Mg II index indicate that these two data sets are consistent to within approximately 0.5% during the overlap period 1989-1994. The NOAA-9 Mg II data suggest that after approximately September 1994, solar activity levels are approaching the minimum level observed between Cycles 21 and 22.

3. SOLAR ACTIVITY DURING CYCLE 21-22 MINIMUM

Figure 2(a) shows the solar UV activity during the minimum activity period between solar cycles 21 and 22, using the Mg II index measured by Nimbus-7 SBUV and NOAA-9 SBUV/2. The NOAA-9 "classical discrete" Mg II data (*dotted line*), which began in May 1986, have an absolute offset of approximately -1.5% from the Nimbus-7 sweep Mg II data (*solid line*) due to 0.03 nm differences in the wavelengths used to construct each index. This absolute offset does not indicate a difference in the sensitivity of each Mg II index to solar variability, as discussed in Cebula, DeLand, and Schlesinger (1992). The NOAA-9 discrete Mg II index shows excellent agreement in both amplitude and phasing with the Nimbus-7 Mg II data (Figure 2(a)). The Nimbus-7 and NOAA-9 Mg II data sets give a consistent picture of solar UV activity during the Cycle 21-22 minimum. No long-term change was observed at the 1% level, and rotational modulation was generally 1% peak-to-peak (p-p) or less, with no rotation as large as 2%. The last rotation with a 2% amplitude observed by Nimbus-7 SBUV in Cycle 21 occurred in mid-1983.

In order to compare the NOAA-9 205 nm irradiance data from 1985-1986 with the Mg II index data, we detrend the 205 nm time series with a 4th order polynomial to remove all large scale changes, both instrumental and solar. This allows us to focus on the short-term variations during this interval. This treatment is not intended to completely characterize long-term instrument changes, and periodicities greater than approximately 3 months should not be considered as significant. The detrended NOAA-9 205 nm irradiance data (Figure 2(b)) show regular 27-day periodicity at the 1-2% p-p level. There are suggestions of 13-day periodicity in Fall 1985 and Fall 1986, but the signature is not clear. A 13-day period in solar UV variations indicates the presence of active regions on opposing faces of the Sun simultaneously, and has previously been seen only at times of rising or high solar activity (*e.g.* Donnelly and Puga, 1990; Schlesinger *et al.*, 1990; Cebula, DeLand, and Schlesinger, 1992). To evaluate the possible presence of such a period, we use the periodogram technique of Horne and Baliunas (1986) to examine the power spectrum of these data sets. Examples of periodogram analyses of solar variability data are given in Lean and Brueckner (1989) and Lean (1990). This technique is well-suited to analyzing noisy data, and accepts unevenly sampled data sets without interpolating to replace missing data points. The periodogram of the Nimbus-7 Mg II data set for the 1985-1986 time interval shows a strong signal at the nominal 27-day rotational period (Figure 3(a)). The 27-day periodicity is weaker in the NOAA-9 205 nm irradiance periodogram (Figure 3(b)) as a result of greater noise, but the signal is still quite clear. The horizontal dashed line in each panel represents a false alarm probability (FAP) of 0.1%, defined as the chance that a peak with the correspond-

ing signal strength is real if the input data were pure noise (Horne and Baliunas, 1986). Using this criterion, we observe that no statistically significant signal is evident in the Nimbus-7 Mg II periodogram at periods near 13 days. The NOAA-9 205 nm data shows a slightly stronger signal at approximately 13.5 days, but the peak is also well below the FAP = 0.1% threshold. Any episodes of 13-day periodicity in the data of Figure 2 have amplitudes of 0.3% p-p or less, which is comparable to the daily $\pm 1 \sigma$ noise in the measurements. Thus, we are unable to demonstrate 13-day periodicity during the 1985-1986 solar minimum at the 99.9% confidence level.

4. SOLAR ACTIVITY NEAR CYCLE 22-23 MINIMUM

The NOAA-9 discrete Mg II index data in Figure 1(b) show a sharp drop in solar UV activity in April 1992, signalling the end of the Cycle 22 maximum. A steady decline in activity was observed from Spring 1992 to Fall 1994, followed by a relatively flat period from Fall 1994 to mid-1996. The precise location of the "minimum" for Cycle 22 has not been identified as yet, and may not have occurred during the currently available data record. However, the September 1994 - May 1996 period appears to be sufficiently quiet that comparisons of it to the Cycle 21-22 minimum are valid. The NOAA-9 discrete Mg II data for July 1994 - May 1996 are shown as the solid line in Figure 4(a). A spacecraft "safe mode" event interrupted all NOAA-9 SBUV/2 measurements in February 1995, and the discrete Mg II measurements were not resumed until September 1995. The NOAA-9 solar data have shown increased noise after a "power upset" in August 1995, and data after August 1995 shown here should be considered as preliminary only. From October 1994 to February 1995, the Mg II index data show a constant approximate 13-day periodicity. While the strength of this modulation is relatively weak, with peak-to-peak amplitudes of $\leq 0.5\%$, every 3rd peak ($\Delta t \approx 40$ days) has an increased amplitude of approximately 1%. This situation is somewhat puzzling, since having a stronger magnetic region on one solar hemisphere to generate approximate 13-day periodicity should produce increased amplitude on every second peak. From September 1995 to May 1996, the dominant period is again approximately 27 days. The detrended NOAA-9 205 nm irradiance data also show a significant episode of 13-day periodicity (Figure 4(b)) from October 1994 to April 1995, with a continuous signal of approximately 1% p-p. The amplitudes of consecutive peaks are more regular than for the Mg II index in Figure 4(a), and considerably stronger. A strong active region at solar minimum conditions was present in June and July 1995, producing rotational modulation with an amplitude of 2% during that time. As stated previously, fluctuations on timescales greater than 2-3 months should not be considered significant in the detrended irradiance data.

The SUSIM solar UV instrument onboard the UARS satellite (Brueckner *et al.*, 1993) is a double monochromator similar to SBUV/2, with a medium resolution operating mode of $\Delta \lambda = 1.1$ nm from which a Mg II index product is created. The response of the SUSIM Mg II index to solar variations is very consistent with that measured by the SBUV/2 instruments (Cebula and DeLand, 1997). SUSIM V18 Mg II index data for July 1994 - January 1996 (Floyd *et al.*, 1997) are shown as a dotted line in Figure 4(a) to illustrate the Mg II index behavior during February-August 1995. The SUSIM Mg II data agree with the NOAA-9 Mg II data to better than 1% in absolute value during this period, and also show relatively weak 13-day periodicity during Fall 1994 with p-p amplitudes less than 1%. Mg II index data produced by UARS SOLSTICE are also very consistent with the NOAA-9 SBUV/2 data (de Toma *et al.*, 1997). The observed short-term variations are larger due to the higher resolution of the SOLSTICE instrument (Cebula and DeLand, 1997; White *et al.*, 1997).

The time series plots in Figure 4 suggest that the 205 nm irradiance measured by NOAA-9 has a stronger response to 13-day periodicity in solar activity than the Mg II index. This difference in amplitude was noted for Nimbus-7 SBUV data during solar cycle 21 by Donnelly and Puga (1990), who ascribed it to differences in the center-to-limb variation between 205 and 280 nm. Periodogram analysis for the period September 1994 - March

1995 verifies this conclusion. The NOAA-9 Mg II data, which are impacted by the data gap beginning in mid-February 1995, show no 27-day power and barely significant power at 13 days during this interval (Figure 5(a)). The SUSIM Mg II index data show 13-day power at roughly the same level as the NOAA-9 Mg II index (Figure 5(b)), and also have some power at a period of approximately 35 days. This latter signal is present at other times when the complete SUSIM Mg II data set is analyzed (Cebula and DeLand, 1997), and coincides with the approximate period of the "yaw maneuver" used to maintain the pointing of the UARS satellite. The periodogram of the NOAA-9 205 nm irradiance shows a much stronger peak at 13 days, again with no power at longer periods (Figure 5(c)).

The results in this section demonstrate that 13-day periodicity in solar UV activity can occur at any phase of the solar cycle. More importantly, the difference in response between the Mg II index and 205 nm irradiance data represents a possible limitation to the use of the Mg II index as a proxy for mid-UV solar variability. The derivation of Mg II index "scale factors" by Heath and Schlesinger (1986) used only 27-day variations, and did not examine shorter or longer timescales. Donnelly and Puga (1990) showed that the ratio of 13-day to 27-day power observed in Nimbus-7 SBUV data during solar cycle 21 maximum in 1979-1982 was approximately 0.4 for upper photospheric and lower chromospheric radiation in the 175-290 nm wavelength region, whereas the chromospheric Mg II absorption line had a smaller 13-day/27-day power ratio of ~0.2. Thus, the Mg II index appears to underpredict solar irradiance variability during episodes of 13-day periodicity in the wavelength region which directly affects stratospheric photochemistry. This conclusion will be tested by comparing the NOAA-9 solar data with NOAA-9 profile ozone data, which will be reprocessed in 1997.

5. CONCLUSION

The NOAA-9 SBUV/2 instrument has made the first regular measurements of solar UV activity over a complete solar cycle, beginning in March 1985 and continuing as of this writing (January 1997). The NOAA-9 solar irradiance data set includes the minimum between Cycles 21-22 and the current minimum at the end of Cycle 22. Although overall solar activity is low during these periods, 27-day rotational modulation is frequently present. The episode of 13-day periodicity observed during September 1994 - March 1995 shows that phenomena previously associated with high levels of solar activity can occur at any point in the solar cycle. The 205 nm irradiance and Mg II index measured by NOAA-9 showed very similar behavior during the Cycle 21-22 minimum in 1985-1986, when 27-day periodicity dominated short-term solar variations, but behaved differently in 1994-1995 during the episode of 13-day periodicity. We plan further investigations into the physical causes of this result, since it affects the extent to which the Mg II index is an accurate proxy for 205 nm irradiance variations during such episodes. The NOAA-9 Mg II data are available electronically from the authors (*cebula@ssbuv.gsfc.nasa.gov*, *mdeland@ccmail.stx.com*).

ACKNOWLEDGEMENTS

Walter G. Planet and H. Dudley Bowman of NOAA/NESDIS provided the raw SBUV/2 data. Dianne Prinz and Linton Floyd kindly supplied UARS SUSIM V18 Mg II index data for this study. Judith Lean provided operational IDL software for the periodogram analysis, as well as valuable advice on its use. This research was supported by NASA grant NASW-4864.

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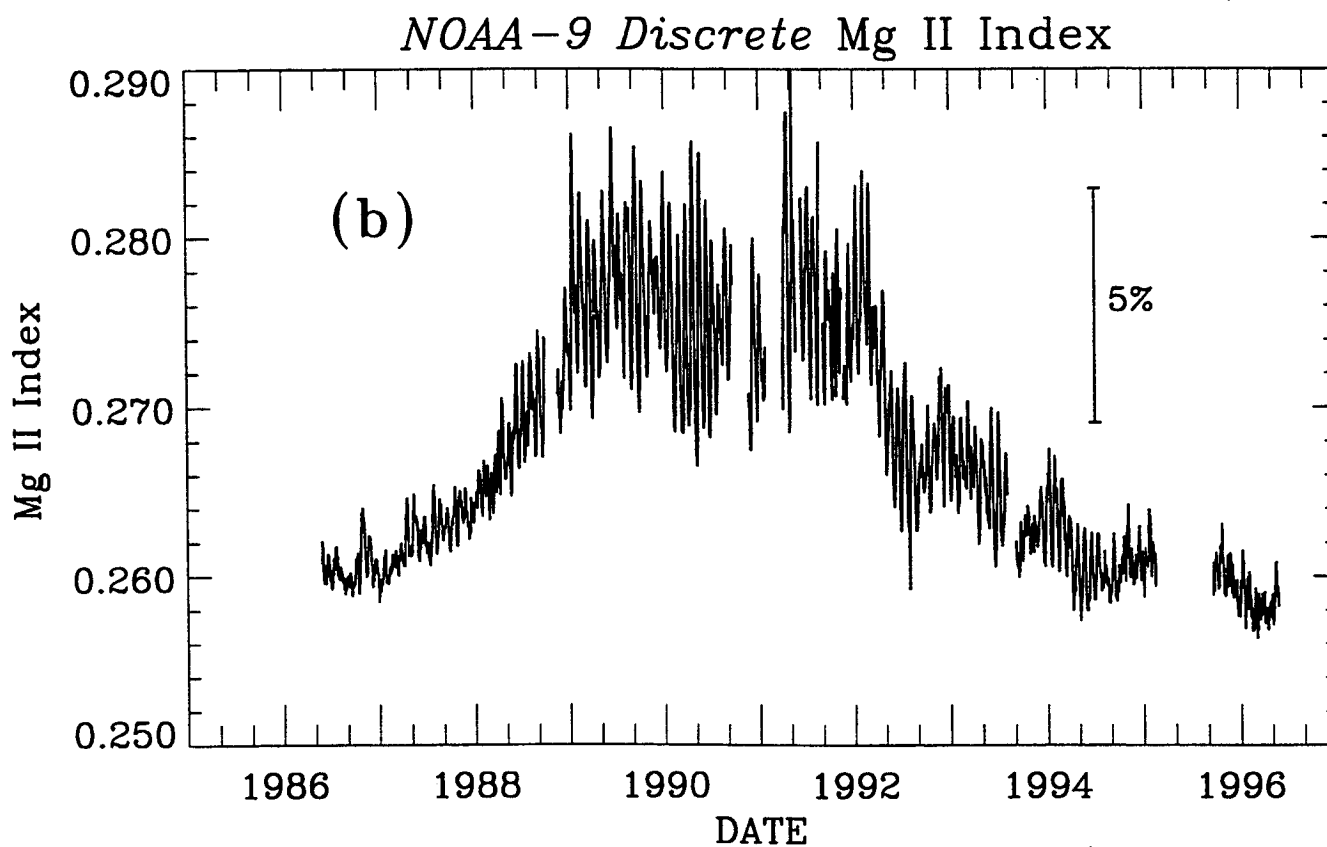
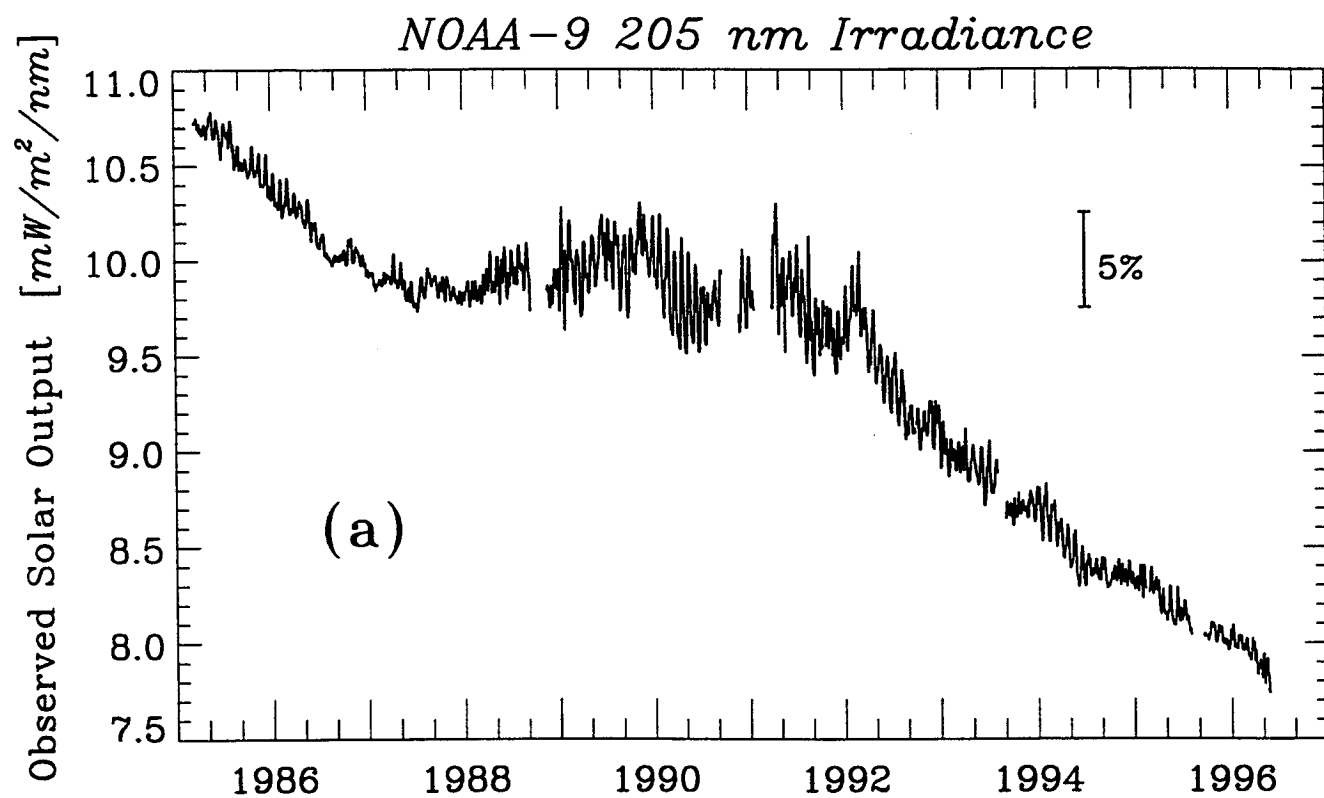
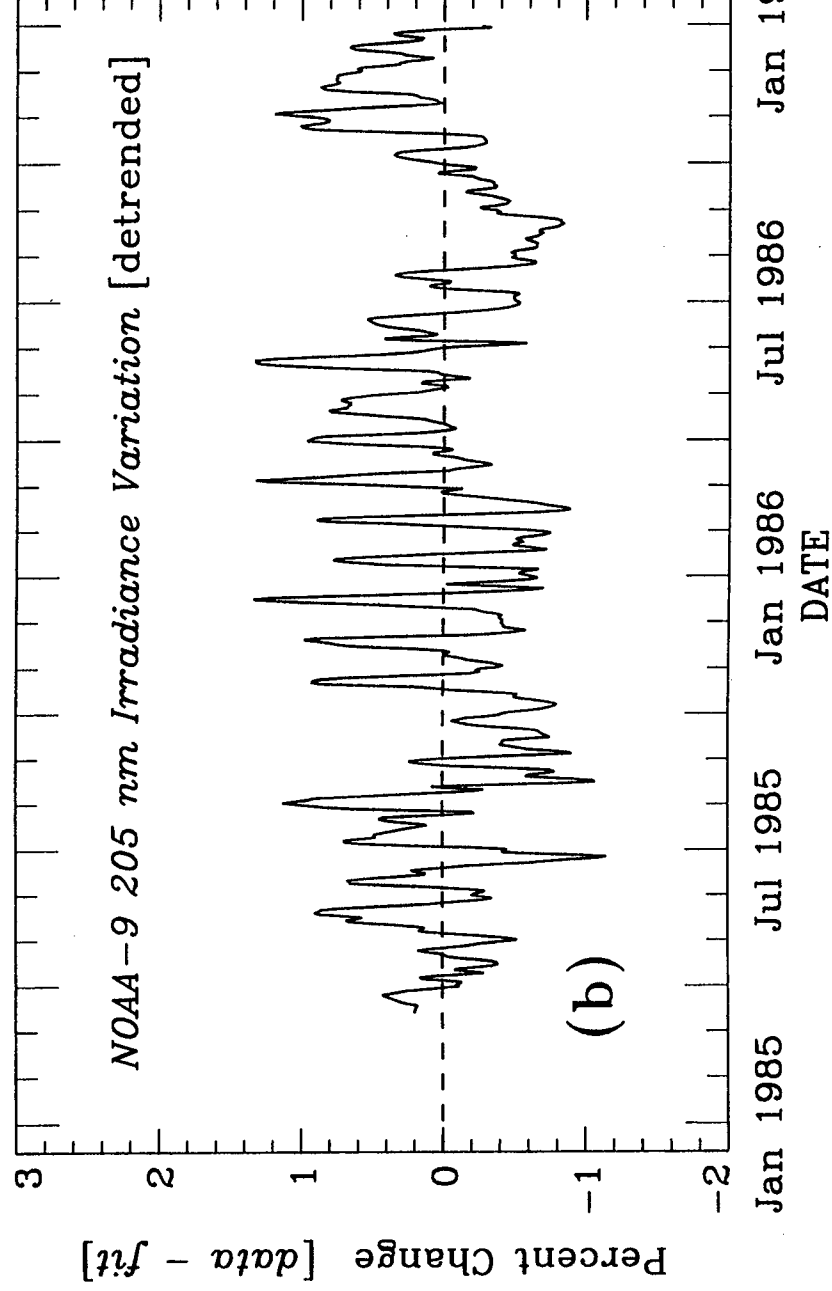
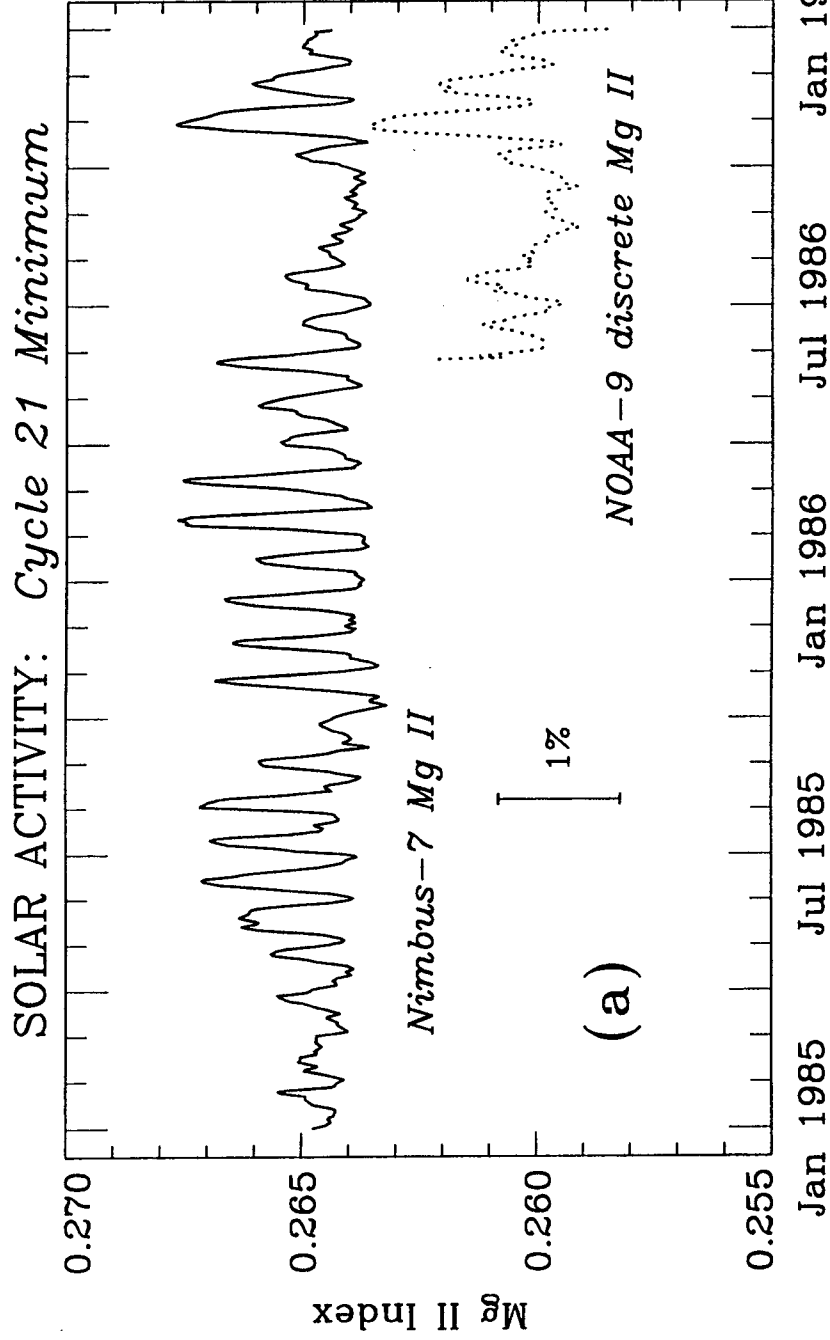


Figure 2



Periodogram for 14 March 1985 to 31 December 1986

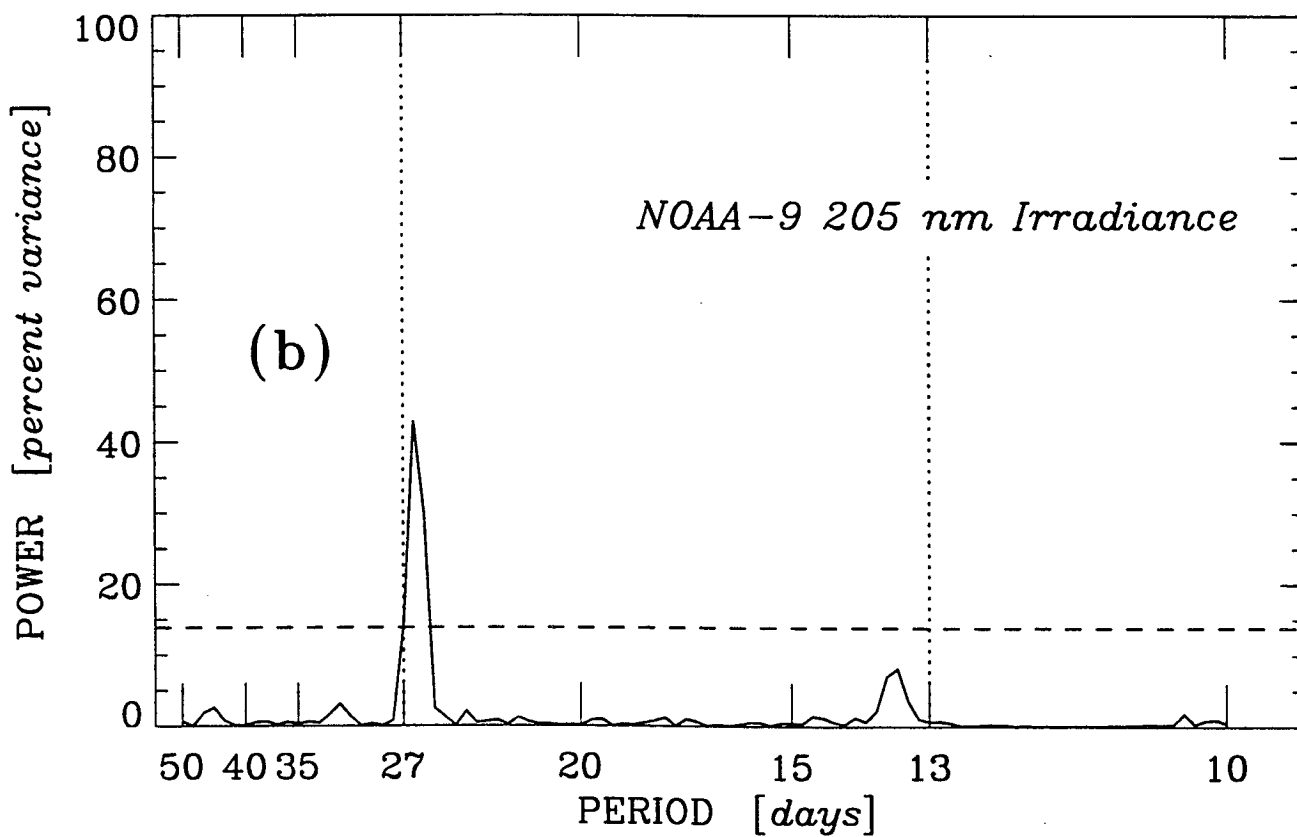
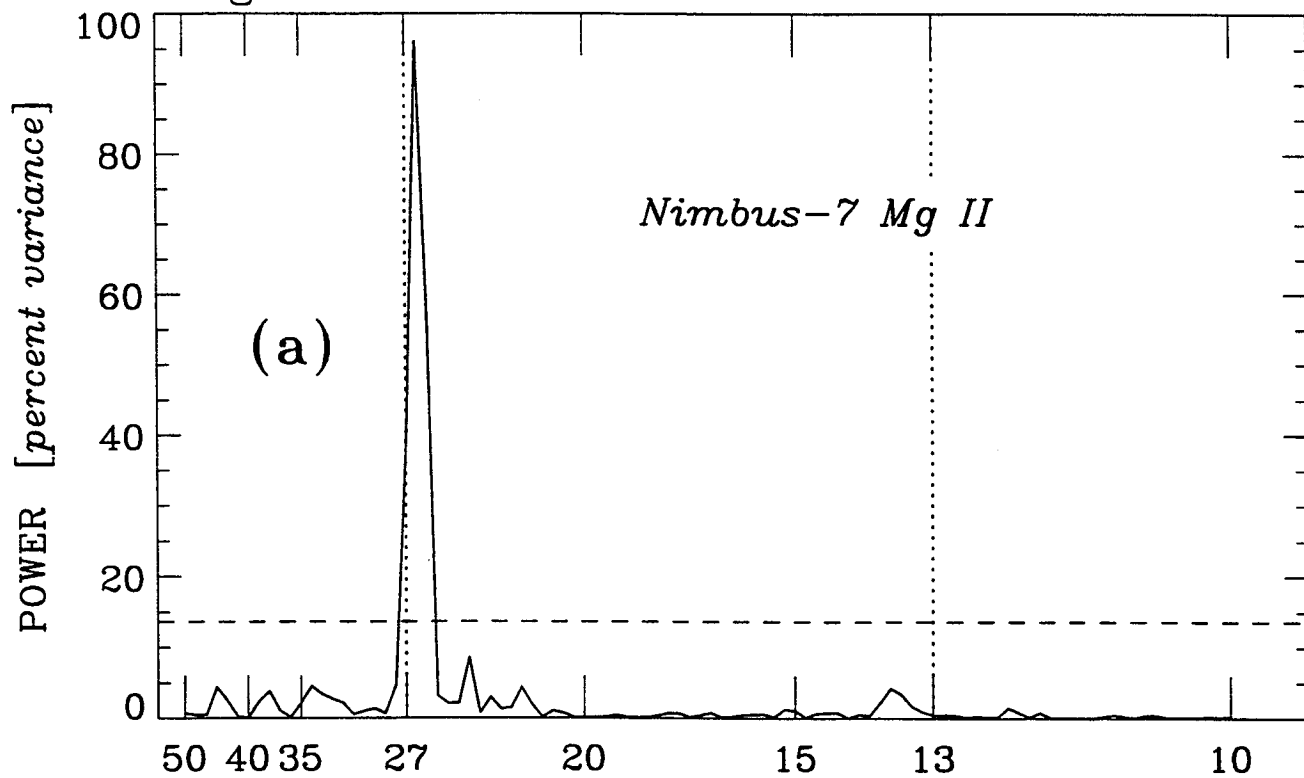
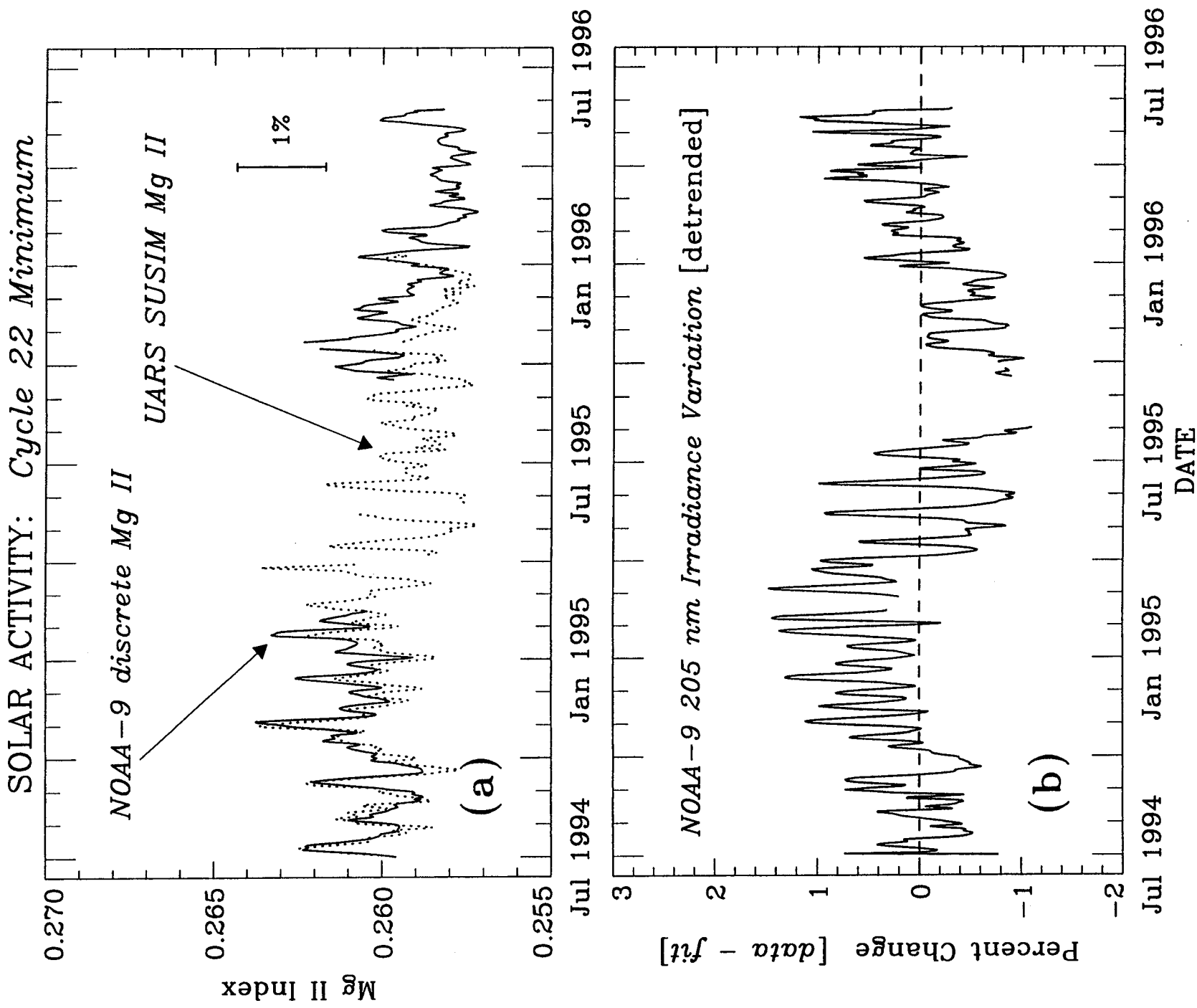
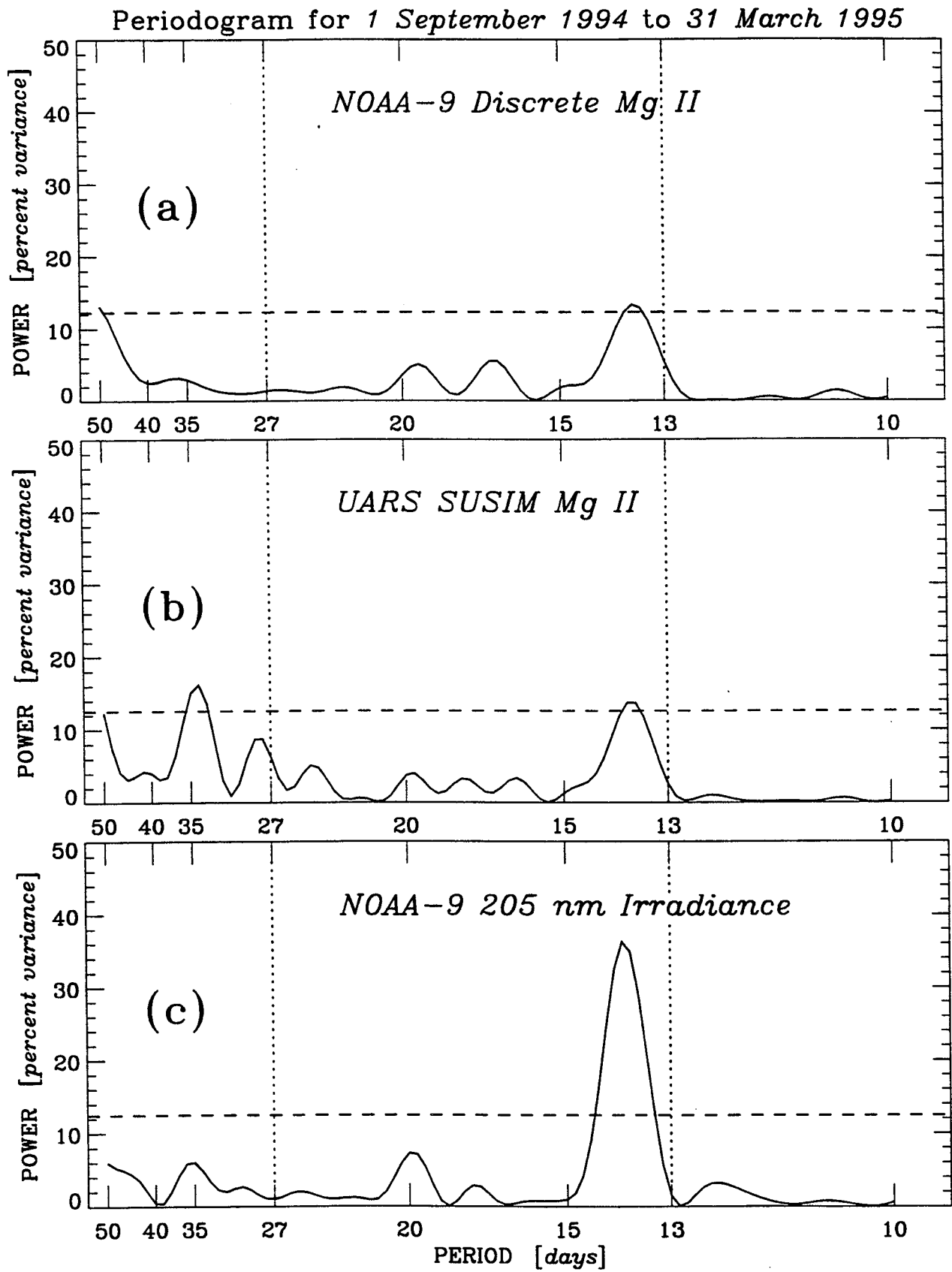


Figure 4





SSBUV Measurements of Solar Spectral Irradiance Variations, 1989-1996

Richard P. Cebula

Hughes STX Corporation

HSTX Center for Astronomy and Solar Physics (CASP) Seminar

26 February 1997

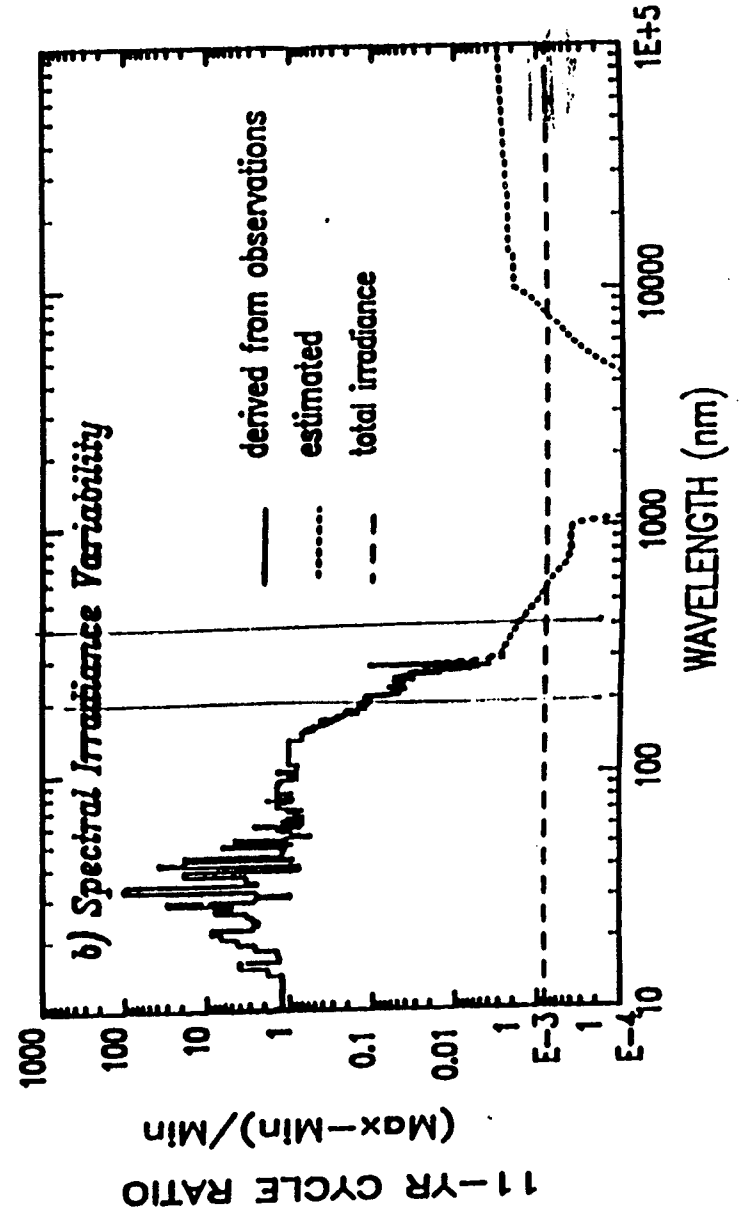
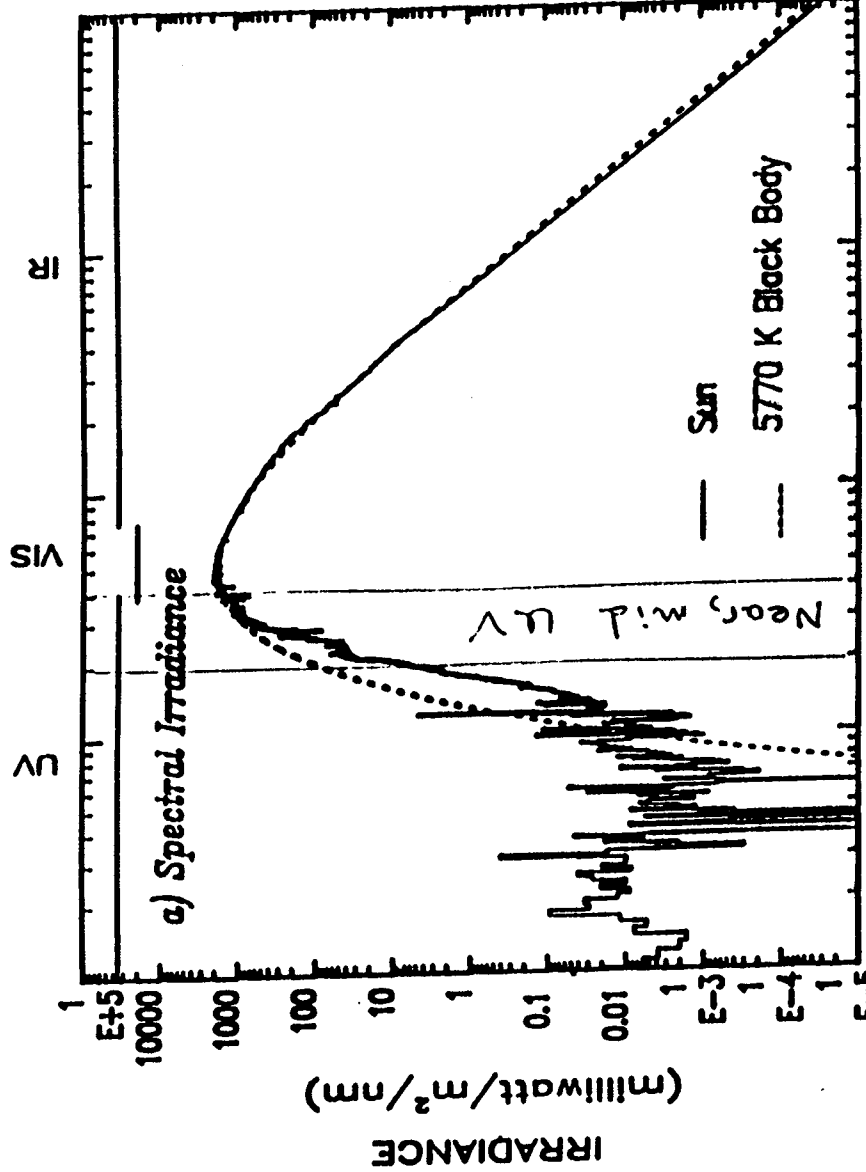
**Supported by NASA Grant NASW-4864 and
NASA Contract NAS5-31755**

Outline

- Justification for UV solar measurements
- Experiment overview
- SSBUV solar measurements
- Absolute solar irradiance comparisons
- SSBUV-measured solar change
- Solar Change comparisons
- Conclusions

Why Measure the Solar UV?

- Understand solar physics
 - changes related to magnetic activity variations
- Solar UV flux provides external forcing to the Earth-atmosphere system
 - ozone production & loss
 - middle atmosphere dynamics
 - stratospheric temperature
 - coupling to biosphere, including UVB flux

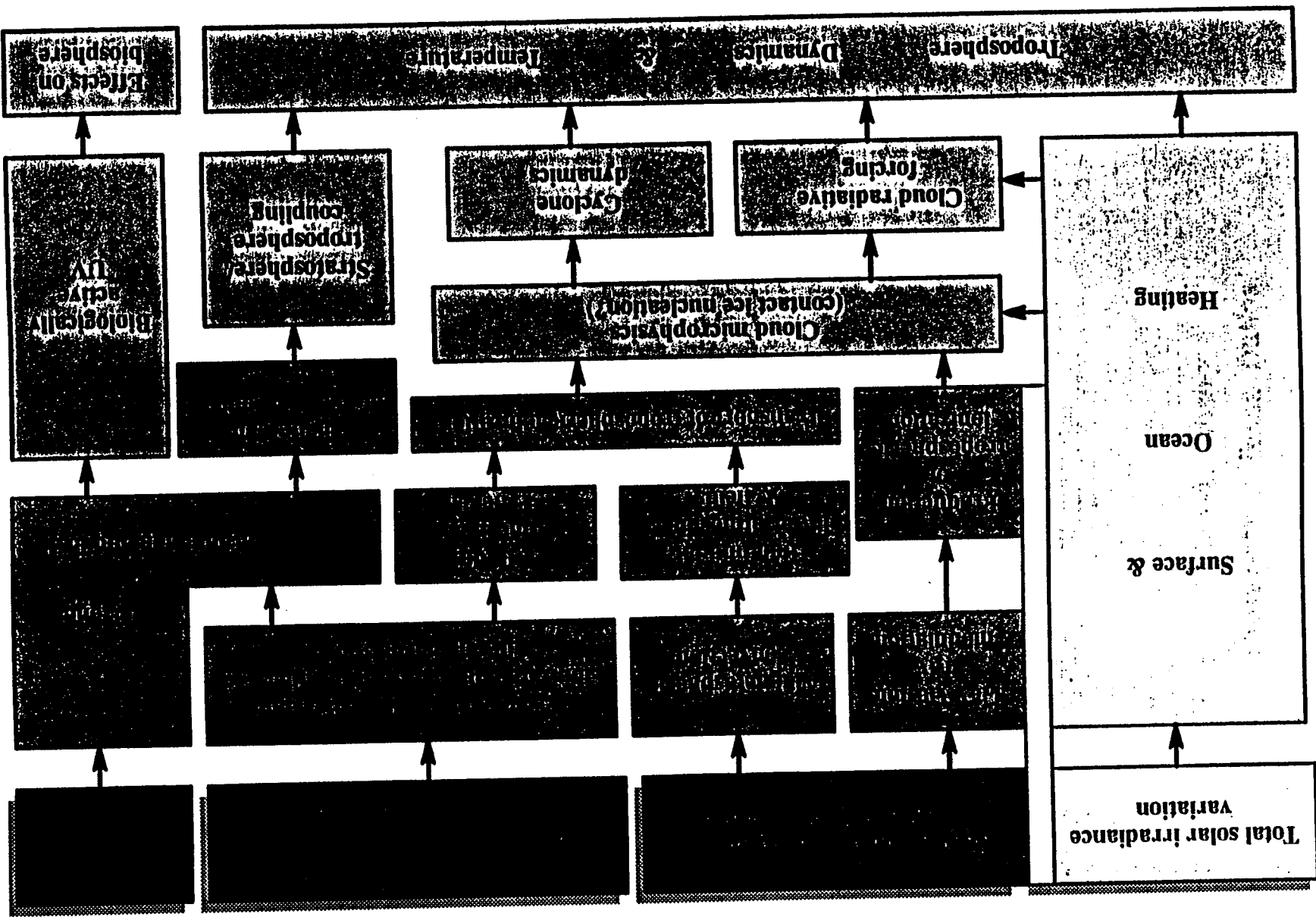


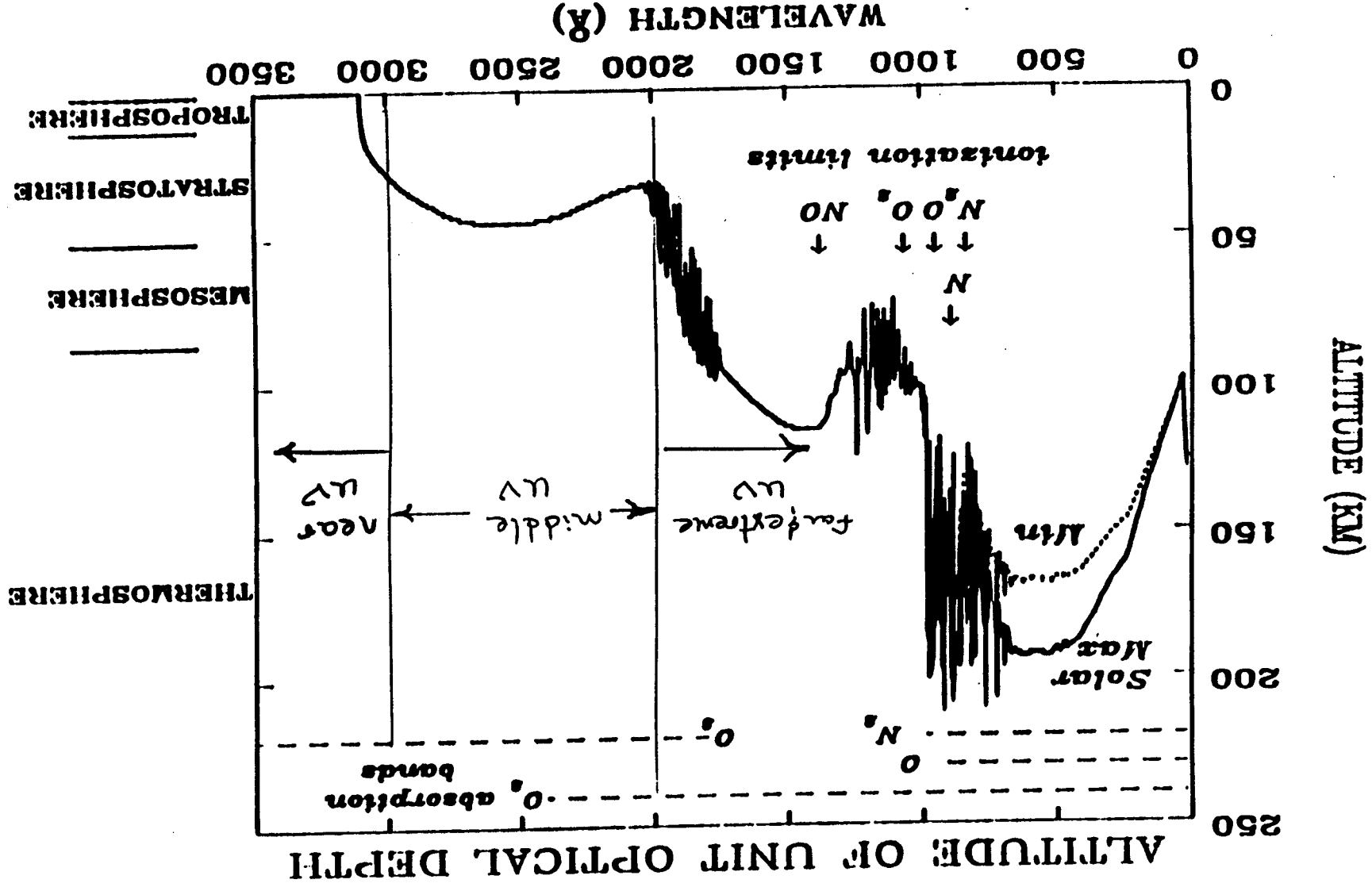
**NEAR & MIDDLE UV:
SMALL IRRADIANCE, BIG VARIATIONS**

SPECTRAL REGION	Irradiance [mW/m²]	Solar Cycle Variation [mW/m²]	Percent Variation
Total Irradiance	1367	1.4	0.1
Mid & Near UV 200 - 400 nm	111 (8% of total)	0.33 (24% of total)	0.3

Although middle & near UV region constitutes ~8% of the total solar irradiance, variations in this spectral region account for nearly one-fourth of the total amount of solar variability!

Solar Influences





Solar Cycle Induced Ozone Change

**Table 1. CONTRIBUTIONS TO SOLAR CYCLE TOTAL OZONE CHANGE
FROM DIFFERENT STRATOSPHERIC PRESSURE RANGES**

Total Change $\approx 1.5\% \times 295 \text{ DU} = 4.4 \text{ DU}$

Upper Stratosphere:

.5 - 1 mbar	4% x .92 DU	= 0.04 DU	} 12%
1 - 2 mbar	4% x 3.3 DU	= 0.13 DU	
2 - 4 mbar	3% x 10.4 DU	= 0.31 DU	

Middle Stratosphere:

4 - 8 mbar	0.5% x 25.2 DU	= 0.13 DU	} 3%
8 - 16 mbar	0% x 47.7 DU	= 0 DU	

Lower Stratosphere:

16 - 32 mbar	1.5% x 70.2 DU	= 1.05 DU	} 85%
> 32 mbar	2.0% x 136.2 DU	= 2.7 DU	

Hood, JGR, 1996

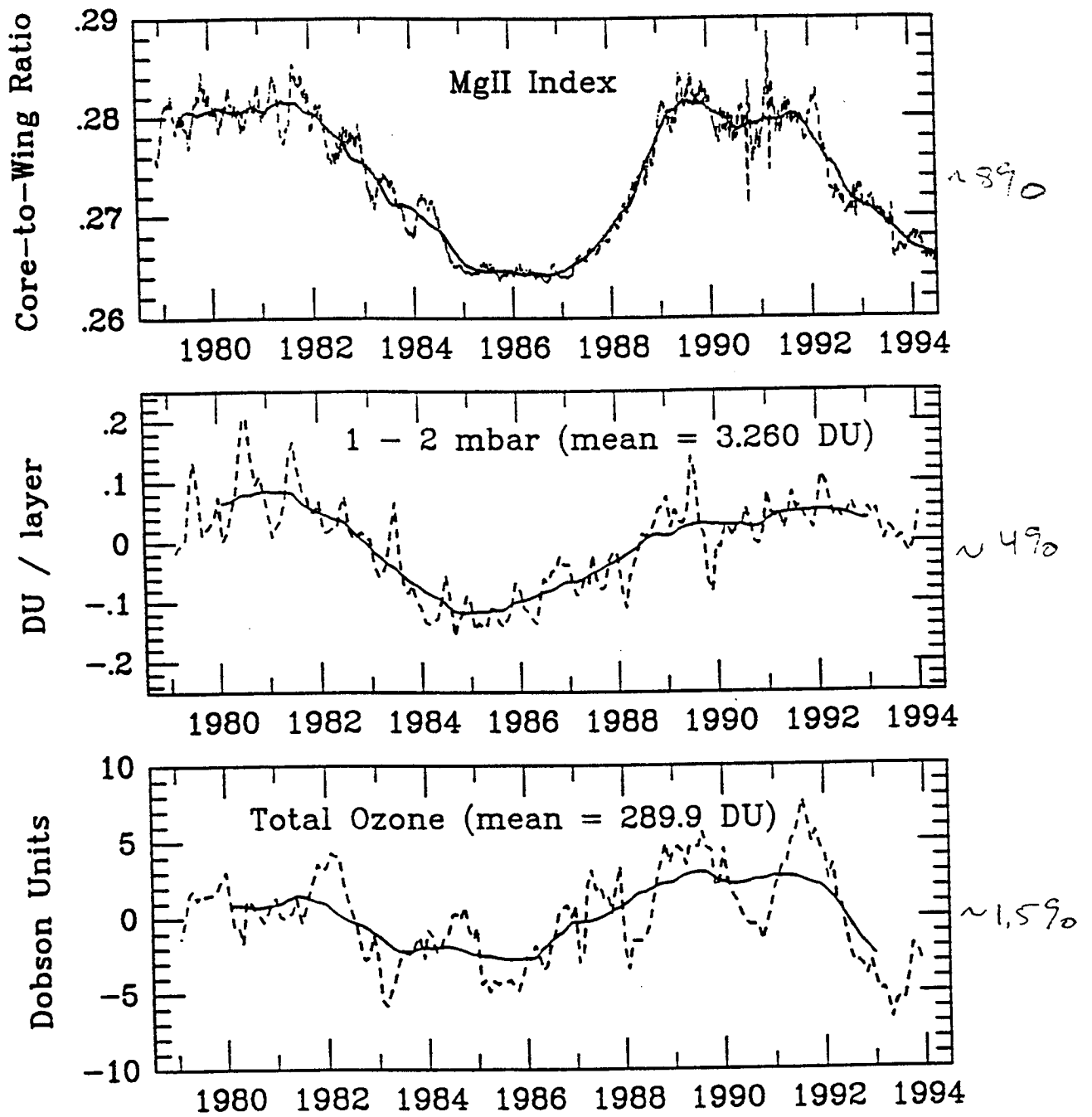
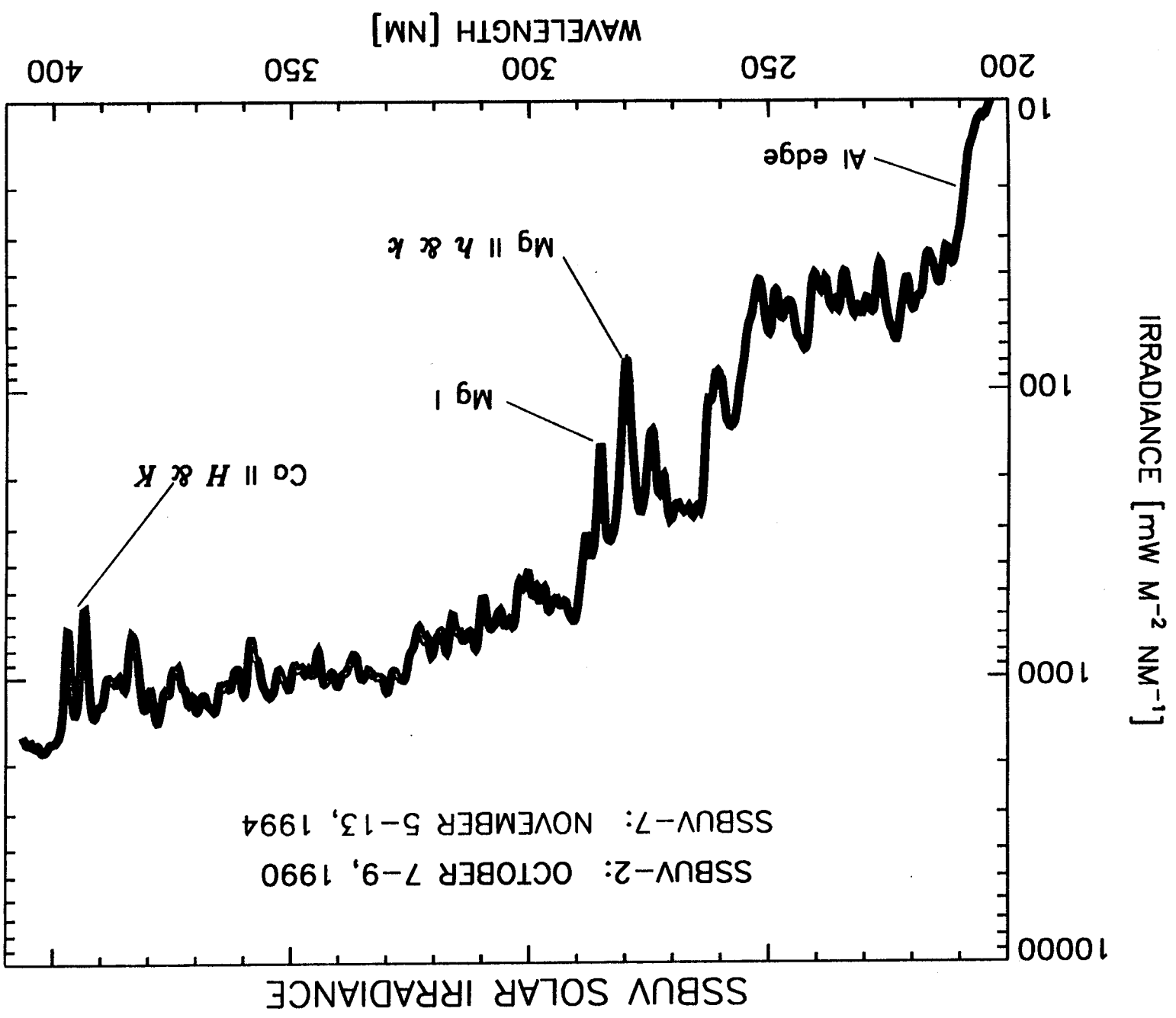


Figure 2

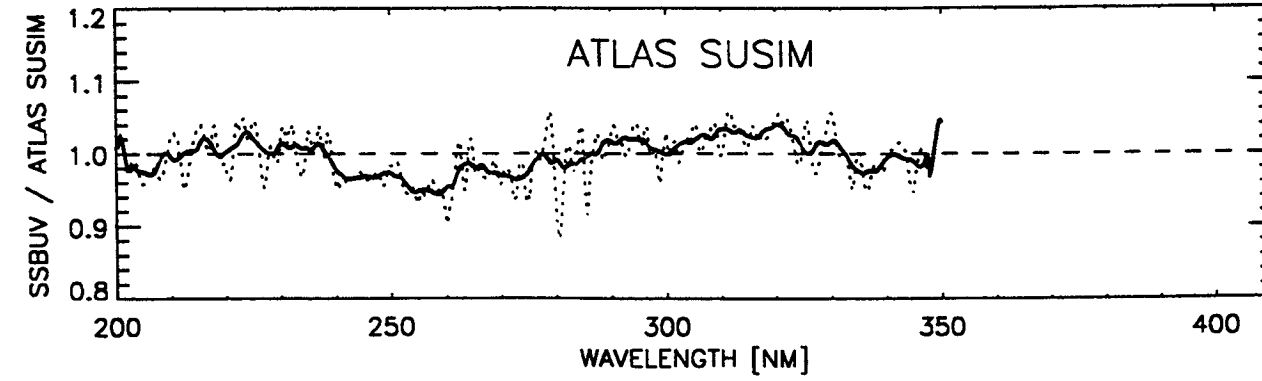
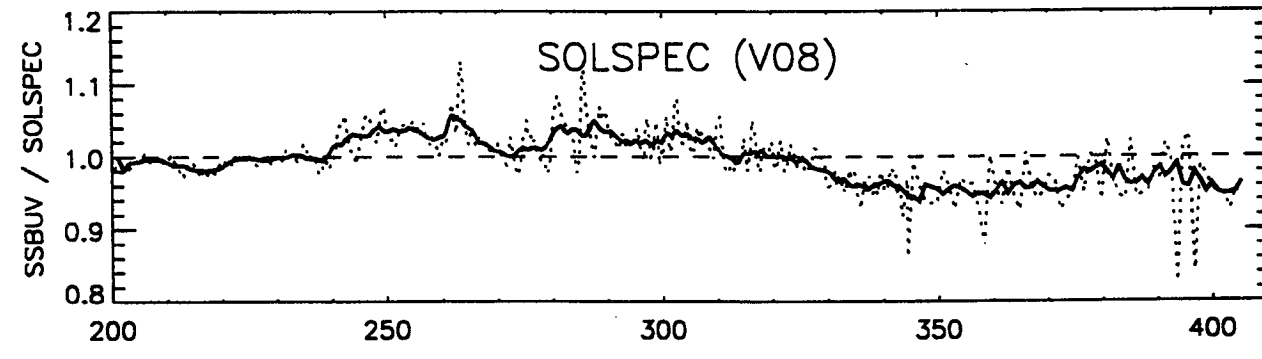
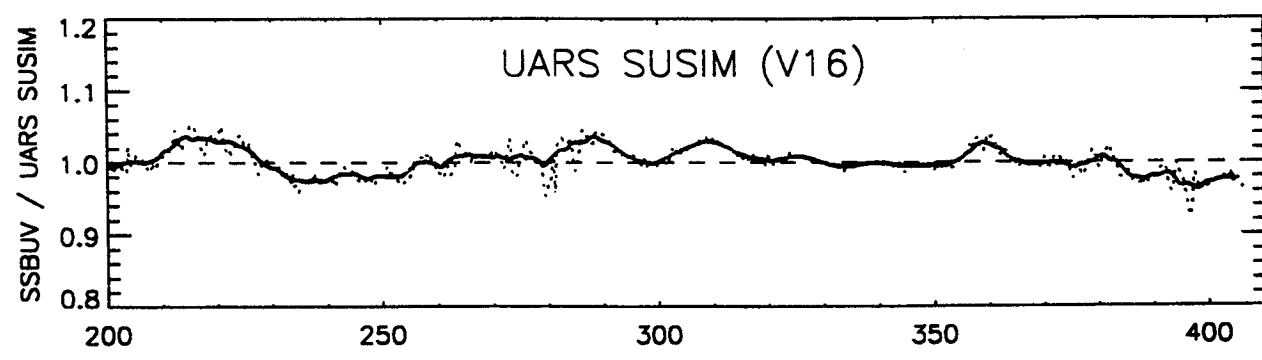
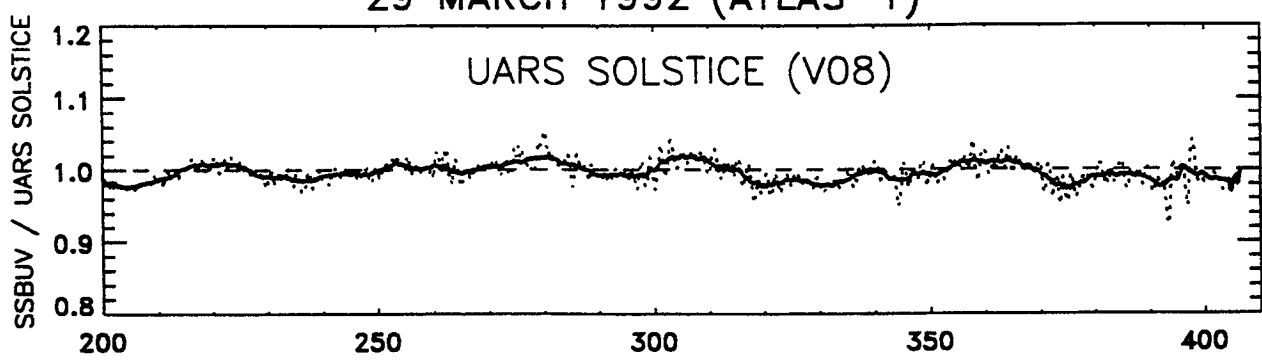
SSBUV Overview

- Instrument Stats
 - spectral range: 200 - 405 nm
 - spectral resolution: 1.1 nm
- Uncertainties (2σ)
 - Absolute irradiance: 2.4 - 6.0%
 - Time dependence: 1.0 - 2.4%
- Missions
 - Eight flights: Oct. 1989 - Jan. 1996
 - Includes three ATLAS flights, Mar. 1992 - Nov. 1994
 - 6-8 scans/solar observation; 3-10 observations /flight



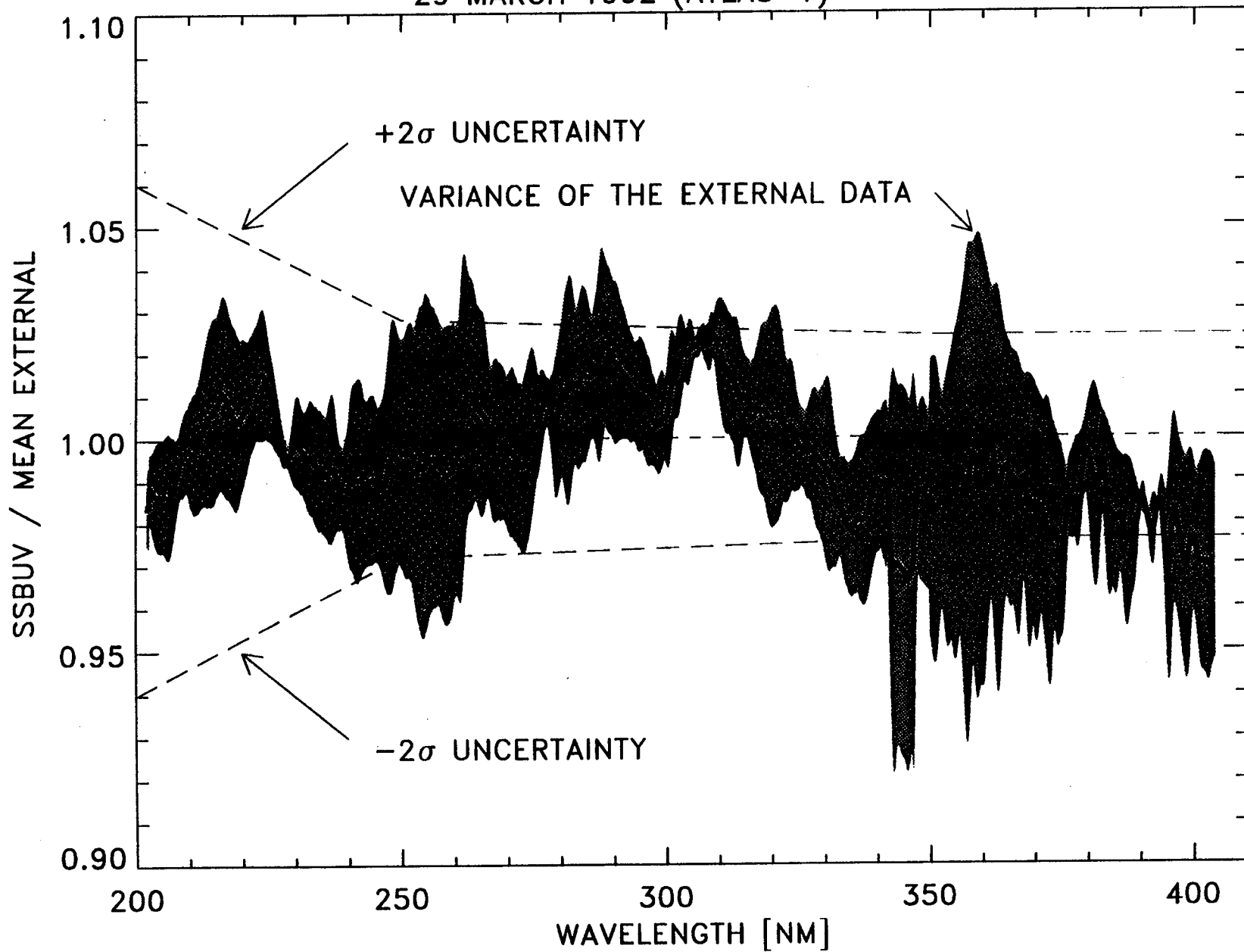
SOLAR IRRADIANCE COMPARISONS

29 MARCH 1992 (ATLAS-1)

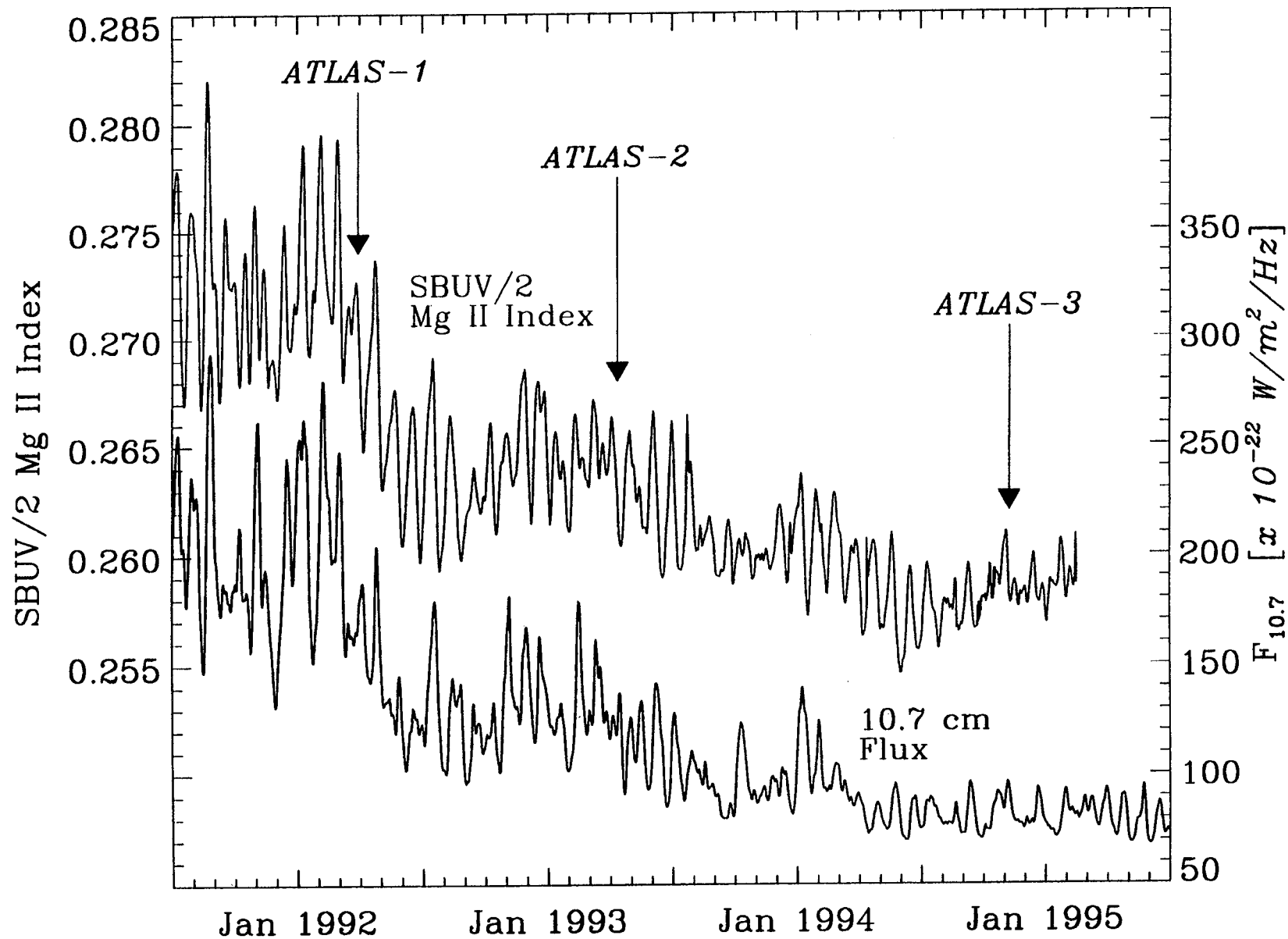


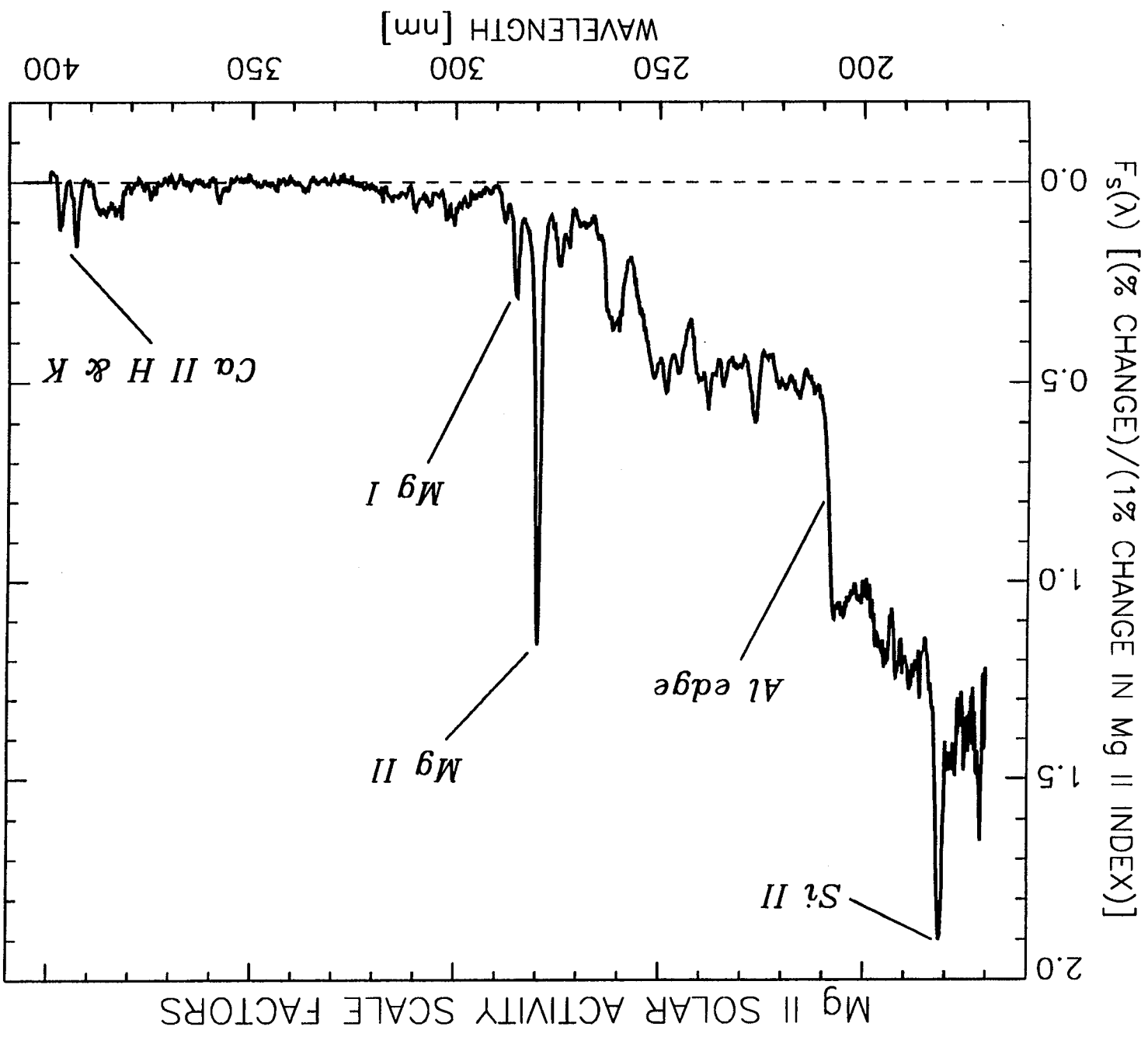
COMPARISON OF SSBUV TO OTHER SOLAR MEASUREMENTS

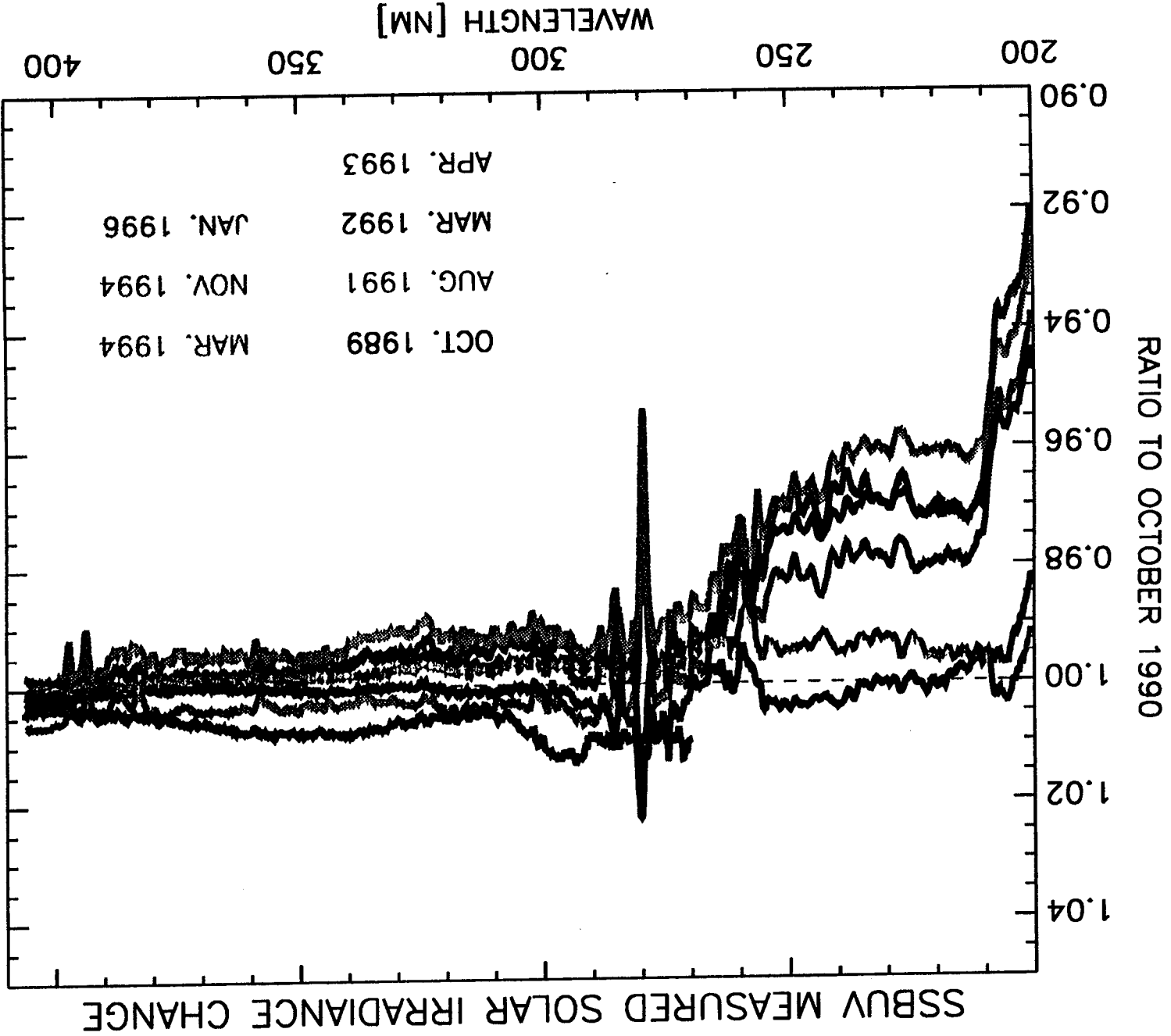
29 MARCH 1992 (ATLAS-1)



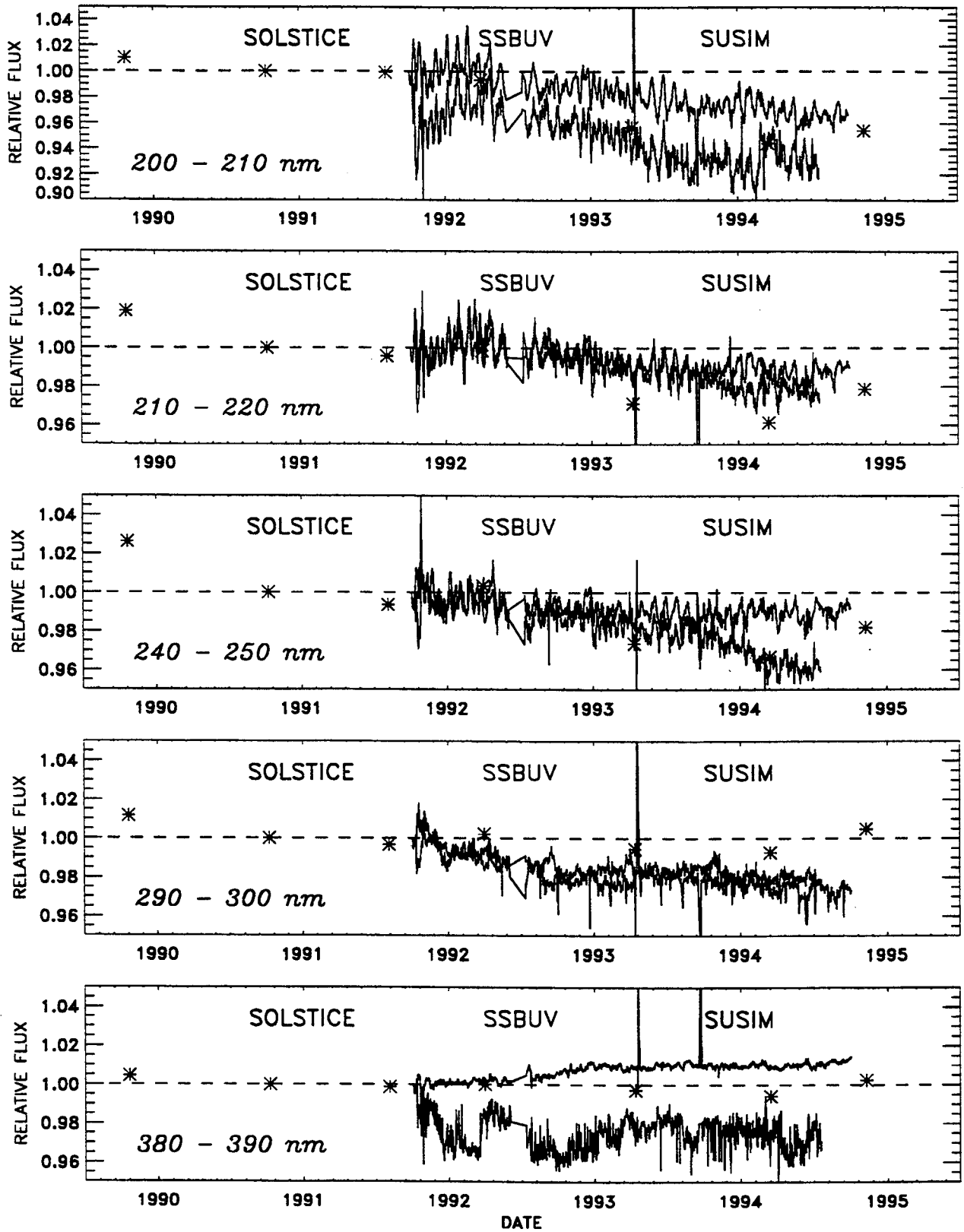
TYPICAL MIDDLE UV PROXY INDEXES





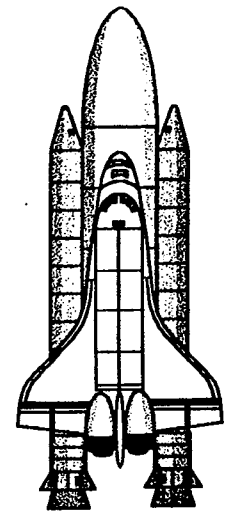


SSBUV-SOLSTICE-SUSIM SOLAR FLUX CHANGE



Conclusions

- Eight SSBUV missions 1989-1996
- SSBUV irradiances agree $\pm 2\%$ with mean of other solar flux measurements
- Measured long-term solar change ('90-'94)
 - 6.5% @ 200 nm (~ 790 1990-1996)
 - 3.0% @ 250 nm
 - less than 1% longward of ~ 300 nm
- SSBUV used to calibrate NOAA-11 SBUV/2
- **Data release anticipated in early 1997**



Solar Spectral Irradiance Variations
Observed by NOAA-11 SBUV/2 During 1989-1994

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presented at the 1996 Fall American Geophysical Union Meeting, San Francisco, CA

19 December 1996

supported by NASA Grant NASW-4864

The NOAA-11 SBUV/2 instrument made daily measurements of the solar UV irradiance between 160 and 405 nm at 1.1 nm resolution from December 1988 to October 1994, covering the maximum and declining phase of solar cycle 22. Instrument sensitivity drift was significant, ranging from approximately 30% near 200 nm to roughly 4% near 400 nm. These changes are 3-4 times larger than the predicted solar irradiance variations in the middle UV and near UV over a solar cycle. The SBUV/2 data have been reprocessed using a long-term characterization determined from both internal and external sources. An onboard calibration system was used to monitor long-term diffuser reflectivity changes, and comparisons with coincident flights of the SSBUV experiment were used to remove additional NOAA-11 instrument sensitivity drift.

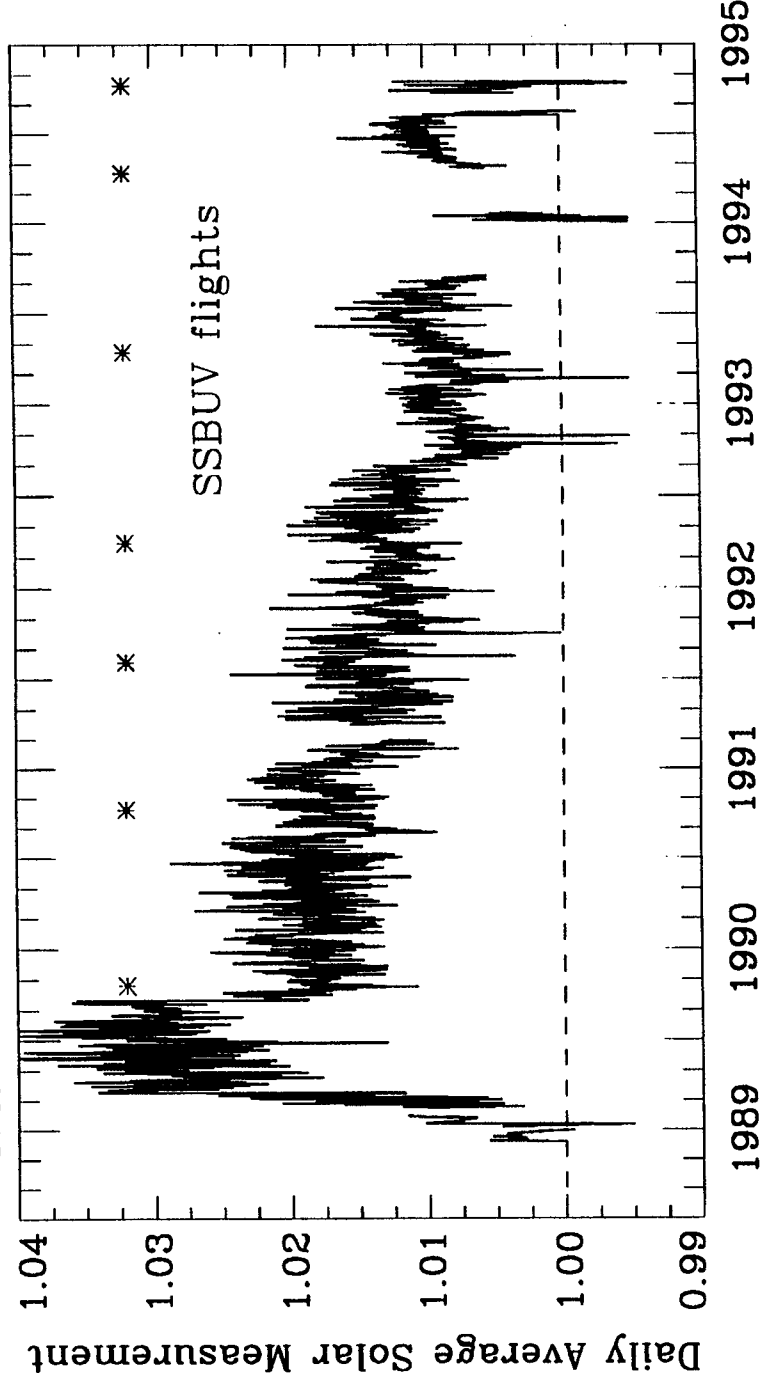
We present NOAA-11 solar UV irradiance observations during 1988-1994 for spectral regions which drive atmospheric photochemistry. The NOAA-11 results indicate a decrease of approximately 5-7% at 205 nm from the maximum of solar Cycle 22 in 1989-1991 through the end of the NOAA-11 record in October 1994, well into the declining phase of Cycle 22. The NOAA-11 irradiance data indicate an upper limit of roughly 1.5% on long-term solar change between 290-310 nm during this period, consistent with predictions from proxy indexes and scaling functions. We will also compare the NOAA-11 observations to the daily spectral irradiances from the UARS SUSIM V16 and UARS SOLSTICE V8 data sets, both of which cover the period September 1991 - October 1994.

- ▶ SBUV/2 onboard calibration system monitors diffuser reflectivity **only**. Long-term diffuser degradation has been removed from time series.
- ▶ Remaining instrument response changes are ~2% near 400 nm, 20% at 200 nm.
- ▶ Short-term solar variations visible at 205 nm, but long-term change cannot be evaluated.
- ▶ 7 SSBUV flights available for coincidences during 1989-1994.

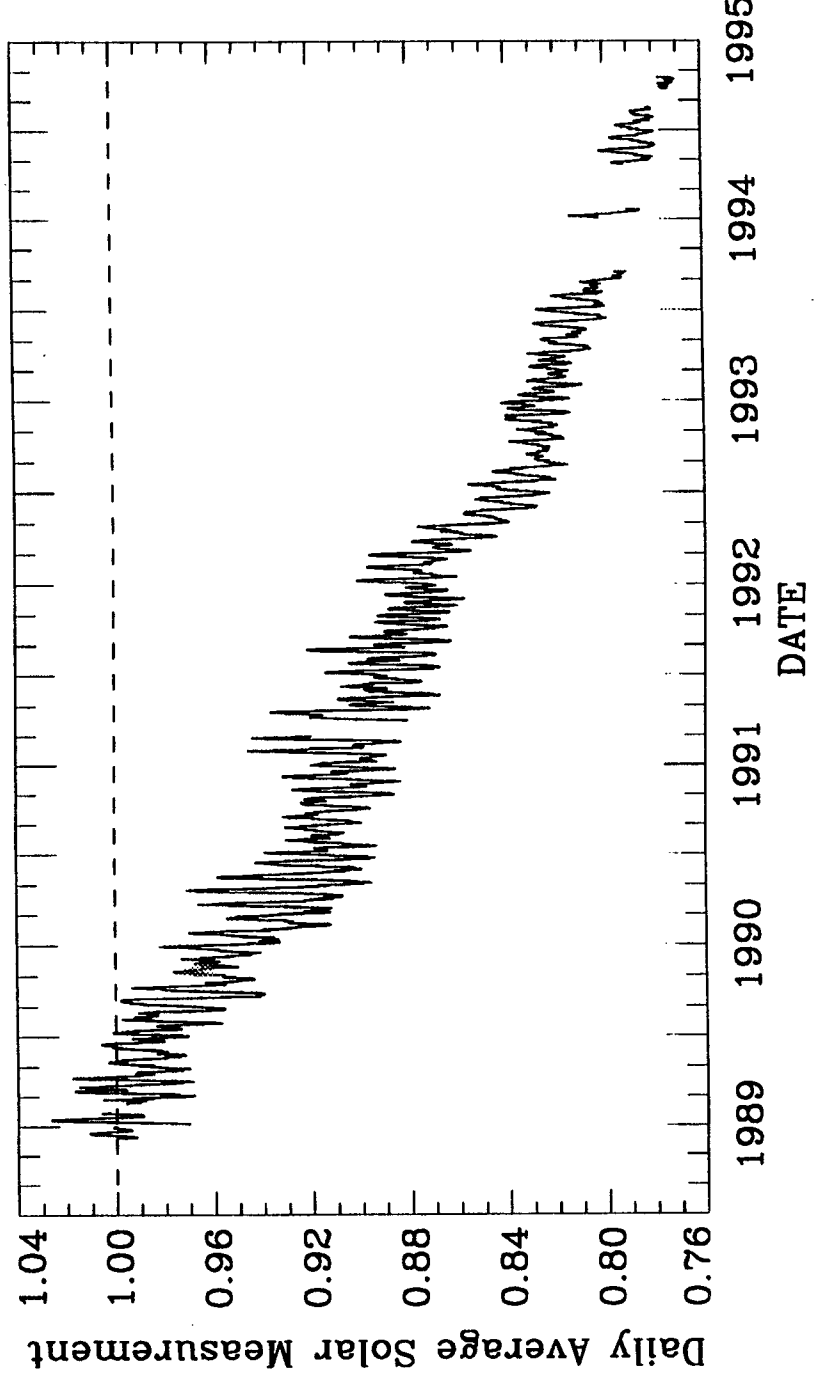
NOAA-11

UNCORRECTED Data

NOAA-11 SWEEP Time Series at 391 nm



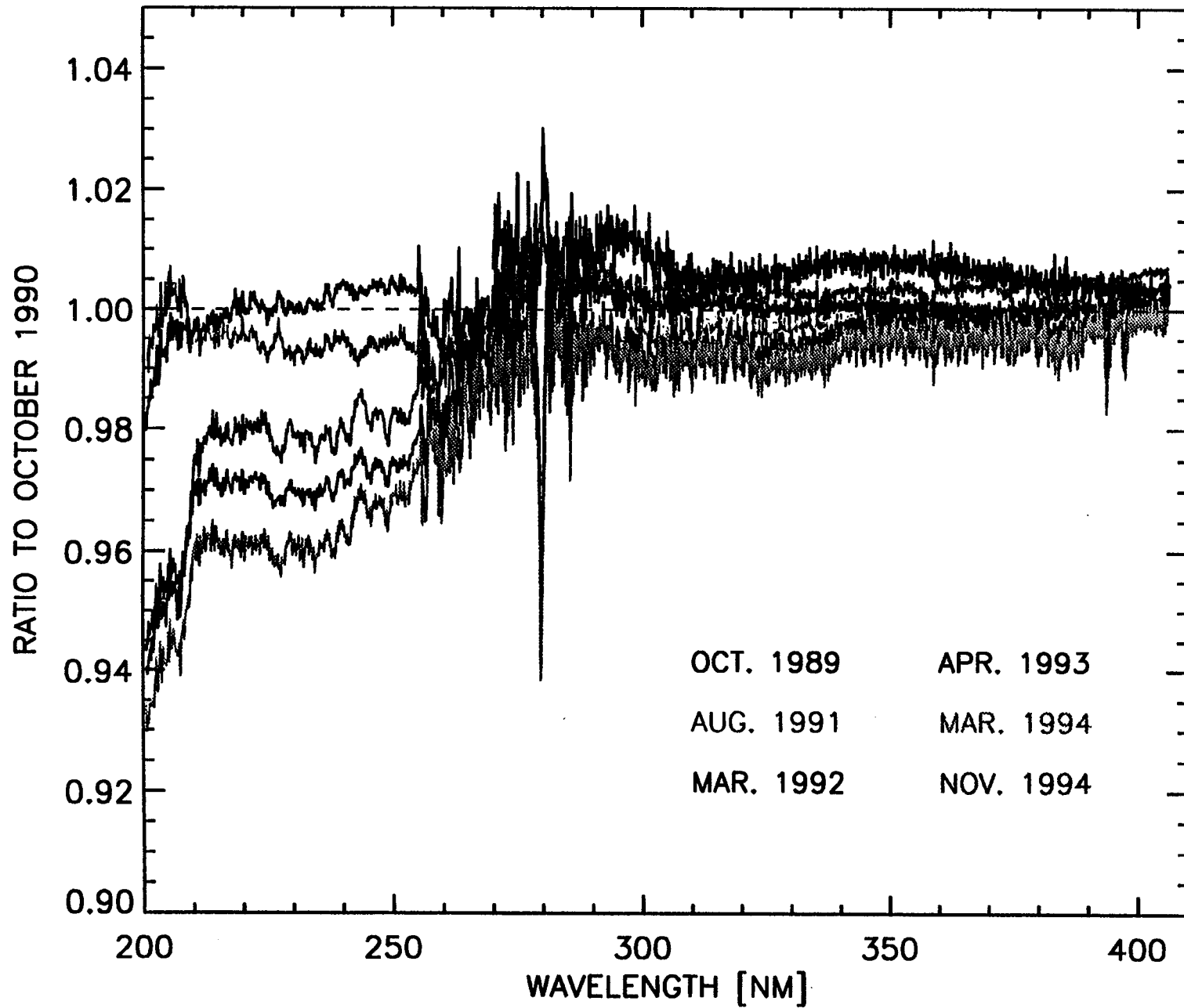
NOAA-11 SWEEP Time Series at 205 nm



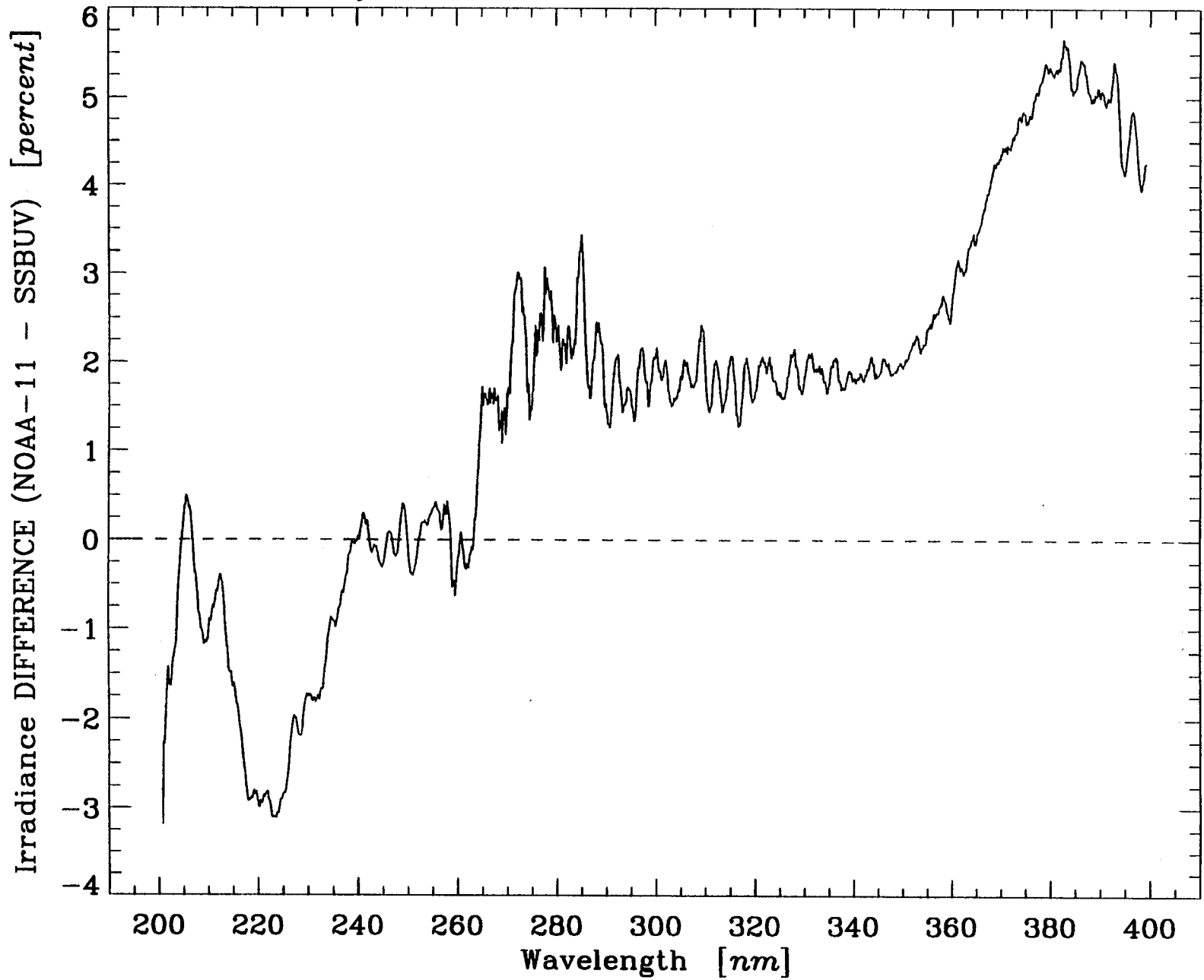
- ▶ SSBUV absolute irradiances in good agreement with other instruments ($\pm 2\%$ vs. UARS, ATLAS means).
- ▶ SSBUV long-term calibration for 200-400 nm wavelength region repeatable to approximately 1.0-2.4%.
- ▶ NOAA-11 "Day 1" irradiance agrees with SSBUV reference spectrum to approximately $\pm 5\%$, with some spectral bias.

SSBUV Absolute Irradiance Comparison

SSBUV MEASURED SOLAR IRRADIANCE CHANGE

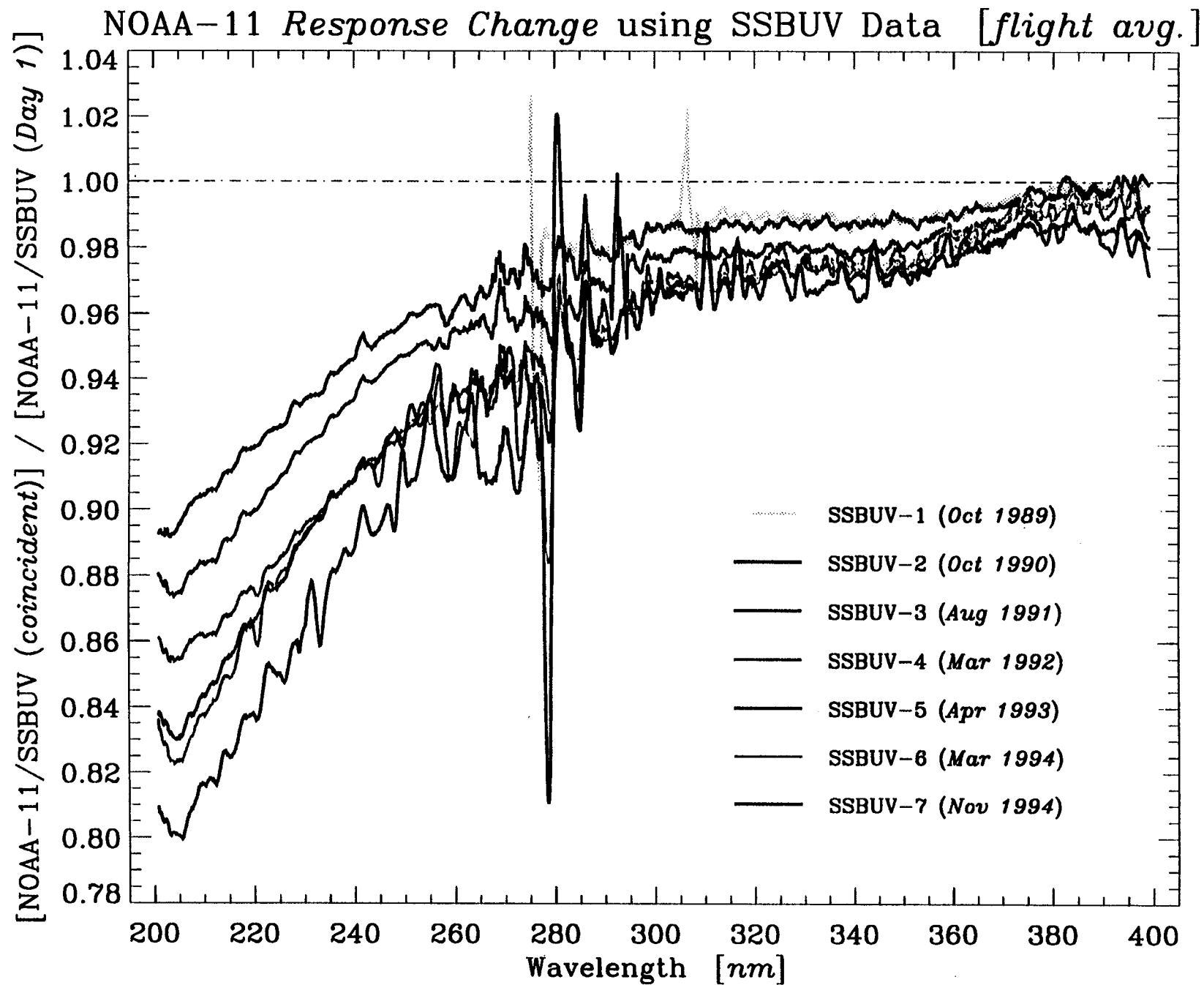


NOAA-11 "Day 1" vs. SSBUV-2: *Irradiance DIFFERENCE*

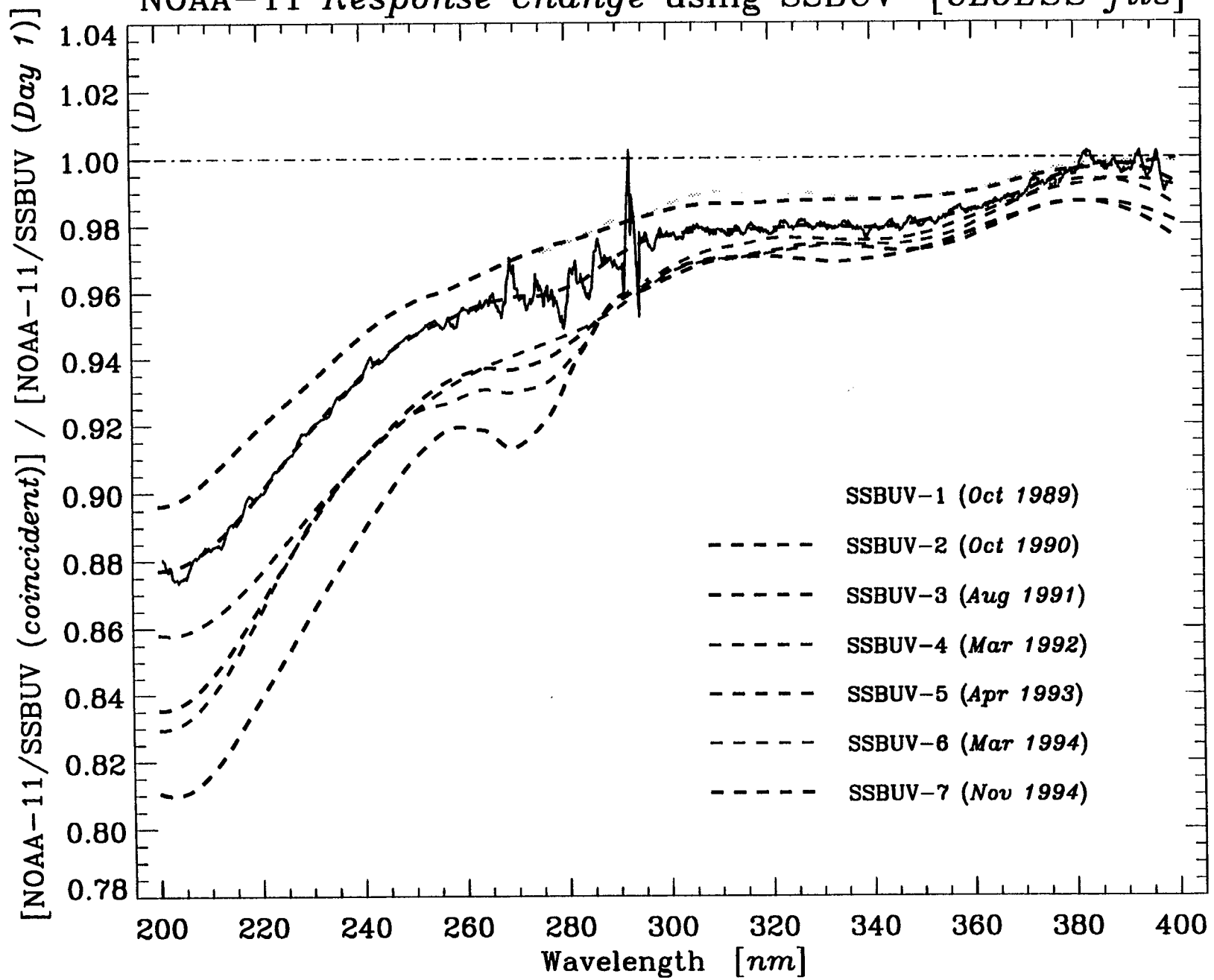


- ▶ Construct ratios of SSBUV flight averages and coincident NOAA-11 data. Use of coincident spectra removes solar change.
- ▶ Remove "Day 1" bias, normalize SSBUV data for each flight at 400 nm (adjustments are $\pm 0.5\%$ or less).
- ▶ Spectral dependence of NOAA-11 response change is fairly smooth. Small-scale structure caused by residual uncorrected wavelength scale drift.
- ▶ Fit each spectral ratio with **smoothing spline** function (CLOESS) to remove residual noise from $\Delta \lambda(t)$ correction, accurately follow large-scale structure.

Characterize NOAA-11 *SPECTRAL* Response



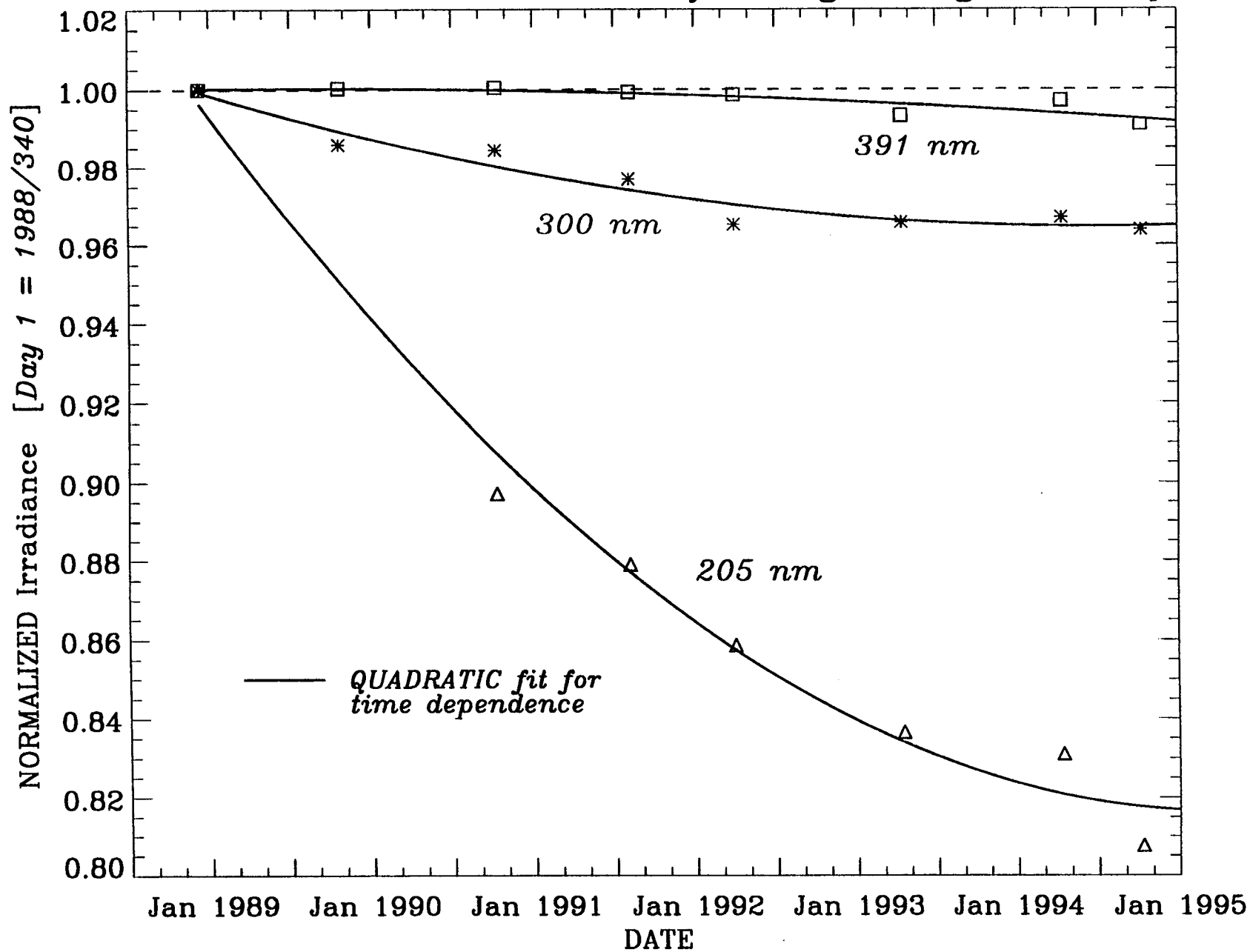
NOAA-11 Response Change using SSBUV [CLOESS fits]



- ▶ At each wavelength, construct **time dependence** using spectral fit values from each SSBUV flight and nominal "Day 1" value.
- ▶ SSBUV-1 data excluded for $\lambda < 275$ nm due to calibration problems.
- ▶ Limited number of points suggests simple time dependence. Quadratic fit works well, although upturn in late 1994 may not be realistic.
- ▶ True calibration changes with short time scales [$t < 1$ year] will not be well-represented.

Characterize NOAA-11 *TEMPORAL* Response

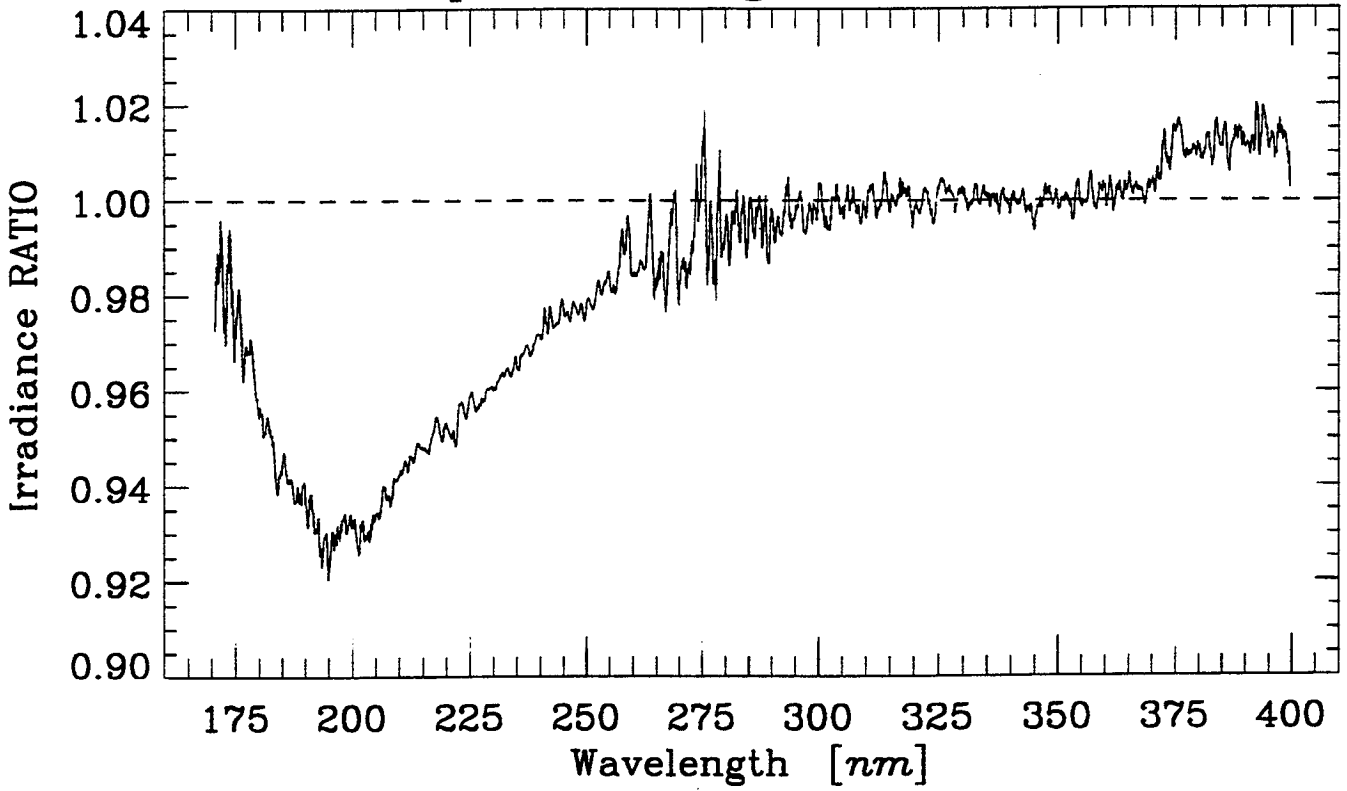
NOAA-11 *CALCULATED* Sensitivity Change using *CLOESS* fits



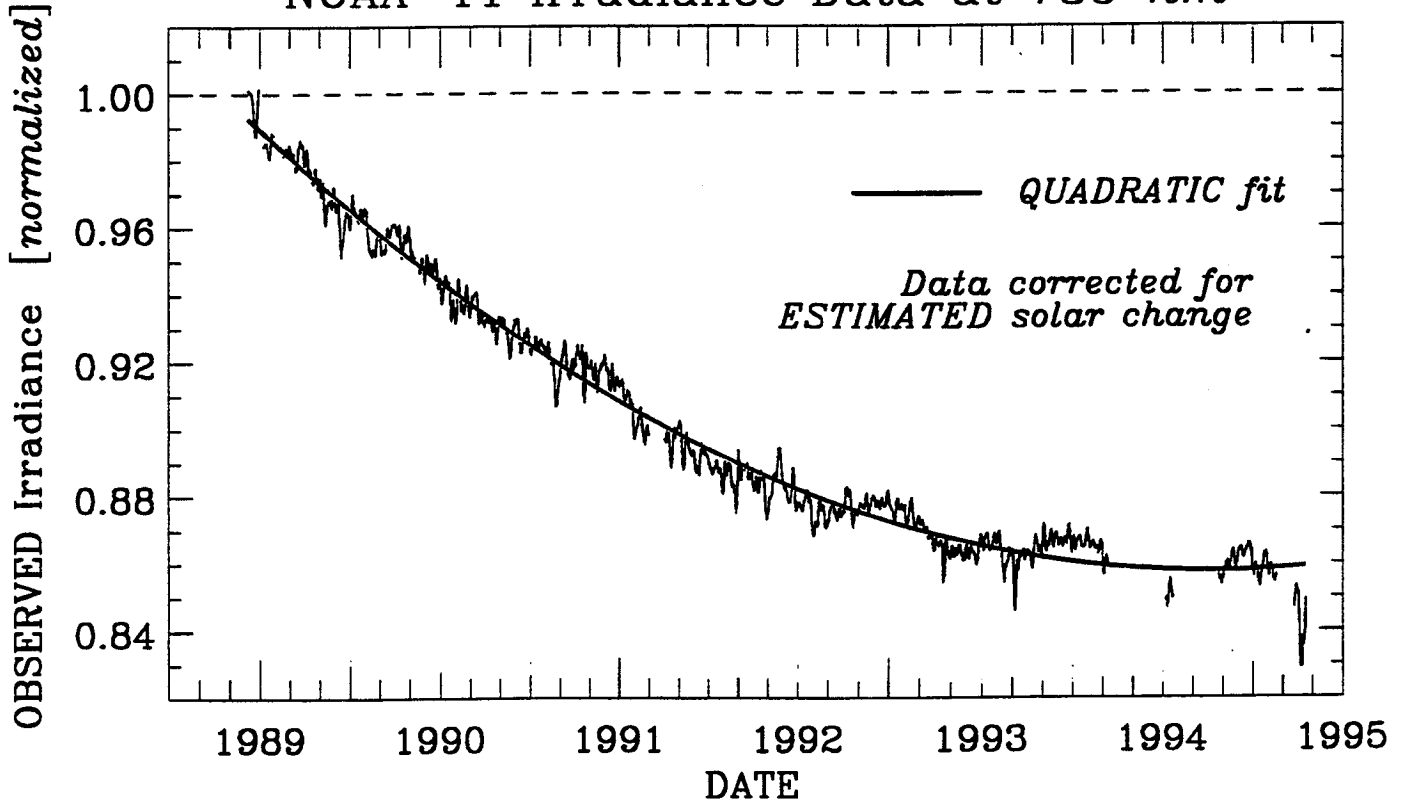
- ▶ NOAA-11 spectral data have adequate S/N down to 170 nm, but SSBUV-based correction only available for 200-400 nm. Spectral dependence of sensitivity change different at $\lambda < 200$ nm \rightarrow can't extrapolate previous fits.
- ▶ **Estimate** sensitivity change at 170-200 nm by removing Mg II index-based predicted solar variation from time series. Fit remaining data with quadratic function for time dependence.
- ▶ Long-term correction for 170-200 nm less precise than 200-400 nm results based on SSBUV data.
- ▶ Select fit values at 5 nm intervals for dates of SSBUV flights, use as new "data" points with previous continuous ratios.
- ▶ CLOESS fits to full wavelength range preserve spectral structure for $\lambda > 200$ nm, give smooth shape for $\lambda < 200$ nm.

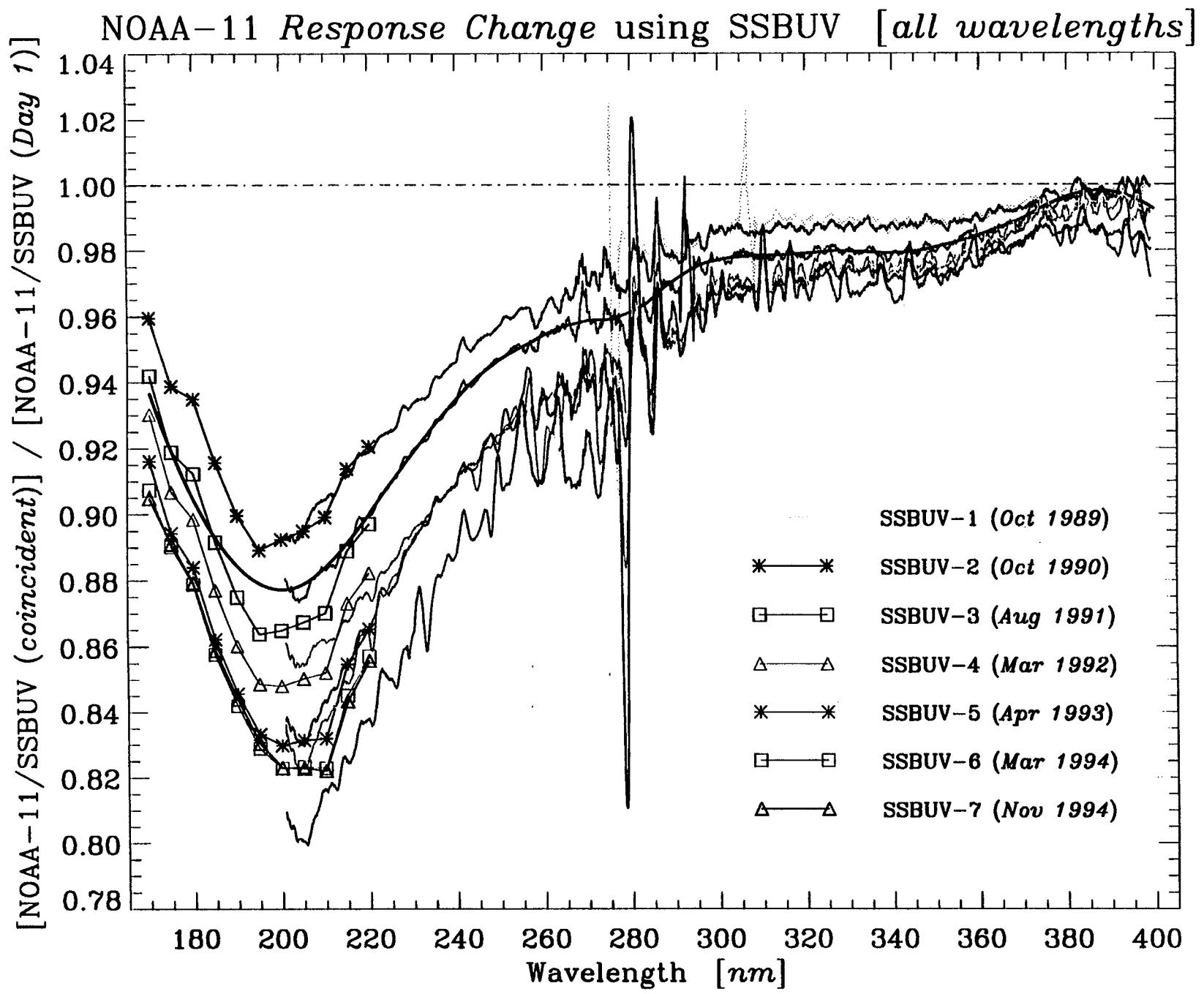
Short Wavelength Data

NOAA-11 Response Change: 1 Year After Launch



NOAA-11 Irradiance Data at 185 nm

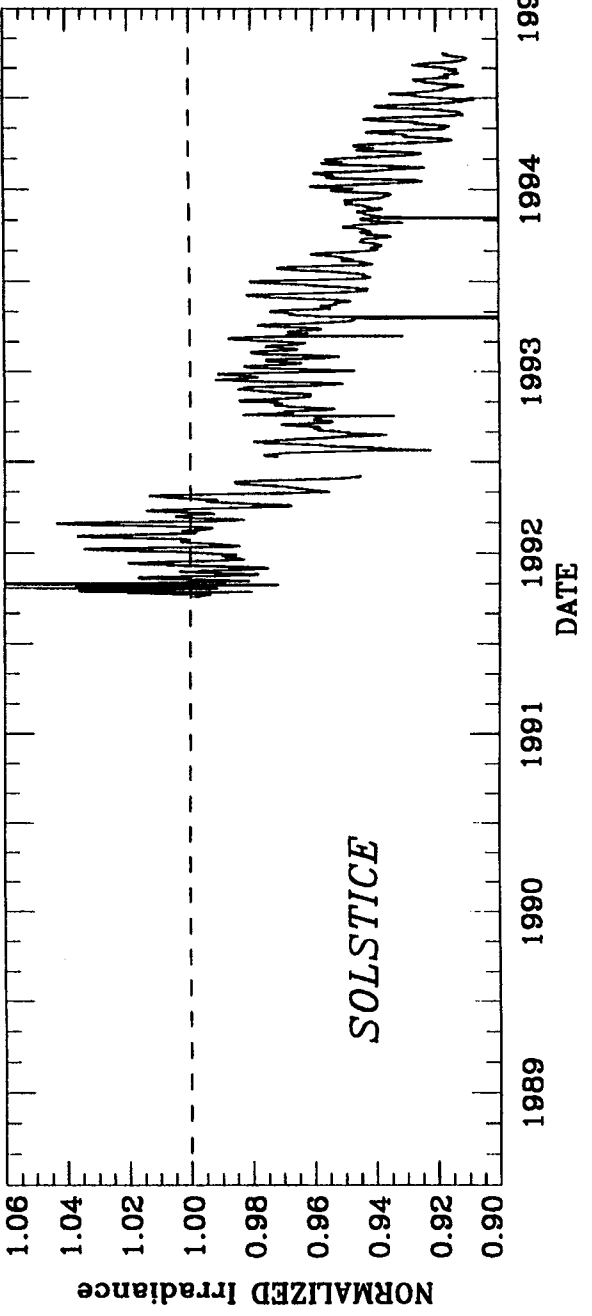
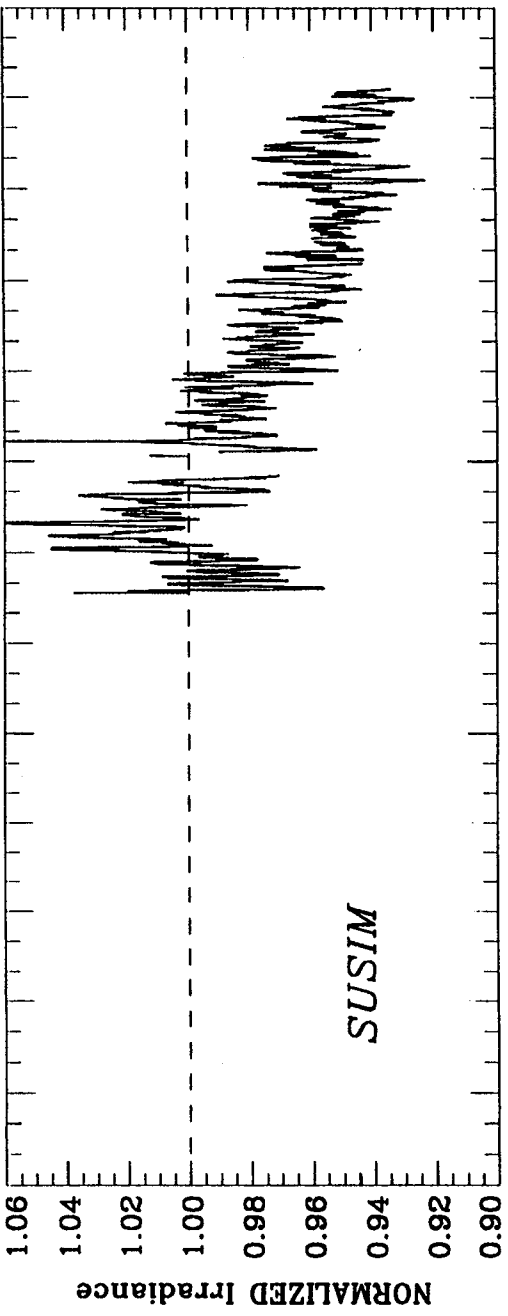
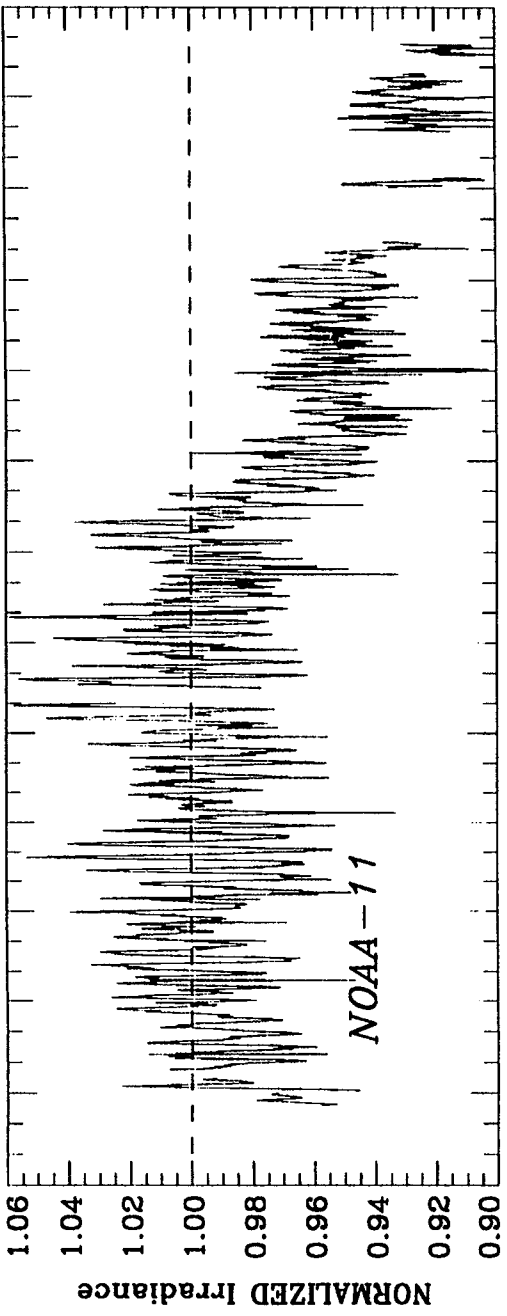




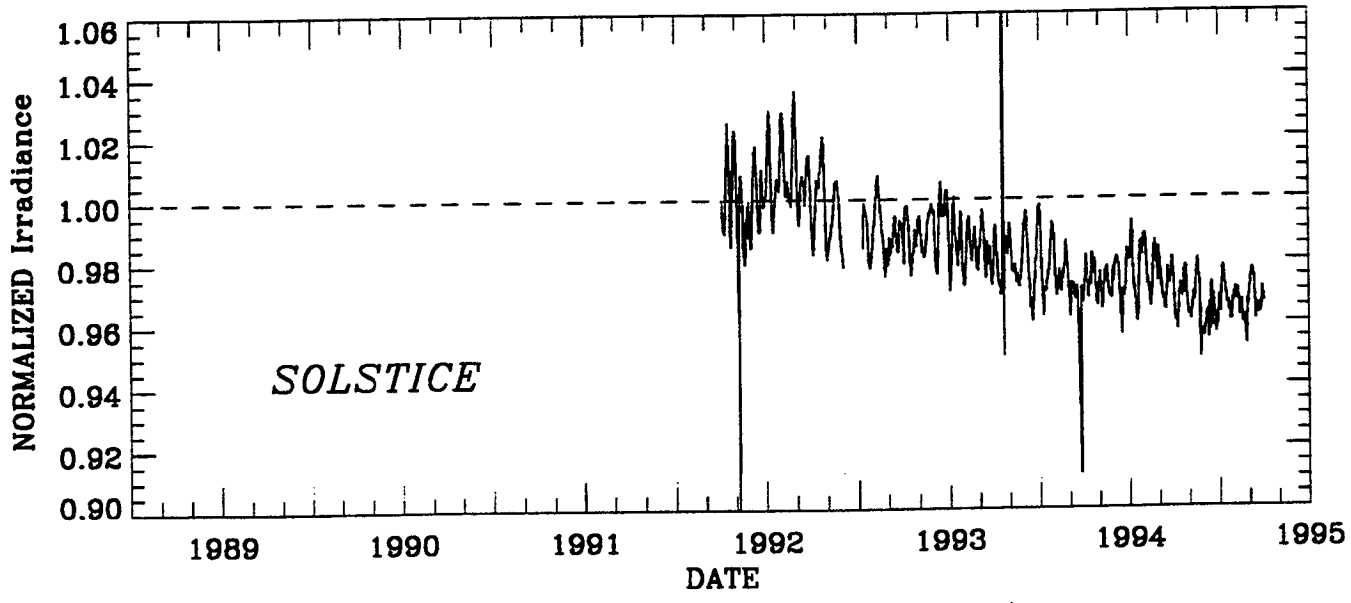
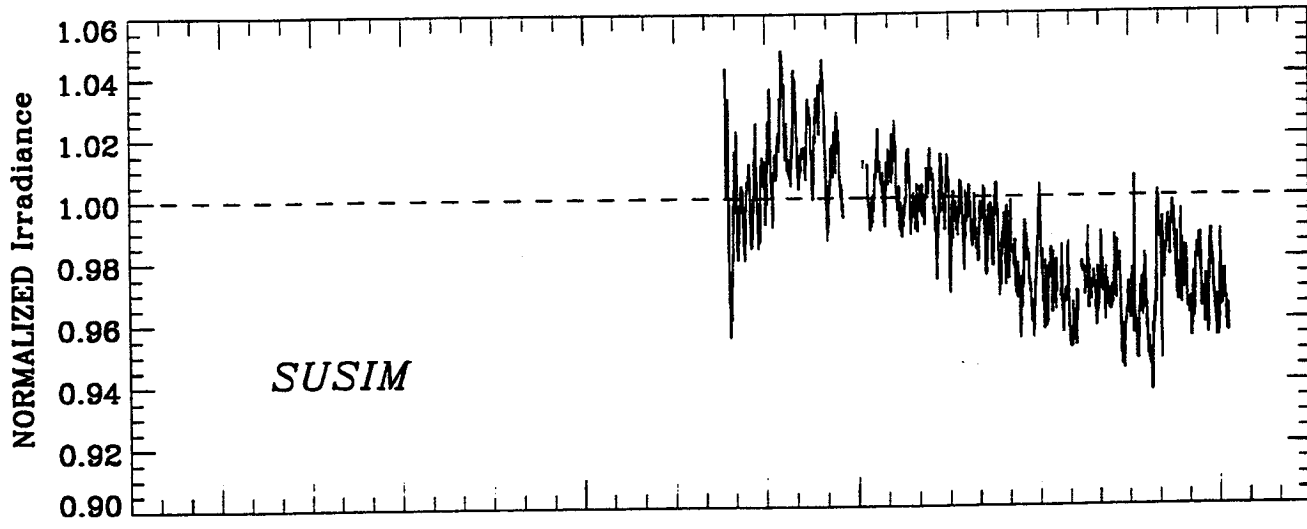
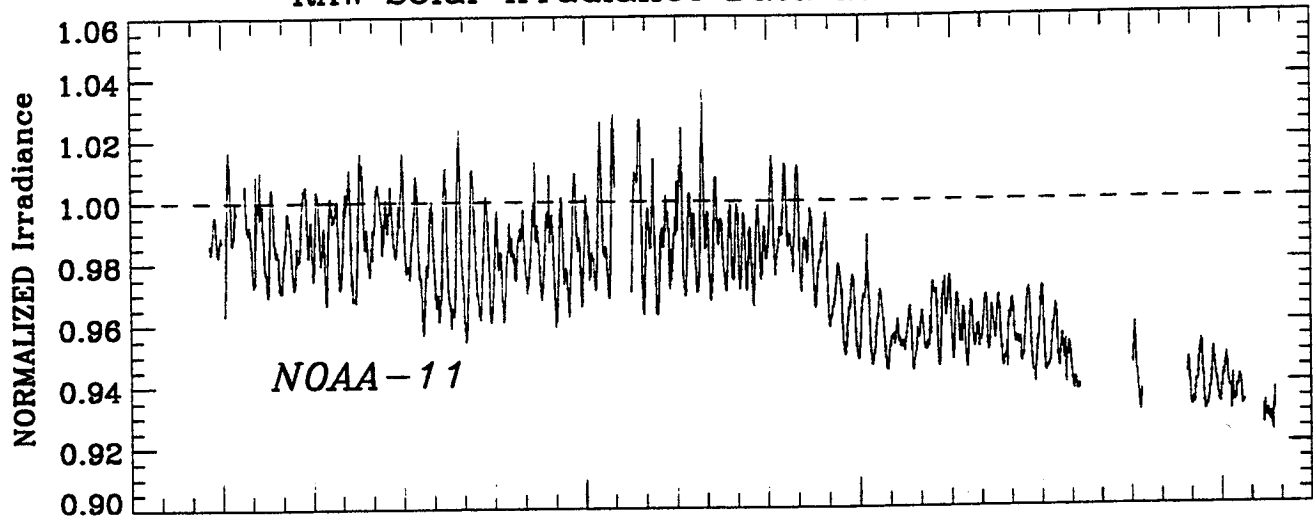
- ▶ Reprocess all NOAA-11 data with corrections for instrument degradation (*derived here*), wavelength scale drift, orbit drift (*goniometry*).
- ▶ NOAA-11 results shown are 1 nm averaged spectra on 0.5 nm centers, for best comparison with UARS SUSIM [V16], UARS SOLSTICE [V08].
- ▶ Daily noise for 10 nm band averages approximately $\pm 0.5\%$ at short wavelengths, $\pm 0.2\%$ at long wavelengths ($\lambda > 300$ nm).
- ▶ Current NOAA-11 sensitivity change correction leaves long-term residuals of $\sim 1\text{-}2\%$ at long wavelengths. This accuracy is comparable to SUSIM, SOLSTICE.

NOAA-11 Corrected Data vs. UARS Instruments

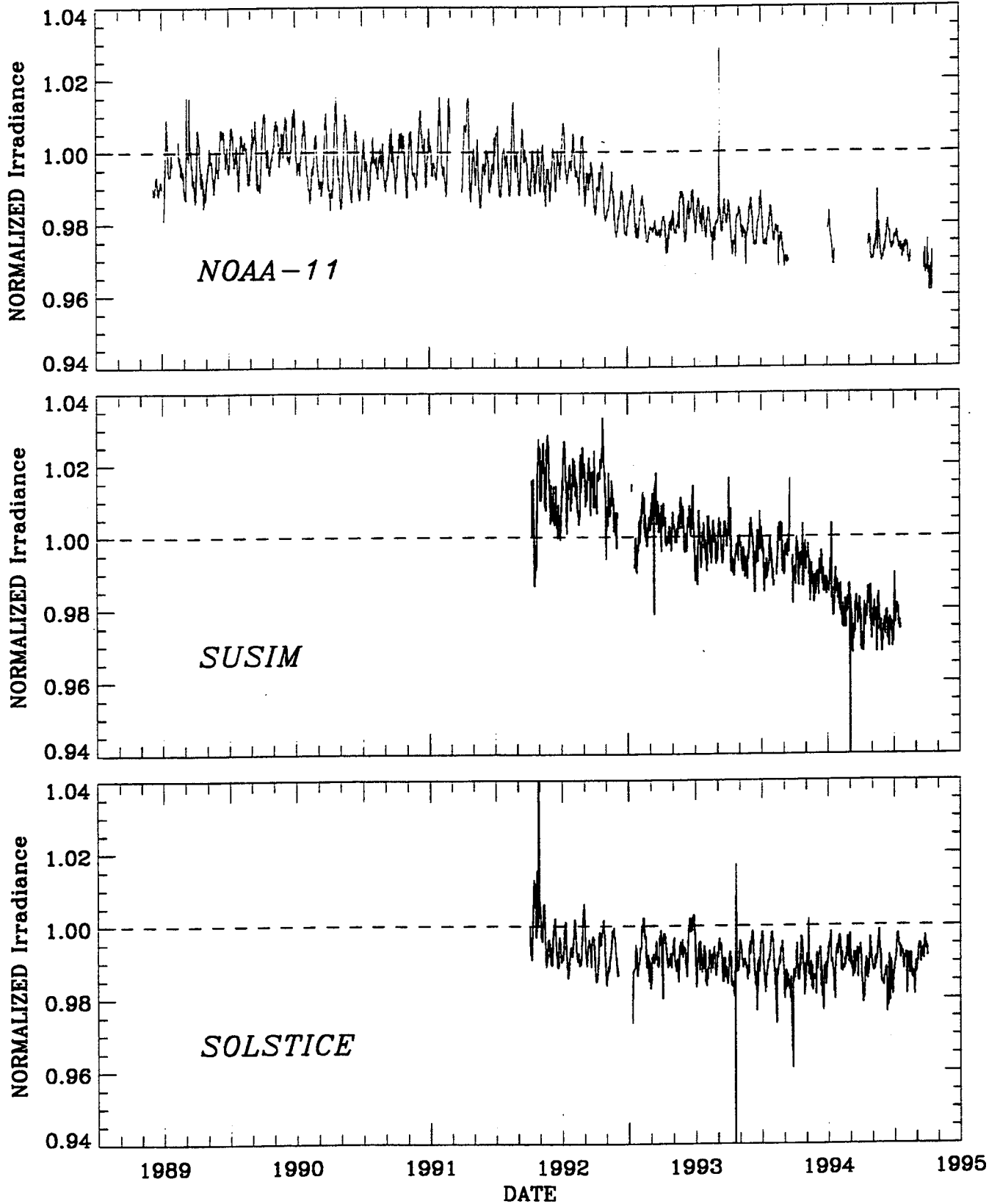
RAW Solar Irradiance Data at 170-180 nm



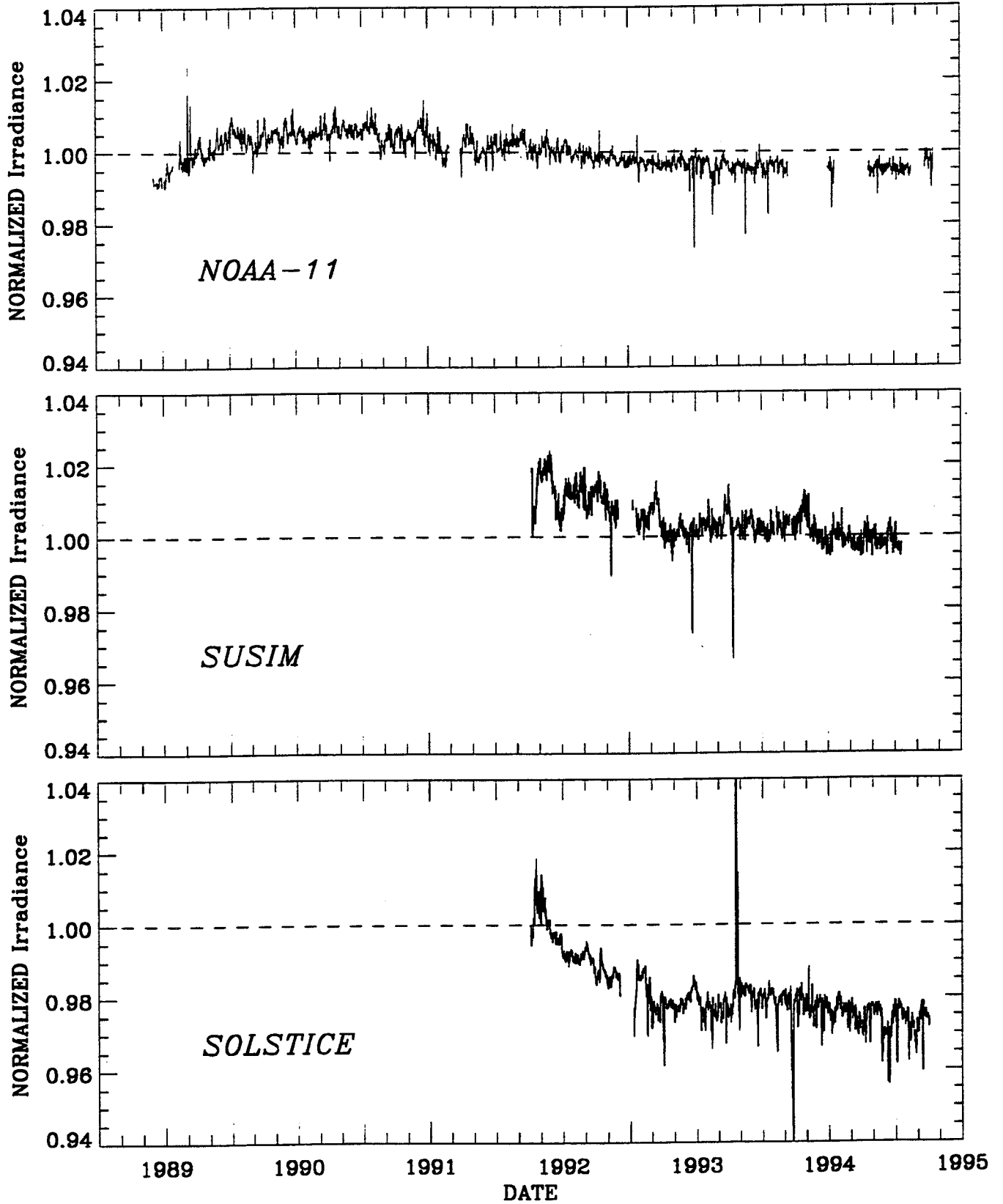
RAW Solar Irradiance Data at 200-210 nm



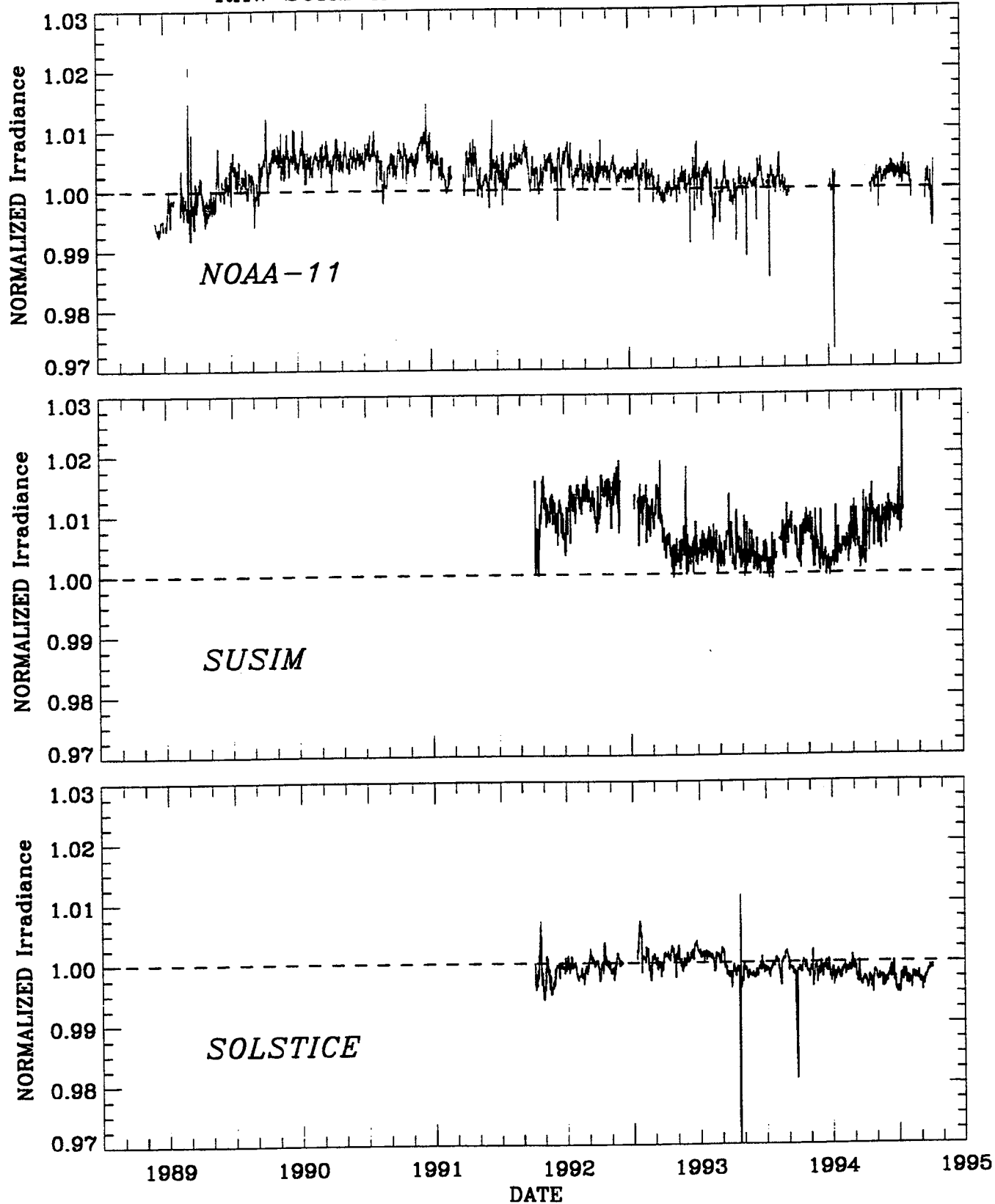
RAW Solar Irradiance Data at 240–250 nm



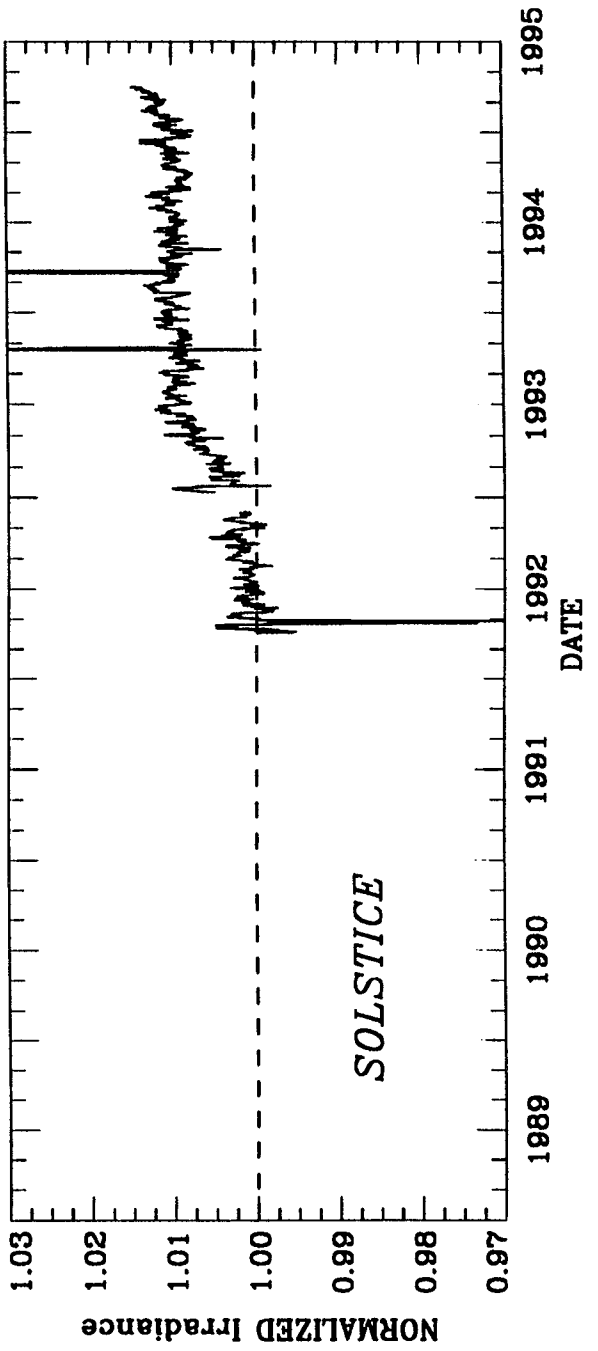
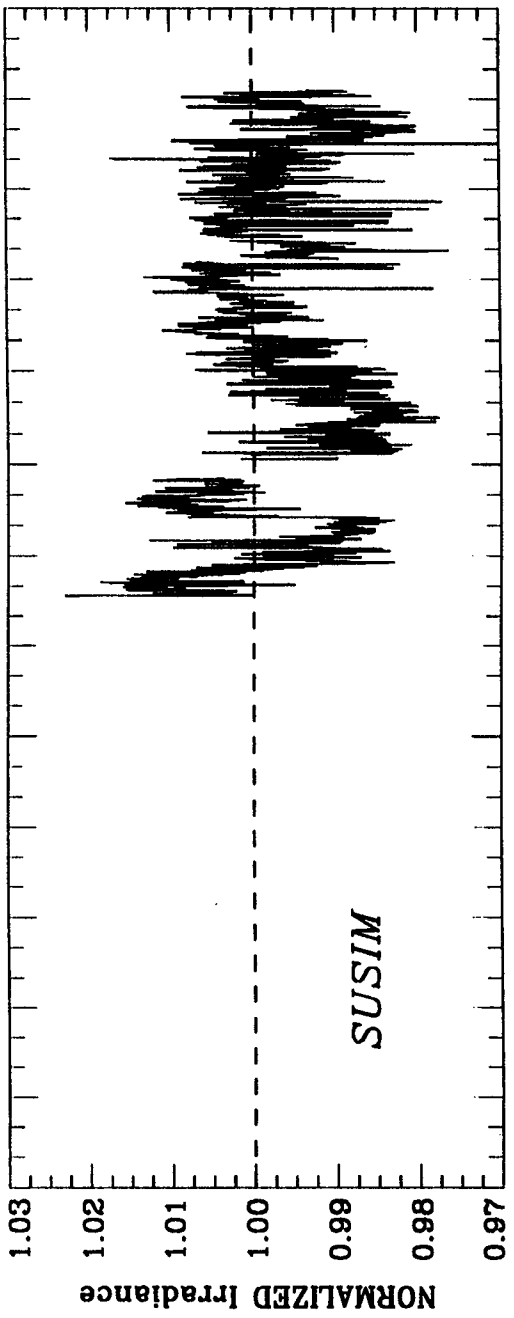
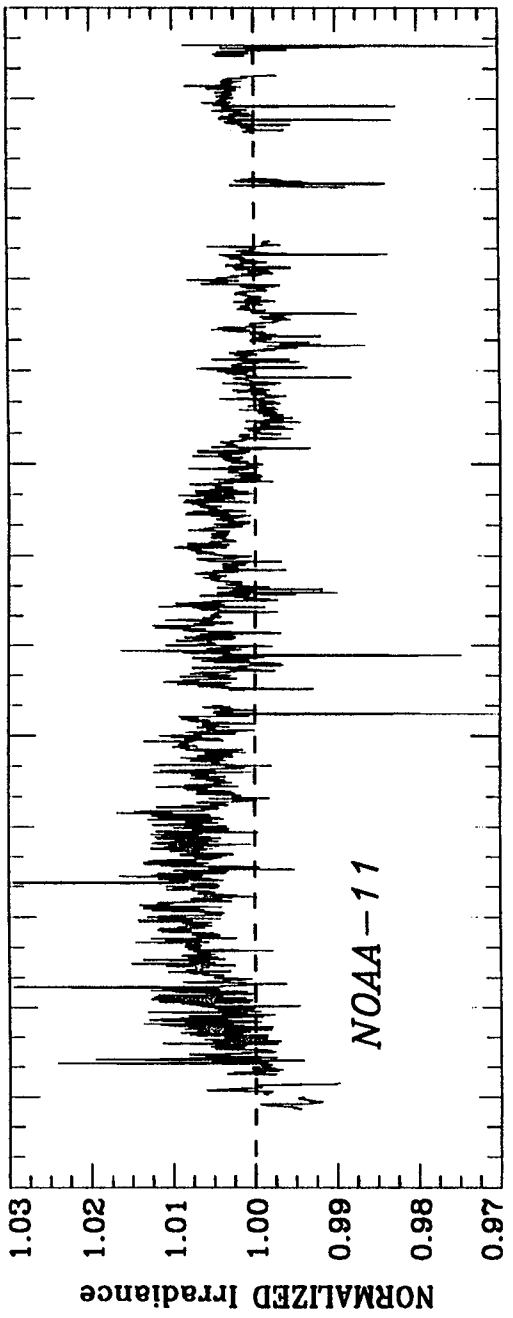
RAW Solar Irradiance Data at 290–300 nm



RAW Solar Irradiance Data at 340-350 nm



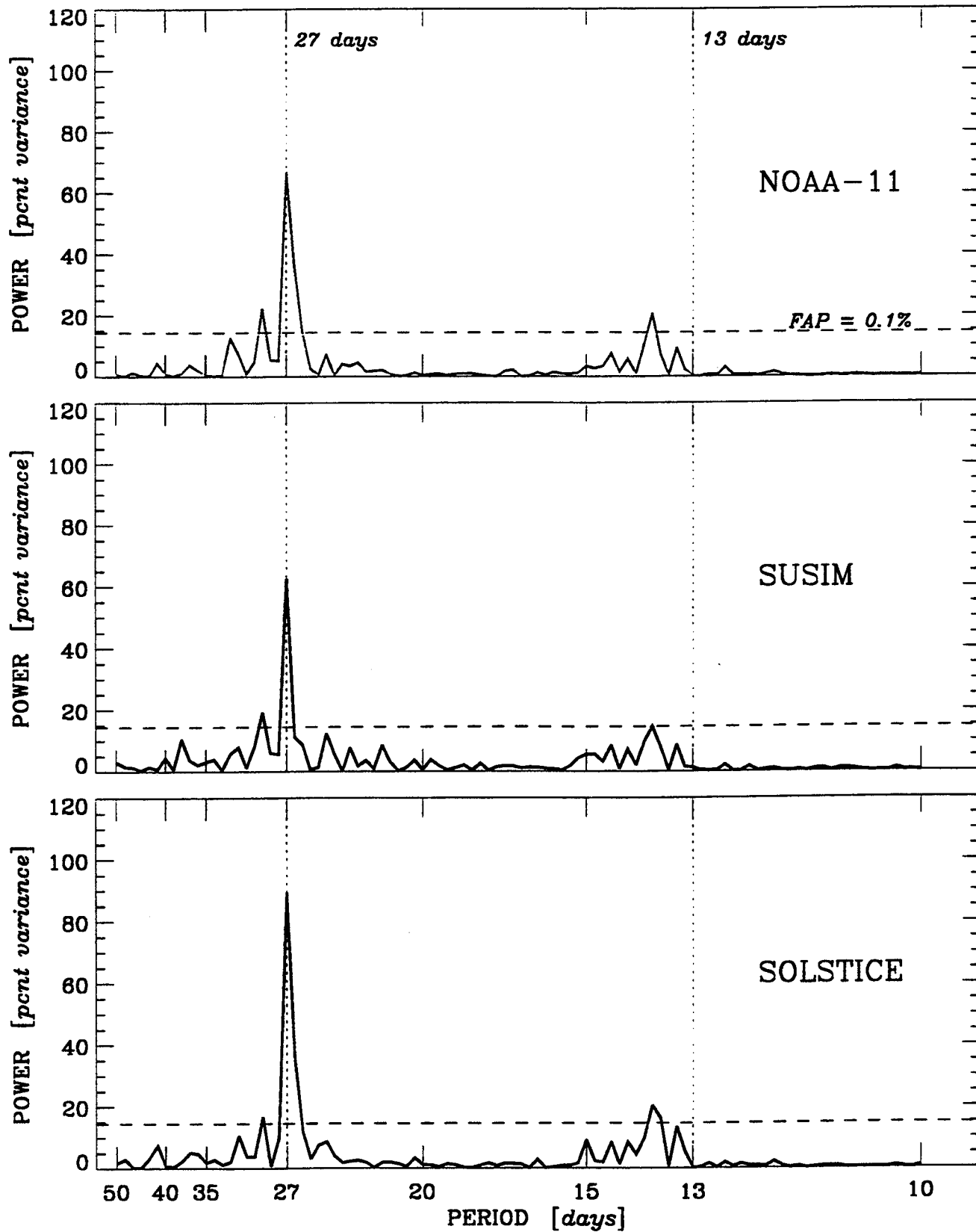
RAW Solar Irradiance Data at 380-390 nm



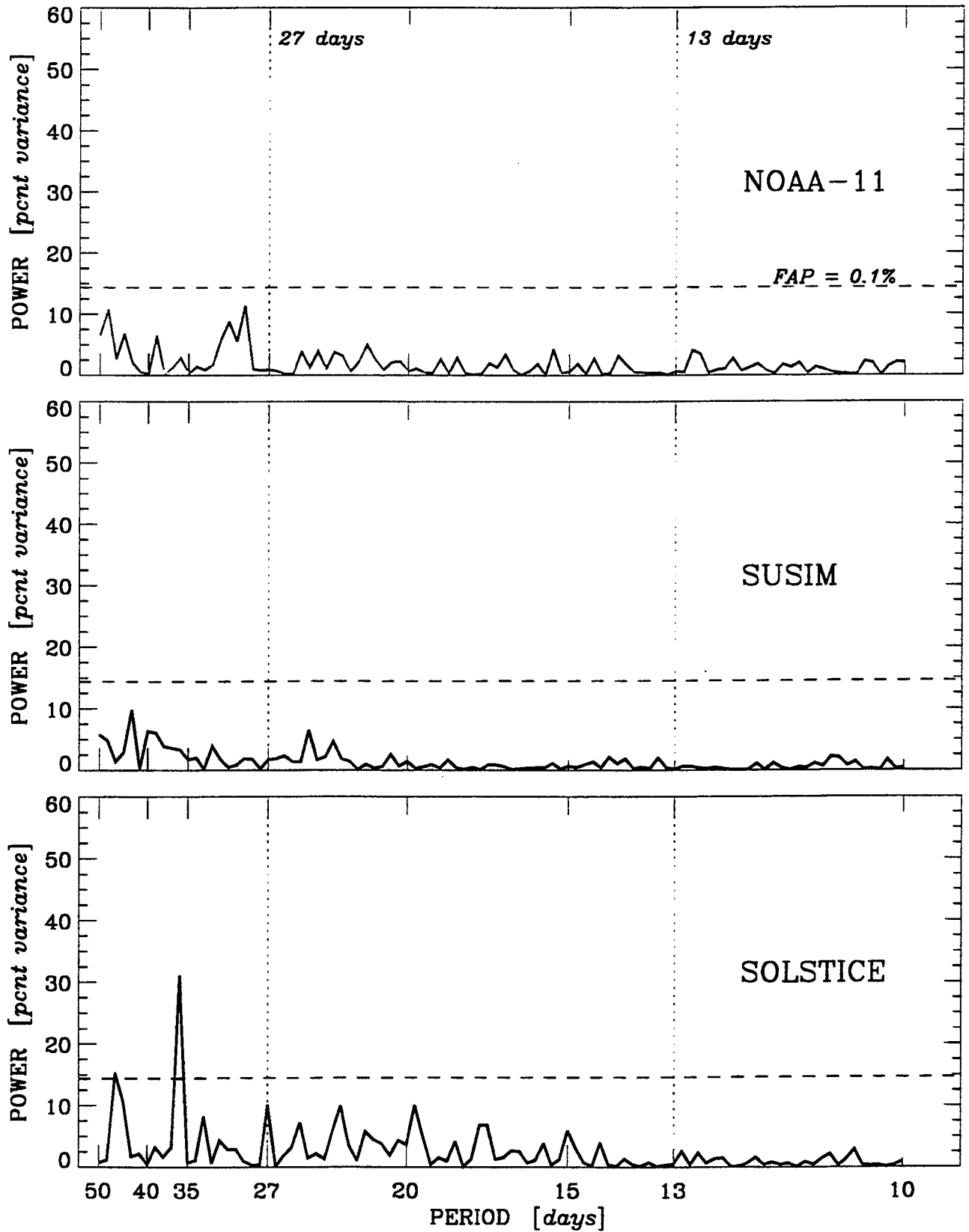
- ▶ NOAA-11 data cover complete solar maximum for Cycle 22. Long-term solar changes (*e.g.* end of maximum in Spring 1992) now visible at short wavelengths.
- ▶ Periodogram analysis shows consistent representation of short-term solar activity at 200-210 nm for all 3 instruments. 27-day rotational modulation present throughout 1991-1994, episode of 13-day periodicity observed in Fall 1991.
- ▶ Use NOAA-11 discrete Mg II index and scale factors to estimate solar activity during 1989-1994. Scale factors derived from short-term variations. Remove this estimate from all time series.
- ▶ Initial results indicate Mg II index predictions represent long-term solar activity to ~1-2% accuracy at 205 nm.

Observed Solar Activity

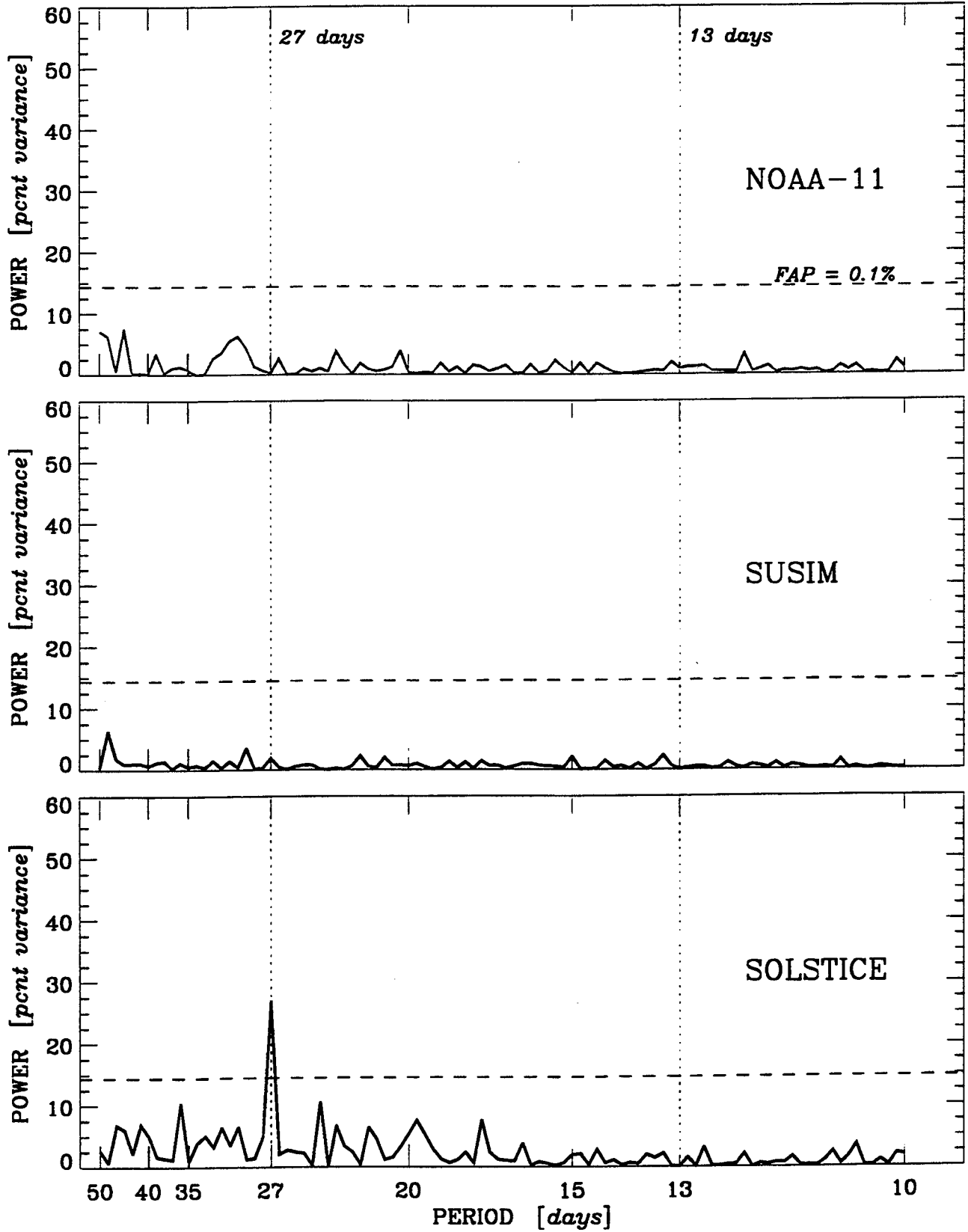
PERIODOGRAM for 200-210 nm Data
Time Interval = 1991/260 to 1994/289



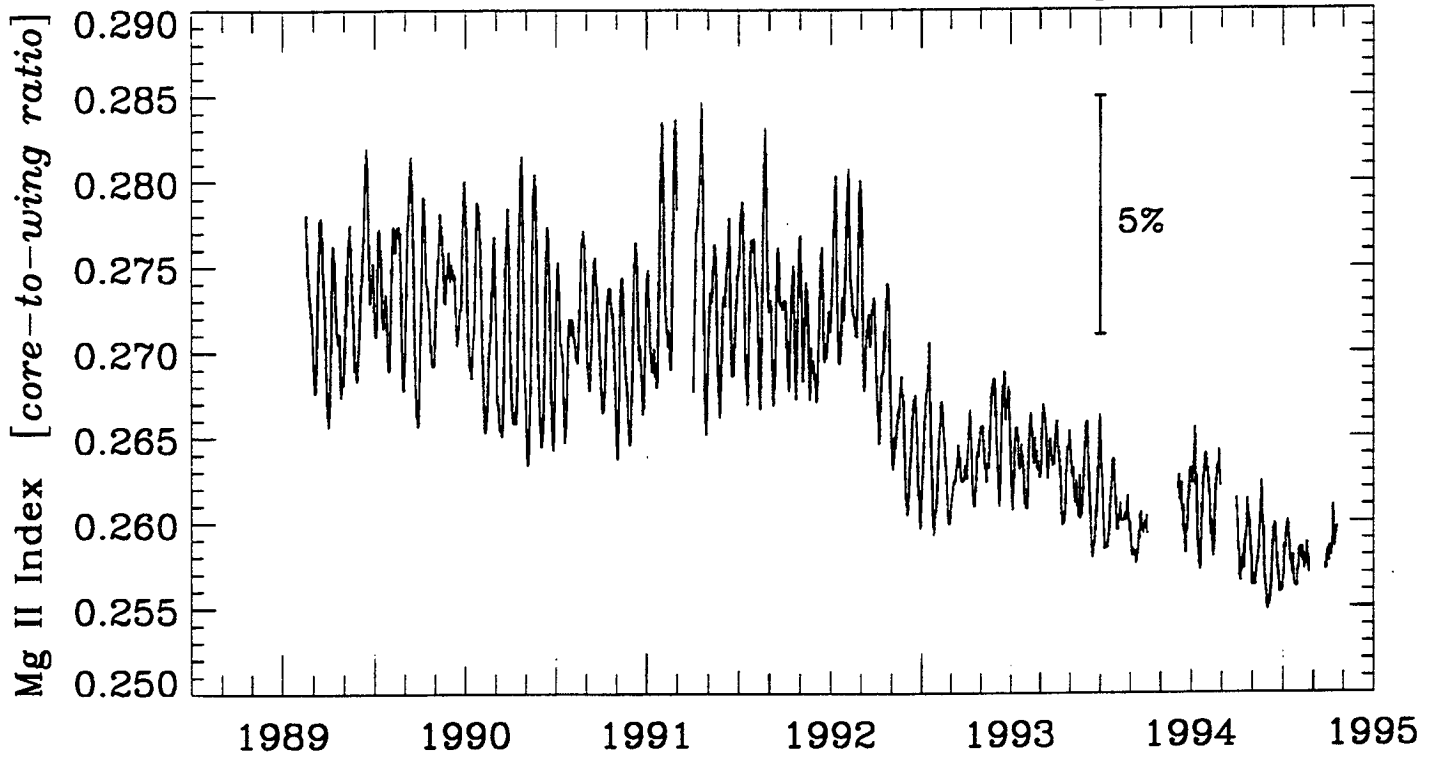
PERIODOGRAM for 340-350 nm Data
Time Interval = 1991/260 to 1994/289



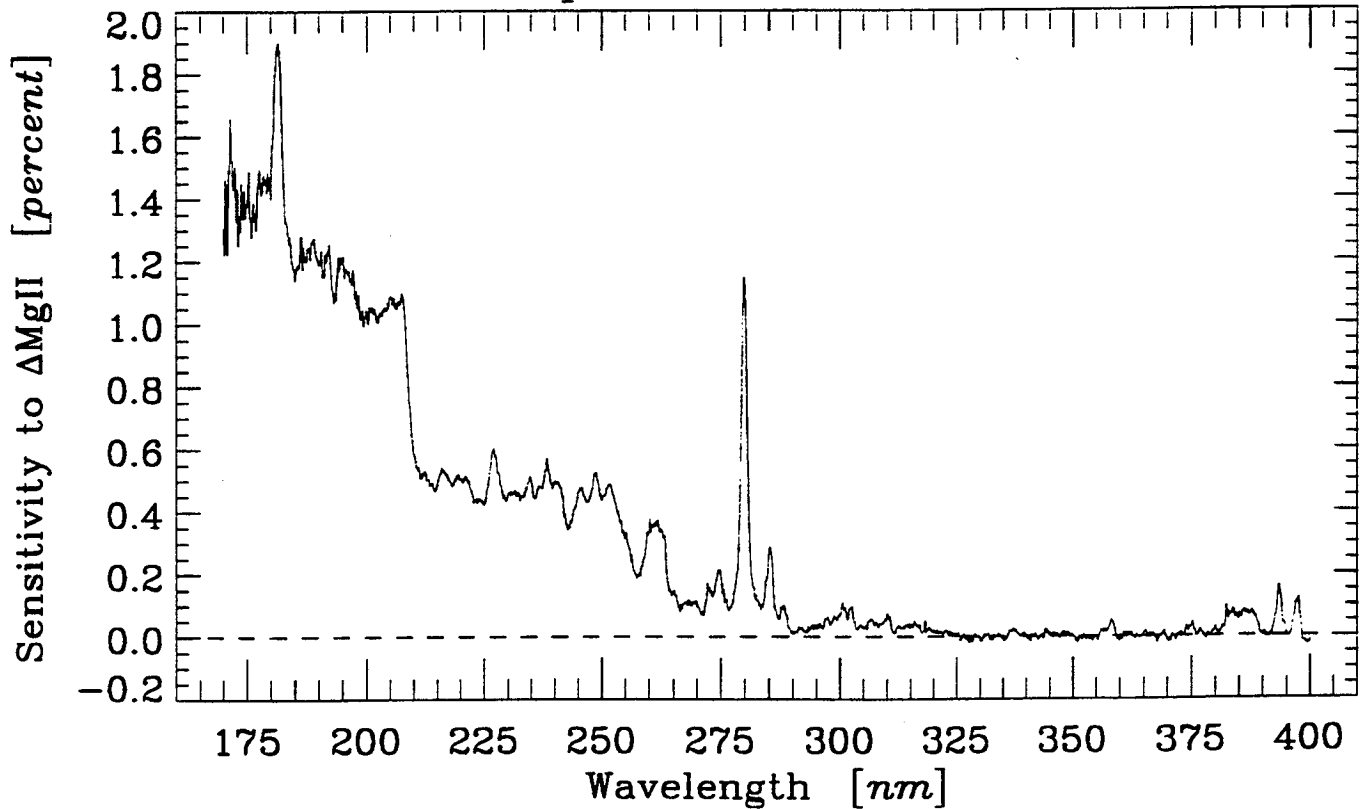
PERIODOGRAM for 380-390 nm Data
Time Interval = 1991/260 to 1994/289



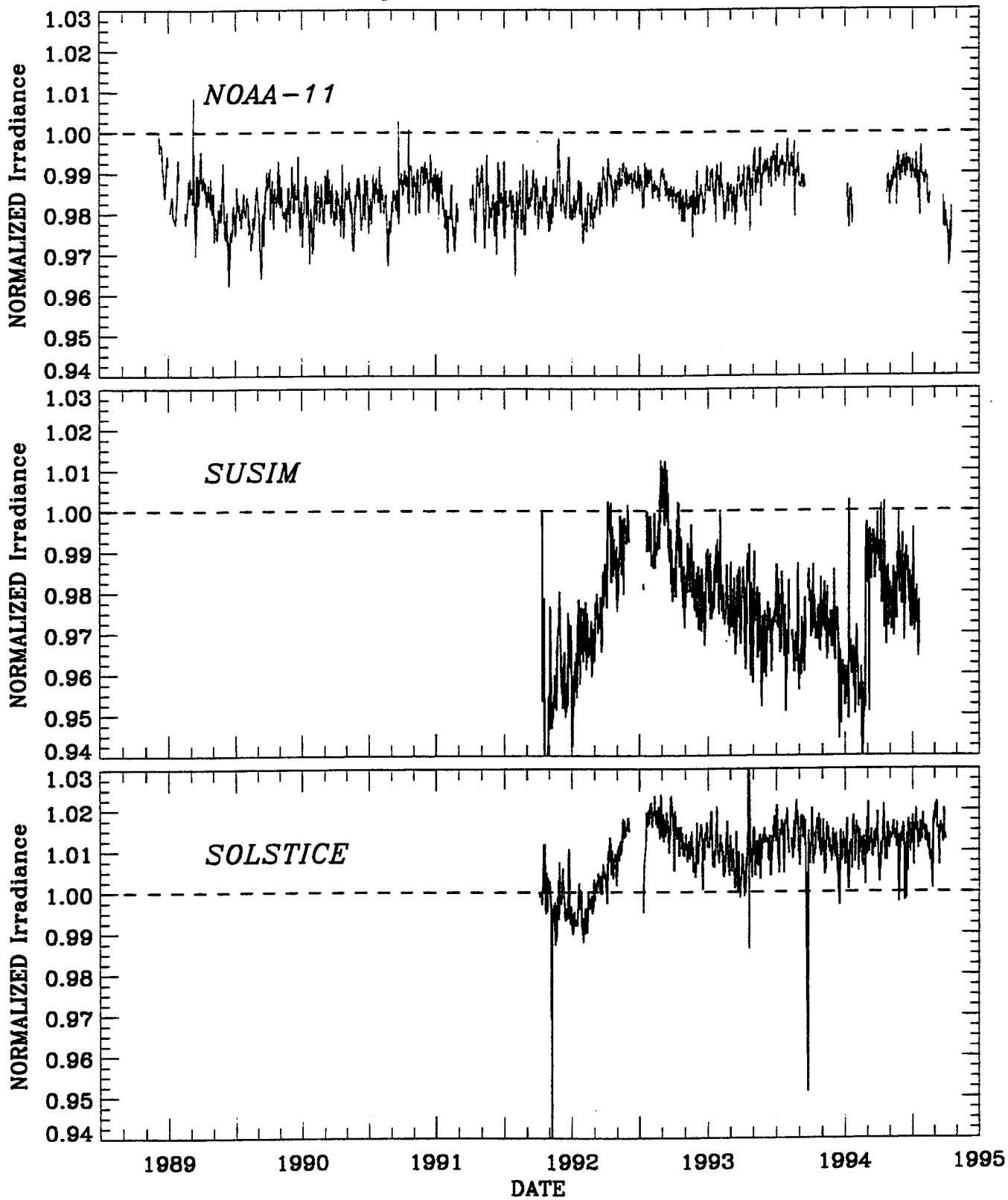
NOAA-11 CLASSICAL DISCRETE Mg II Index



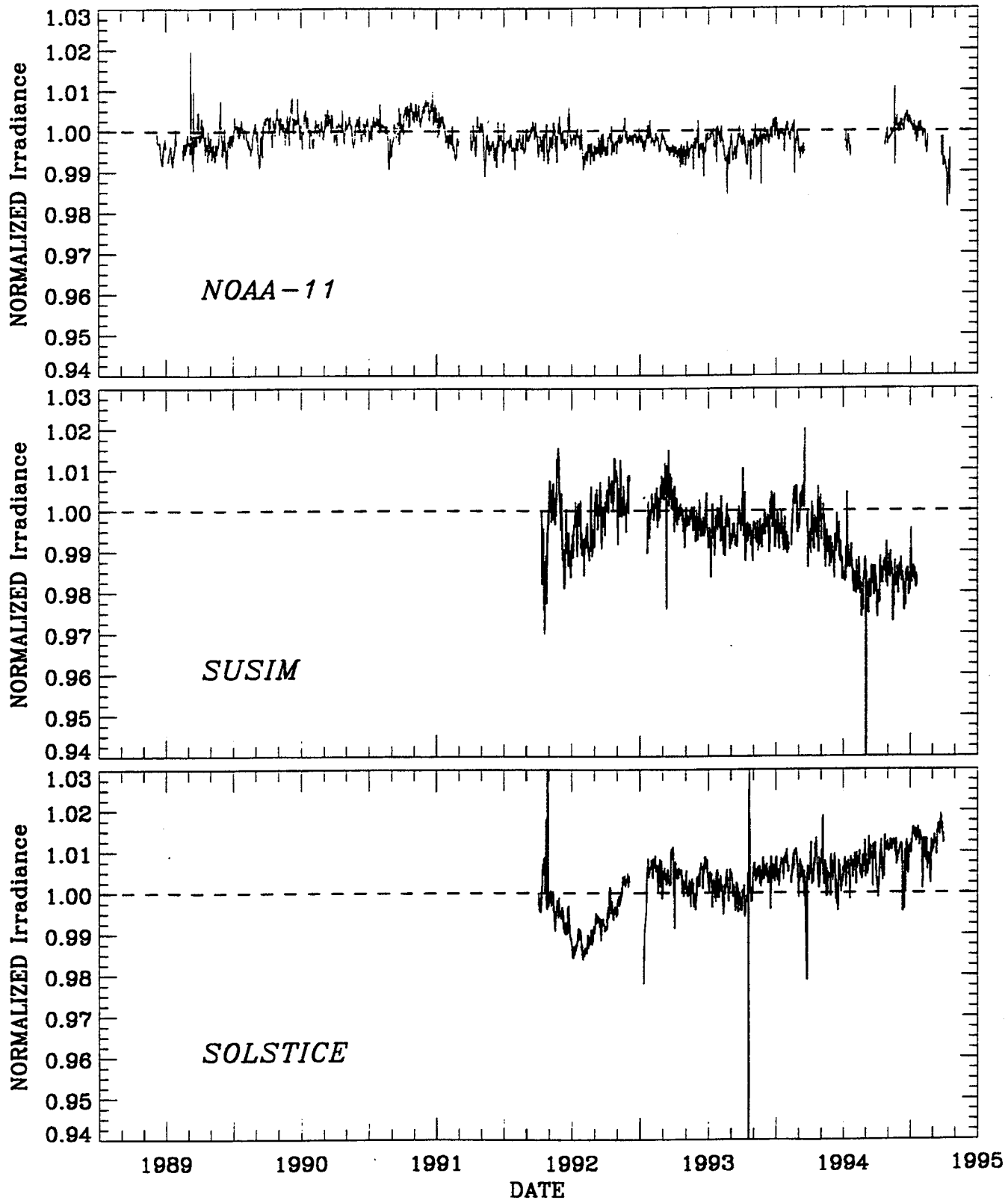
Composite Scale Factors



Irradiance Data at 200-210 nm
Corrected for ESTIMATED SOLAR CHANGE



Irradiance Data at 240–250 nm
Corrected for ESTIMATED SOLAR CHANGE



- ▶ NOAA-11 SBUV/2 solar irradiance data for December 1988 - October 1994 have been corrected for long-term instrument sensitivity changes using SSBUV comparisons.
- ▶ Residual long-term errors estimated to be approximately 1-3%. Results are comparable to UARS SUSIM, UARS SOLSTICE.
- ▶ Observed solar activity for maximum and decline of Cycle 22 consistent with Mg II index data.
- ▶ **NOAA-11 spectral irradiance data (1 nm average) will be available in early 1997. See signup sheet and/or authors if interested.** Full instrument sampling product ($\Delta \lambda = 0.15$ nm) also available on request.

CONCLUSIONS