Solar extreme ultraviolet irradiance: Present, past, and future

J. L. Lean,1 T. N. Woods,2 F. G. Eparvier,2 R. R. Meier,3 D. J. Strickland,4 J. T. Correira,4 and J. S. Evans4

Received 2 July 2010; revised 8 September 2010; accepted 12 October 2010; published 20 January 2011.

New models of solar extreme ultraviolet (EUV) irradiance variability are constructed in 1 nm bins from 0 to 120 nm using multiple regression of the Mg II and F10.7 solar activity indices with irradiance observations made during the descending phase of cycle 23. The models have been used to reconstruct EUV spectra daily since 1950, annually since 1610, to forecast daily EUV irradiance and to estimate future levels in cycle 24. A two-component model developed by scaling the observed rotational modulation of the two solar indices underestimates the solar cycle changes that the Solar EUV Experiment (SEE) reports at wavelengths shorter than 40 nm and longer than 80 nm. A three-component model implemented by including an additional term derived from the smoothed Mg II index better reproduces the measurements at all wavelengths. The three-component model is consistent with variations in the EUV energy from 0 to 45 nm that produces the far ultraviolet (FUV) terrestrial dayglow observed by the Global Ultraviolet Imager (GUVI). However, the spectral structure of this third component is complex, and its origin is uncertain. Analogous two- and three-component models are also developed with absolute scales determined by the NRLEUV2 spectrum of the quiet Sun rather than by the SEE average spectrum. Assessment of the EUV absolute spectrum and variability of the four different models indicate that during solar cycle 23, the EUV irradiance (0 to 120 nm) increased 100 ± 30%, from 2.9 ± 0.2 to 5.8 ± 0.9 mWm−2, and may have been as low as 1.9 ± 0.5 mWm−2 during the 17th-century Maunder Minimum. Near the peak of upcoming solar cycle 24, EUV irradiance is expected to increase 40% to 80% above the 2008 minimum values.


1. Introduction

Prior to the launch of the Solar EUV Experiment (SEE) on the Thermospheric Ionospheric Mesospheric Electrodynamic General Circulation Model (TIMEGCM) [Solomon and Qian, 2005], revised empirical models [Ennert et al., 2008], and assimilative capabilities such as the Global Assimilative Ionospheric Model [Schunk et al., 2004] all require solar EUV irradiance inputs.

Prior to the launch of the Solar EUV Experiment (SEE) on the Thermospheric Ionospheric Mesospheric Energy and Dynamics (TIMED) spacecraft in 2002 [Woods et al., 2005], observations of solar EUV irradiance were infrequent and suffered from significant, poorly quantified instrumental effects. This motivated the development of models to elucidate the causes of the variations, isolate instrumental effects, and specify the variations during times when observations are lacking. The initial empirical solar EUV spectral irradiance variability models were developed primarily from 5 years (1976–1980) of Atmospheric Explorer-E (AE-E) data [Hinteregger et al., 1981] with subsequent increases in the shortest wavelength fluxes to account for independently observed photoelectron fluxes [Richards et al., 1994]. For practical applications, these models use parameterizations of the 10.7-cm radio flux, F10.7.

With the goal of utilizing the physical properties of the solar atmosphere to better understand and model EUV spectral irradiance variability, Warren et al. [2001] developed the NRLEUV model for optically thin lines by constructing differential emission measures from radiance observations made...
by the Harvard College Observatory Spectroheliometer on Skylab. Optically thick lines and continua were modeled using directly observed (by Skylab) contrast factors. Although formulated using \textit{Ca II K} chromospheric and \textit{Yohkoh} coronal images to classify quiet, active, and coronal hole regions during the descending phase of solar cycle 22, NRLEUV is implemented with the \textit{Mg II} and \textit{F}_{10.7} proxies for, respectively, chromospheric emissions and continua (\(T \leq 0.8 \times 10^{6} \text{K}\)) and coronal emissions (\(T > 0.8 \times 10^{6} \text{K}\)). Comparisons of NRLEUV with other models, as well as with EUV irradiance data made prior to the SEE observations, indicated that the absolute levels and solar cycle variability of the EUV irradiance were uncertain by a factor of 2 [Warren et al., 2001; Lean et al., 2003].

[5] SEE observations provide a new, calibrated database of solar EUV irradiance variations during the descending phase of solar cycle 23 and the current solar cycle minimum. Absolute uncertainties are estimated to be 10\%–20\% and long-term repeatability (precision) a few percent per year. The data have been used to constrain six solar proxies (\textit{Mg II}, \textit{F}_{10.7}, 0–4, 30.5, 121.5, and 35.5 nm irradiances) of the seven used in the Flare Irradiance Spectral Model (FISM) [Chamberlin et al., 2009] and to construct a high-resolution version of EUVAC (HEUVC) based on \textit{F}_{10.7} [Richards et al., 2006]. SEE data are also the basis for the recent assertion [Amblard et al., 2008] that the solar EUV irradiance at any time is better represented not as the disk-integrated effect of magnetic features (as in NRLEUV) but simply by the superposition of three elementary spectra, each representing different layers of the solar atmosphere (nominally an average Sun approximated by the \textit{Mg II} index, hot coronal lines represented by \textit{F}_{10.7}, and cool chromospheric emissions).

[6] We use the SEE database to parameterize 1 nm binned EUV irradiances with wavelength-dependent combinations of the \textit{Mg II} and \textit{F}_{10.7} indices to account for chromospheric and coronal variability, respectively. Differences between SEE observations, the new empirical models, and the NRLEUV model are characterized to investigate whether they are traceable to solar sources, instrumental influences, or model deficiencies, as well as to quantify the capability of proxy models to represent EUV irradiance variations on multiple time scales.

[7] For independent validation, we compare the SEE observations with the inferred solar EUV energy that is needed to produce the far ultraviolet (FUV) terrestrial daylight, obtained from near-simultaneous measurements made by the Global Ultraviolet Imager (GUVI), also on TIMED [Christensen et al., 2003]. Strickland et al. [1995] showed that this solar energy between 0 and 45 nm, termed \textit{Q}_{EUV}, closely tracks independent solar EUV irradiance observations made by the Solar EUV Monitor (SEM) on the Solar Heliospheric Observatory (SOHO) on time scales of flares and solar rotation [Strickland et al., 2004, 2007]. Furthermore, the incompatibility of \textit{Q}_{EUV} and large irradiance increases during flares present in the SEE version 8 data motivated revision of SEE observations. Flare irradiance increases are less in the current version 10 of the database than the initial increases reported by Woods et al. [2005].

[8] In addition to reconstructing solar EUV irradiances during recent activity cycles (since 1950), we use the new empirical models to consider, for the first time, plausible variations in the EUV spectrum since the 17th-century Maunder Minimum [Eddy, 1976]. We estimate the irradiance increase since this epoch of anomalously low solar activity by relating the \textit{Mg II} and \textit{F}_{10.7} indices to simulations of long-term accumulation in the total magnetic flux on the Sun’s surface made by a flux transport model [Wang et al., 2005; Lean et al., 2005]. Using recently developed auto-regressive algorithms that forecast short-term changes in both the \textit{Mg II} and \textit{F}_{10.7} indices [Lean et al., 2009], we also employ the models to forecast the entire EUV spectrum 1 to 10 days in advance. We further estimate the level of EUV irradiance to be expected in cycle 24.

[9] The new \textit{Mg II}- and \textit{F}_{10.7}-based empirical EUV models, which we designate the Naval Research Laboratory Solar Spectral Irradiance (NRLSSI) 2C and 3C models, augment analogous models of the ultraviolet, visible, and infrared spectrum variability. With this implementation, the NRLSSI model is now available across the entire electromagnetic spectrum from 1 to 100,000 nm [Lean and Woods, 2010], daily since 1950, monthly since 1882, and annually since 1610 at LISIRD (http://lasp.colorado.edu/LISIRD/) and SOLARIS (http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/input_data/index.html). The spectral irradiances are inputs to various terrestrial model simulations in support of the emerging next generation of coupled geospace models that require knowledge of the entire solar irradiance spectrum and as inputs for geophysical applications to anticipate environmental conditions that may affect a range of operational activities on time scales from days to weeks to the solar cycle [National Space Weather Strategic Plan, 1995; National Research Council, 2003].

2. Irradiance Variability Models

2.1. Observed Irradiance Variations

[10] During the descending phase of solar activity cycle 23, the total solar EUV irradiance (i.e., the integrated spectral irradiance from 0 to 120 nm) measured by SEE version 10.2 is shown in Figure 1 to decrease by a factor of about 2 (from >6 to 3 mW m\(^{-2}\)) synergistically with both the \textit{Mg II} and \textit{F}_{10.7} indices of solar activity, also shown in Figure 1. SEE measures the solar EUV spectral irradiance with two instruments that together cover the wavelength region from 0.1 to 194 nm. The EUV Grating Spectrograph (EGS) is a normal incidence Rowland circle spectrograph with a spectral range from 27 to 194 nm and 0.4-nm spectral resolution. The XUV Photometer System (XPS) includes nine silicon XUV photodiodes on which thin film filters are directly deposited. This XUV photometer set measures the solar irradiance from 0.1 to 27 nm, with each filter having a spectral passband of about 7 nm. Woods et al. [1998] provide a detailed description of the SEE instrument, Woods et al. [1999] and Eparvier et al. [2001] give some preflight calibrations, and Woods et al. [2005] describe the SEE irradiance algorithms and validation. SEE version 10.2 data are produced with a new XPS algorithm that models the solar XUV irradiance based on the Ti/C diodes (0–7 nm) using both TIMED and SORCE XPS observations [Woods et al., 2008].

[11] The \textit{Mg II} and \textit{F}_{10.7} time series in Figure 1 are widely used indices of solar activity that are available for much longer, and with superior calibration stability, than are the directly measured EUV irradiances. The primarily coronal \textit{F}_{10.7} radio flux, the longest and most stable extant irradiance

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record, is monitored routinely by the Dominion Radio Astrophysical Observatory [Tapping and Detracey, 1990] and is available since 1947 from the National Geophysical Data Center. The Mg II index of chromospheric variability, available since 1978, is constructed from space-based measurements of the solar spectrum in the vicinity of the Mg II h and k Fraunhofer lines near 285 and 288 nm. The index is the ratio of the emission in the core of the (unresolved) lines to that in the nearby photospheric continuum. Comparisons of the Mg II index with other chromospheric indices verify its utility as a stable indicator of the variability of the solar chromosphere [Lean et al., 2001] and a useful proxy for EUV irradiance variations [Viereck et al., 2001; Dudok de Wit et al., 2009]. Since the magnitude of the Mg II index depends on the spectral resolution of the measurements, different data sets must be carefully cross-calibrated during periods of overlap. In this way, Viereck et al. [2004] compiled a composite index from November 1978 to September 2003. We extend this record to the present by further cross-calibrating measurements of the Mg II index made by the Solar Stellar Intercomparison Experiment (SOLSTICE) on the Solar Radiation and Climate Experiment (SORCE) mission [Snow et al., 2005].

2.2. Empirical Parameterizations

[12] Solar EUV spectral irradiance correlates highly with both the Mg II and $F_{10.7}$ indices. The correlation coefficients of total EUV irradiance (0–120 nm) with the Mg II and $F_{10.7}$ time series in Figure 1 are, respectively, 0.98 and 0.97 for 2820 common daily values from the beginning of 2002 to the end of 2009. The wavelength dependence of the correlation of irradiance and proxy variations arising from ~27 day modulation imposed by solar rotation (i.e., the variations in Figure 1 after removing the longer-term solar cycle) is shown in Figure 2, which illustrates that Mg II is a better indicator of EUV irradiance variations than is $F_{10.7}$ at all wavelengths longer than ~27 nm. Only for variations in the shortest wavelength (primarily coronal) emissions that occur at temperatures in excess of $10^6$ K is $F_{10.7}$ superior to Mg II. Since the time series are detrended (with 81 day running means) prior to calculating their correlation, the coefficients in Figure 2 reflect reliable solar-driven associations between the EUV irradiances and the proxies; any instrumental trends that may contaminate the longer-term, solar cycle observations are much less likely to influence rotationally modulated changes on time scales of days to months.

[13] A two-component (2C) model of the observed EUV irradiance variations is constructed by parameterizing the rotationally modulated variations in each 1 nm binned irradiance time series in terms of the equivalent variations in Mg II and $F_{10.7}$. The coefficients that relate the irradiance and indices are determined from multiple linear regression of the detrended time series normalized to their mean values (analogous to the approach that Lean et al. [1997] utilized to model the UV spectrum). Specifically, a detrended, normalized time series, $T(t)^{DET}$, is obtained from an observed
time series, $T(t)$, by subtracting the (centered) 81 day running mean, $T(t)^{81}$, and then dividing by $T^{3V}$, the average value over the entire time interval (2002 to 2009), i.e.,

$$T(t)^{DET} = \frac{T(t) - T(t)^{81}}{T^{3V}}.$$  

(1)

The relationship of the detrended, normalized irradiance at wavelength $\lambda$ and time $t$ to the two proxies is then

$$F(\lambda, t)^{DET} = a(\lambda) + b(\lambda) Mg(t)^{DET} + c(\lambda) F_{10.7}(t)^{DET},$$  

(2)

where $a(\lambda), b(\lambda)$, and $c(\lambda)$ are linear regression coefficients. The solar EUV irradiance variations in each 1 nm bin due just to solar rotational modulation, $F(\lambda, t) - F(\lambda, t)^{81}$, is obtained directly from equations (1) and (2) as follows:

$$F(\lambda, t) - F(\lambda, t)^{81} = F(\lambda)^{4V} \left[ a(\lambda) + b(\lambda) \frac{Mg(t) - Mg(t)^{81}}{Mg^{4V}} + c(\lambda) \frac{F_{10.7}(t) - F_{10.7}(t)^{81}}{F_{10.7}^{4V}} \right],$$  

(3)

with the absolute scale of the modeled, rotationally modulated spectral irradiance specified by the average spectral irradiance over the entire data set (i.e., $F(\lambda)^{4V}$). To reconstruct the EUV irradiance variations arising from the solar cycle as well as from solar rotation, we replace the 81 day running mean time series in equation (3) with the time series average value, so that

$$F(\lambda, t) = F(\lambda)^{4V} \left[ a(\lambda) + b(\lambda) \frac{Mg(t) - Mg^{4V}}{Mg^{4V}} + c(\lambda) \left( \frac{F_{10.7}(t) - F_{10.7}^{4V}}{F_{10.7}^{4V}} \right) \right] + F(\lambda)^{4V}.$$  

(4)

In this way, the solar cycle changes in the two proxies determine the solar cycle changes in the EUV irradiance on the basis of the linear associations of their simultaneous rotational modulation.

[14] The 2C model underestimates the observed solar cycle irradiance changes in the shortest (0–40 nm) and longest (80–120 nm) EUV spectral regions, either because it neglects additional solar variability sources or because of undetected instrumental drifts in the SEE observations (or both). This is evident in Figure 3a, where 1 nm bins of the SEE spectra (for all days of the TIMED mission) have wider spread than 1 nm bins of the 2C model spectra, and in Figures 4a, 4b, and 4c, which compare time series of the SEE and modeled EUV irradiances in three broadband. Table 1 lists the observed and modeled irradiance values in these bands near the solar cycle maximum (15–28 February 2002) and minimum (15–28 August 2008) epochs, with the times indicated by the vertical lines in Figure 4. Comparison of the wavelength dependence of the solar cycle variations of SEE data and the 2C model in 1 nm bins in Figure 5 again demonstrates the smaller solar cycle changes in the 2C model than are observed.

[15] To better replicate the SEE data, we derive a three-component (3C) empirical model, retaining the reported long-term trend in the SEE irradiances and adding a term based on the smoothed $Mg II$ index. This third term allows for additional trends in SEE irradiances not accounted for by the rotational (short-term) parameterizations of the daily indices. In the 3C model, the solar EUV irradiance is calculated as follows:

$$\frac{F(\lambda, t) - F(\lambda)^{4V}}{F(\lambda)^{4V}} = d(\lambda) + e(\lambda) \frac{Mg(t) - Mg^{4V}}{Mg^{4V}} + f(\lambda) \frac{F_{10.7}(t) - F_{10.7}^{4V}}{F_{10.7}^{4V}} + g(\lambda) \frac{Mg(t)^{81} - Mg^{4V}}{Mg^{4V}},$$  

(5)

where the coefficients $d(\lambda), e(\lambda), f(\lambda)$, and $g(\lambda)$ are determined using multiple regression.

[16] The 3C model, like the 2C model, reproduces the observed short-term EUV irradiance variations with high fidelity, as illustrated in three broadband in Figures 6a, 6b, and 6c, and by the excellent agreement of the observed and modeled wavelength-dependent rotationally modulated.
irradiance changes compared in Figure 7a. Amplitudes of rotational modulation were determined by demodulating each 1 nm binned time series at a period centered on 27 days [Bloomfield, 1976]. The maximum (peak-to-valley) rotational modulation amplitudes in the TIMED epoch, shown in Figure 7a, occurred in October 2003, when both the observations and the 2C and 3C models indicated changes of the order of 30% to 40% at longer EUV wavelengths and in the range 30% to >100% for EUV emissions at the shortest wavelengths.

[17] The scaling coefficients for the daily Mg II index are almost identical in the 2C and 3C models. This is evident in Figure 7b, which compares the wavelength dependence of the $b(\lambda)$ coefficients in equation (4) (used to construct the 2C model) and the $e(\lambda)$ coefficients in equation (5) (used to construct the 3C model). Although, as Figure 5 shows, the 3C model reproduces the solar cycle changes that SEE observes, the wavelength dependence of the additional (third) component (the 81 day smoothed Mg II index), shown in Figure 7c (the $g(\lambda)$ coefficient in equation (5)), differs distinctly from the wavelength dependence of the daily Mg II component in Figure 7b. This third component reflects the extent to which the relative variations in observed irradiance differ from those of the proxies. It contributes minimally to variations in the spectral region from 40 to 80 nm (the long-term scaling coefficient is ~0 in Figure 7c), is largest for wavelengths less than 35 nm (specifically at 28–29 nm and 33–34 nm), and is also nonzero at wavelengths longer than 80 nm. For completeness, Figure 7d shows the wavelength dependence of the $F_{10.7}$ scaling coefficients ($c(\lambda)$ for the 2C model, equation (4), and $f(\lambda)$ for the 3C model, equation (5)), confirming the results in Figure 2 that this index is more applicable than the Mg II index for representing EUV irradiance variations only at the very shortest wavelengths.

### 2.3. Comparisons With NRLEUV

[18] Solar spectra calculated by the NRLEUV model (in 1 nm bins) for every day of the TIMED mission are shown in Figure 3b to differ in complex ways from SEE spectra. The time series of EUV irradiance variations in three broadbands in Figures 4d, 4e, 4f, and Figures 6d, 6e, and 6f illustrate wavelength-dependent differences in absolute scale, temporal structure, solar cycle amplitude, and rotational modulation. Particularly apparent in Figure 3b are systematically lower NRLEUV irradiances near the beginning of each of the four EUV emission continua (C I at 110.12 nm, H I at 91.18 nm, He I at 60.43 nm, and He II at 22.79 nm), with the result that NRLEUV estimates steeper continua slopes than SEE observes. At wavelengths longer than 60 nm, the variability of NRLEUV spectra during both the solar cycle (Figure 5) and solar rotation (Figure 7) is systematically smaller than SEE observes. This is evidenced by the more narrow spread of the NRLEUV daily spectra (Figure 3b) in this wavelength region.

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**Figure 3.** All daily solar EUV spectra in 1 nm bins measured by SEE are shown and estimated by (a) the NRLSSI 2C proxy model and (b) the NRLEUV model during the TIMED mission from 2002 to 2009.
The likely reason for SEE’s larger fluxes than NRLEUV at wavelengths near the beginning of EUV emission continua, where the EUV emission is weakest, is instrumental scattered light. A higher spectral resolution measurement on 14 April 2008 made with a rocket-borne prototype of the Extreme Ultraviolet Variability Experiment (EVE) on the Solar Dynamics Observatory (SDO) [Woods et al., 2010] shows lower irradiance values than SEE, but still higher than NRLEUV levels, in the valleys of the EUV spectrum [Chamberlin et al., 2009]. SDO EVE spectra further suggest that scattered light in TIMED SEE observations is larger than expected, especially in the 27 to 37 nm range. Differences between the SEE and NRLEUV absolute irradiance scales are a consequence of instrumental calibration offsets. Whereas SEE measurements are traceable to the synchrotron at the National Institute of Standards and Technology (NIST), the NRLEUV embodies EUV spectra measured by the Harvard College Observatory Spectroheliometer on Skylab [Warren et al., 1998a, 1998b]. The spectral irradiance of the quiet Sun in NRLEUV is generally consistent with that of a newer version of the model, NRLEUV2, obtained from high spectral resolution measurements made by the Coronal Diagnostic Spectrometer (CDS) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER) on the Solar and Heliospheric Observatory (SOHO) [Warren, 2005]. Table 1 lists the NRLEUV2 irradiance of the quiet Sun for the total EUV irradiance and in three broadbands, and Figure 8 compares the NRLEUV and NRLEUV2 quiet Sun spectra with SEE observations during solar minimum, determined as the average of spectra between 15 and 28 August 2008.

Significant differences in solar EUV irradiance variability observed by SEE and modeled by NRLEUV arise from model deficiencies. At times other than solar minimum, the NRLEUV model estimates the EUV irradiance by adjusting the adopted quiet solar spectrum for the contributions from active regions, network, and coronal holes [Warren et al., 2001], whose parameterizations in the model therefore determine irradiance variability. NRLEUV systematically underestimates (by as much as a factor of 3) rotationally modulated EUV irradiance changes at most wavelengths longer than ~30 nm, especially in transition region emission.

Figure 4. Compared with the SEE observations in three broad wavelength bands made throughout the TIMED mission are concurrent changes estimated by the NRLSSI 2C model at (a) 0 to 40 nm, (b) 40 to 80 nm, and (c) 80 to 120 nm, and by the NRLEUV model at (d) 0 to 40 nm, (e) 40 to 80 nm, and (f) 80 to 120 nm. The vertical shaded lines indicate the times of high and lower solar activity used to estimate solar cycle changes in Figure 5 and Table 1.
lines and continua [Warren, 2006]. This is apparent in the comparison of the broadband time series in Figures 6e and 6f and in the comparison of the wavelength dependences of the rotational modulation in Figure 7a. Except for a few selected 1 nm emission bands, NRLEUV also systematically underestimates the solar cycle changes that SEE observes at all wavelengths longer than \(\sim 30\) nm (Figure 5). Differences are especially pronounced in the longer wavelength EUV region from 80 to 120 nm, where NRLEUV underestimates both the rotational modulation and the solar cycle fractional changes by about a factor of 2.

The rotational modulation comparison in Figure 7a suggests that improvements are needed in the NRLEUV model, since the differences are unlikely instrumental in origin. Model deficiencies are especially evident in the EUV continua and are likely associated with the active region contrasts and/or areas. The emissions of continua and optically thick lines in NRLEUV are not computed using differential emission measures, but inferred (with large uncertainties) directly from Skylab data. Continua slopes are assumed to be the same in active regions and the quiet Sun. Increasing the contrast of active regions in NRLEUV would improve significantly the agreement of NRLEUV and SEE. For example, a factor of 2 larger contrast for He I 58.4 nm active region emission would increase NRLEUV’s 11% rotational modulation to better match SEE’s observed 22% modulation at this wavelength. A factor of 3 larger active region contrast is needed for NRLEUV to match the observed C I and H I continua variations.

### 2.4. Comparisons With the Terrestrial Dayglow

[23] The terrestrial dayglow at FUV wavelengths has an unambiguous association with solar EUV irradiance at wavelengths less than 45 nm. When solar photons with energies in excess of \(\sim 27\) eV (wavelengths <45 nm) ionize gases in the upper atmosphere, the emitted photoelectrons have sufficient energy to produce dayglow, such as the OI 135.6 nm and N2 Lyman-Birge-Hopfield (LBH) emissions [Meier, 1991]. Fluctuations in the photoelectron-excited FUV dayglow therefore afford validation of directly measured EUV irradiance variations. The FUV dayglow, which extends down to \(\sim 100\) km in the Earth’s atmosphere, can be observed by satellite instruments against Earth’s disk, since pure absorption (extinction) by O2 attenuates the emission arising from below that altitude. Strickland et al. [1995] describe the utilization of OI 135.6 nm and LBH dayglow observations to specify \(Q_{EUV}\), the term they used to designate the solar EUV irradiance from 0–45 nm that produces the terrestrial FUV dayglow, as well as \(\Sigma O/N_2\) (the vertical column density ratio referenced to a fixed column value for N2).

[24] The GUVI instrument on TIMED images both limb and disk terrestrial FUV dayglow. Disk imaging measures the vertical column emission, whereas limb imaging measures the altitude variation, allowing the derivation of thermospheric composition and temperature profiles [Meier and Picone, 1994]. Both disk and limb imaging retrieve the solar 0–45 nm EUV irradiance that is required to produce the measured magnitude of the dayglow. The limb retrieval is, in principle, independent of the retrieved compositional information. Furthermore, the disk and limb retrievals are themselves independent because qualitatively different algorithms are used to extract the 0–45 nm solar energy (albeit both GUVI algorithms are based on the AURIC code [Strickland et al., 1999]).

[25] Daily mean values of GUVI \(Q_{EUV}\) derived from terrestrial radiance measurements of the Earth’s disk, \(Q_{EUV}^{\text{disk}}\),
are compared in Figure 9a with SEE’s observations of solar EUV irradiance in the 0 to 45 nm band, $Q_{EUV}^{\text{SEE}}$. Orbital average values of $Q_{EUV}^{\text{disk}}$ and $Q_{EUV}^{\text{limb}}$ (derived from GUVI radiance measurements of the Earth’s limb) are compared with $Q_{EUV}^{\text{SEE}}$ in 2003 (moderate to high solar activity) in Figures 9b and 9c and in 2005 (moderate to low solar activity) in Figures 9d and 9e. Because the absolute scales of the three time series differ somewhat, the GUVI $Q_{EUV}$ values shown in Figure 9 have each been transformed by linear regression with $Q_{EUV}^{\text{SEE}}$. For 1975 common daily mean values of $Q_{EUV}^{\text{SEE}}$ and $Q_{EUV}^{\text{disk}}$ between 2002 and 2007, the average value of the 0–45 nm band energy according to SEE is 2.7 mW m$^{-2}$, higher by 17% than the average value of this energy inferred by the GUVI FUV disk observations whose corresponding average value is 2.3 mW m$^{-2}$. The average of $Q_{EUV}^{\text{SEE}}$ for the 366 common daily mean values of $Q_{EUV}^{\text{SEE}}$ and $Q_{EUV}^{\text{limb}}$ (version 10) is 2.6 mW m$^{-2}$, higher by 34% than the $Q_{EUV}^{\text{limb}}$ average value of 1.9 mW m$^{-2}$. [26] As expected, the GUVI $Q_{EUV}$ derived from both disk and limb observations closely track each other as well as the 0–45 nm irradiance that SEE observes. The correlations of SEE daily mean values with the disk and limb daily mean time series (Figure 9a) are 0.97 and 0.98, respectively. In agreement with the SEE data, both $Q_{EUV}^{\text{disk}}$ and $Q_{EUV}^{\text{limb}}$ indicate larger changes in the 0–45 nm EUV irradiance band during the descending phase of solar cycle 23 than is evident in the 2C model. However, large differences between SEE and GUVI are evident in Figure 9 during flares, when $Q_{EUV}^{\text{SEE}}$ increases significantly more (by factors of 2 to 3) than does $Q_{EUV}^{\text{disk}}$, primarily as a result of large SEE irradiance increases in the 0–12 nm range [Strickland et al., 2007]. Comparisons of orbital averages (Figures 9b, 9c, 9d, and 9e) on these very short time scales are only qualitative, since SEE makes one 3-minute observation per orbit, whereas GUVI $Q_{EUV}^{\text{disk}}$ are orbit averages (from derived values over tens of minutes). Note that this was not the case in the earlier analysis by Strickland et al. [2007], which compared the GUVI radiance with SEE observations at suborbital temporal resolution, finding excessive SEE (version 8) flare increases when compared to both the FUV dayglow and concomitant electron density increases.

[27] GUVI $Q_{EUV}$ values include both random and systematic uncertainties. Random uncertainty, based on counting

Table 1. Solar EUV Irradiance (in mW m$^{-2}$) in Four Broadbands, According to Observations and Models During Solar Maximum and Minimum Epochs and Estimated for the Maunder Minimum Using Long-Term Changes Simulated by Flux Transport Simulations$^a$

<table>
<thead>
<tr>
<th>Wavelength Band</th>
<th>Cycle 23 Maximum</th>
<th>Cycle 23 Minimum</th>
<th>Cycle 23 Maximum/Minimum</th>
<th>Maunner Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–120 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEE: NIST scale</td>
<td>6.8 ± 1</td>
<td>2.8 ± 0.8</td>
<td>2.4 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>NRLEUV2: SOHO scale</td>
<td>2.8 ± 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2C model: SEE scale</td>
<td>5.6</td>
<td>3.2</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>3C model: SEE scale</td>
<td>6.7</td>
<td>2.8</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>2C model: NRLEUV2 scale</td>
<td>4.6</td>
<td>2.8</td>
<td>1.6</td>
<td>2.2</td>
</tr>
<tr>
<td>3C model: NRLEUV2 scale</td>
<td>6.2</td>
<td>2.8</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Model average and 1σ uncertainty</td>
<td>5.8 ± 0.9</td>
<td>2.9 ± 0.2</td>
<td>2.0 ± 0.3</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>0–40 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEE: NIST scale</td>
<td>4.7 ± 0.9</td>
<td>1.7 ± 0.6</td>
<td>2.8 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>NRLEUV2: SOHO scale</td>
<td>1.4 ± 0.3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2C model: SEE scale</td>
<td>3.7</td>
<td>2.0</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>3C model: SEE scale</td>
<td>4.6</td>
<td>1.7</td>
<td>2.7</td>
<td>0.7</td>
</tr>
<tr>
<td>2C model: NRLEUV2 scale</td>
<td>2.5</td>
<td>1.4</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>3C model: NRLEUV2 scale</td>
<td>3.4</td>
<td>1.4</td>
<td>2.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Model average and 1σ uncertainty</td>
<td>3.6 ± 0.9</td>
<td>1.6 ± 0.3</td>
<td>2.2 ± 0.6</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>40–80 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEE: NIST scale</td>
<td>0.53 ± 0.05</td>
<td>0.35 ± 0.08</td>
<td>1.5 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>NRLEUV2: SOHO scale</td>
<td>0.40 ± 0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2C model: SEE scale</td>
<td>0.56</td>
<td>0.35</td>
<td>1.6</td>
<td>0.28</td>
</tr>
<tr>
<td>3C model: SEE scale</td>
<td>0.57</td>
<td>0.34</td>
<td>1.7</td>
<td>0.27</td>
</tr>
<tr>
<td>2C model: NRLEUV2 scale</td>
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<td>0.40</td>
<td>1.6</td>
<td>0.33</td>
</tr>
<tr>
<td>3C model: NRLEUV2 scale</td>
<td>0.64</td>
<td>0.40</td>
<td>1.6</td>
<td>0.33</td>
</tr>
<tr>
<td>Model average and 1σ uncertainty</td>
<td>0.60 ± 0.04</td>
<td>0.38 ± 0.03</td>
<td>1.6 ± 0.2</td>
<td>0.3 ± 0.03</td>
</tr>
<tr>
<td>80–120 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEE: NIST scale</td>
<td>1.5 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>NRLEUV2: SOHO scale</td>
<td>1.0 ± 0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2C model: SEE scale</td>
<td>1.4</td>
<td>0.9</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>3C model: SEE scale</td>
<td>1.6</td>
<td>0.8</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2C model: NRLEUV2 scale</td>
<td>1.5</td>
<td>1.0</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>3C model: NRLEUV2 scale</td>
<td>2.1</td>
<td>1.0</td>
<td>2.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Model average and 1σ uncertainty</td>
<td>1.6 ± 0.3</td>
<td>0.9 ± 0.1</td>
<td>1.8 ± 0.4</td>
<td>0.7 ± 0.1</td>
</tr>
</tbody>
</table>

$^a$The uncertainties indicated for the SEE observations near cycle 23 maximum (15–28 February 2002) are ±15%, ±20%, ±10%, and ±10% for the 0–120, 0–40, 40–80, and 80–120 nm bands, respectively. During solar minimum (15–28 August 2008), 6.5 years later, the SEE observations have additional uncertainty of ±13% (assuming precision of 2% per year). Uncertainties of ±20% are indicated for the NRLEUV2 quiet Sun spectrum.
Statistics, is of the order of 4% to 7% (for high to low solar activity). Systematic uncertainty relates to the absolute radiance measured by the OI 135.6 nm and N₂ LBH channels, for which the principal systematic contributors are the GUVI absolute calibration (∼15%) and the photoelectron impact excitation cross sections for O (∼70%) and N₂ (∼25%). In both the limb and disk retrievals, the photoelectron impact excitation cross section used in the core algorithms is a scaled version of that measured by Ajello and Shemansky [1985]. A new measurement of this cross section by Young et al. [2010] yields a value that is different in shape and magnitude (by nearly a factor of 2). A preliminary reanalysis of a limited set of GUVI data appears to eliminate the 34% and 17% biases, so that the average values of the GUVI limb and disk retrievals of $Q_{\text{EUV}}$ agree with each other and with the SEE direct measurements of $Q_{\text{EUV}}$ to within a few percentage points, well within the uncertainties in the absolute calibrations. Using the new N₂ value results in a lower overall systematic uncertainty of the order of 30% for $Q_{\text{EUV}}^{\text{lmb}}$.

The long-term relative variations in GUVI $Q_{\text{EUV}}$ are thought to have stabilities of the order of 10%, comparable to the directly measured SEE irradiances. The main sources of long-term instabilities include drifts in the GUVI instrument calibration and assumptions of time invariance in the algorithms. GUVI stellar measurements throughout the TIMED mission suggest that the GUVI calibration has remained stable throughout the mission. The $Q_{\text{EUV}}^{\text{sec}}$ requires a lookup table constructed from multiple simulations of the FUV column emission rates made with the AURIC model using a constant input solar spectrum [Strickland et al., 1999]. The lookup table relates columnar emission with solar zenith angle and scaling factors for the atmospheric constituent densities and absorption cross sections.

Errors in long-term relative $Q_{\text{EUV}}$ variations from the choice of spectral shape associated with the lookup table are also expected to be small. The $Q_{\text{EUV}}^{\text{sec}}$ sensitivity to the solar EUV spectrum adopted for the AURIC calculations was investigated by producing three additional lookup tables for three daily averaged SEE spectra (only spectral shape is relevant here) corresponding to a wide range of $F_{10.7}$ values (of 71, 138, and 232). Since AURIC requires input solar spectra at 0.1 nm resolution, the higher-resolution NRLEUV model was used to specify the spectral irradiance within each 1 nm bin, which was then normalized to the 1 nm SEE.

Figure 6. Compared with the SEE observations in three broad wavelength bands during the first 180 days of 2003 are the concurrent changes estimated by the NRLSSI model at (a) 0 to 40 nm, (b) 40 to 80 nm, and (c) 80 to 120 nm, and by the NRLEUV model at (d) 0 to 40 nm, (e) 40 to 80 nm, and (f) 80 to 120 nm.
spectra. Differences in $Q_{EUV}$ among the tables were of the order of ∼5% or less.

3. Irradiance Changes Since the Maunder Minimum

[30] Solar EUV irradiance and solar indices vary as solar activity evolves through multiple 11-year cycles and on longer time scales. Emerging bipolar magnetic flux regions and transport processes alter the distribution of magnetic flux on the Sun’s surface, thus the relative proportion of bright active features that alter disk-integrated fluxes. Shown in Figure 10a are daily values of total EUV irradiance since 1950, reconstructed by inputting past changes in the $Mg$ II and $F_{10.7}$ indices to the 2C and 3C models. Daily values of $F_{10.7}$ are available from direct observations since 1950, but only since 1978 for the $Mg$ II index. We estimate the $Mg$ II index since 1950 from its close association with the $Ca$ II K index, whose daily variations since 1950 were estimated using the $Ca$ II plage index [Lean et al., 2001]. According to both the 2C and 3C models, EUV irradiance levels peaked in 1957–1958. Levels are comparable during all six solar minima since 1950, including during the prolonged 2008 minimum.
The scenario that produces the least (negligible) EUV irradiance decrease during the Maunder Minimum assumes that the solar activity cycle is the only source of long-term irradiance variability. The estimates of solar EUV irradiance cycles during the past 4 centuries, shown by the green curves in Figure 10, are determined in Figure 10b by the 2C model and in Figure 10c by the 3C model. The Mg II and F10.7 indices needed to reconstruct this scenario are obtained from direct linear regression of the indices with sunspot numbers (available since 1610).

Superimposing the solar cycle variations on a varying background produces a larger EUV irradiance decrease in the Maunder Minimum. In one approach, indicated by the black lines in Figures 10b and 10c, EUV irradiance levels during the Maunder Minimum are from 25% (2C model) to 48% (3C model) lower than in current minima. In this case, the magnitude of plausible background changes is estimated from simulations of the transport of magnetic flux on the solar surface since 1710. Using sunspots to indicate the strength and number of emerging bipolar regions, Wang et al. [2005] found a small accumulation of total magnetic flux from the end of the Maunder Minimum to the present, which implies a corresponding long-term increase in bright active regions and consequently in the Sun’s EUV emission. The magnitude of the simulated long-term total magnetic flux accumulation is about one third of the increase from the minimum to the maximum of recent solar cycles. Assuming that in the Maunder Minimum the values of the Mg II and F10.7 indices are correspondingly lower than their contemporary minimum, then \( M_{\text{g, min}} = 0.2576 \) and \( F_{10.7}^{\text{min}} = 2 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1} \). Annual mean values of the long-term secular irradiance component are assumed to track the relative changes in the 13-month smoothed sunspot number time series, following the approach of analogous historical reconstructions of solar irradiance variations at longer wavelengths [see Lean et al., 2005; Lean and Woods, 2010]. Table 1 lists EUV irradiance values during the Maunder Minimum according to the NRLSSI 2C and 3C models. Also listed are alternative values corresponding to the NRLEUV2 absolute scale.

In the event that coronal fluxes were negligible during the Maunder Minimum and the Mg II index was reduced accordingly (Figures 10b and 10c; purple curve, \( M_{\text{g, min}} = 0.2547 \) and \( F_{10.7}^{\text{min}} = 0 \)), the total EUV flux in the Maunder Minimum is estimated to be in the range of 36% (2C model) to 70% (3C model) below its current solar minimum value.
This latter scenario is compatible with data reported by Tapping et al. [2007], who suggested a somewhat larger Maunder Minimum decrease than Wang et al. [2005] by assuming interior solar structure changes. A scenario for even larger EUV irradiance reductions during the Maunder Minimum assumes the absence of chromospheric faculae, as suggested by variations in the Ca II K fluxes of sunlike stars [Lean et al., 1992], for which the corresponding EUV irradiance reduction (Figure 10, red curve, \( F_{10.7}^{\text{min}} = 0 \)) is in the range of 49% (2C model) to 100% (3C model).

4. Irradiance Forecasts

Estimates of future as well as past EUV irradiances are also possible using the 2C and 3C model parameterizations described in section 2.2. Because of the dominant role of solar EUV irradiance in establishing the dynamic,
chemical, and radiative state of the thermosphere and ionosphere, forecasting EUV irradiance changes on multiple time scales is an essential component of forecasting the space environment for space applications [National Research Council, 2003]. Using forecasts of the Mg II and F10.7 indices obtained from autoregressive procedures [Lean et al., 2009], we quantify the skill of forecasting short-term EUV irradiance variations from 1 to 10 days ahead. We also estimate EUV irradiances during solar cycle 24 using the U.S. National Weather Service (NWS) Space Weather Prediction Center (SWPC) forecasts of the strength of this impending cycle.

4.1. Short-Term Forecasts

The NWS SWPC issues forecasts of solar activity days to weeks ahead in terms of $F_{10.7}$. The forecasts have accuracies similar to those obtained using a third-order autoregressive algorithm [Lean et al., 2009], which we use to forecast both the Mg II and $F_{10.7}$ solar activity indices [Lean et al., 2009] as follows. An activity index, $I$, at some time, $t$ (days), is expressed in terms of its values at prior times, $t - \Delta t$, as follows:

$$I(t) - I_d = x_0 + x_1[I(t - \Delta t_1) - I_d] + x_2[I(t - \Delta t_2) - I_d] + x_3[I(t - \Delta t_3) - I_d],$$

where $x_i$ are coefficients determined from multiple linear regression of the time series at lags $\Delta t_i = 1, 4, $ and 23 days over a finite time period, called the “training interval.” The choice of the 3 $\Delta t$ lagged days is guided by the cross-correlation function of the activity indices and the EUV irradiance and the resultant forecast skill [see Lean et al., 2009].
Prior to the regression, the data, \( I(t) \), within the training interval are converted to zero-mean time series by subtracting \( I_d \), the average of the time series in that interval. The regression coefficients are determined in successive sliding (by 1 day) training intervals of 162 days (six solar rotations). Following the interval of the training period, the solar activity forecasts, \( I_F(t + f) \), are estimated for \( f = 1 \) to \( f = 10 \) days, using the regression coefficients determined in each training interval. The 1 day forecast, \( I_F(t + 1) \), of the solar activity index is determined directly from prior observations, \( I_O(t) \), by

\[
I_F(t + 1) = x_0 + x_1[I_O(t - \Delta t_1 + 1) - I_d] + x_2[I_O(t - \Delta t_2 + 1) - I_d] + x_3[I_O(t - \Delta t_3 + 1) - I_d] + I_d
\]

Forecasts for subsequent days are determined from a combination of prior observations, \( I_O(t - \Delta t_i + f) \) where \( f \leq \Delta t_i \), and forecasts, \( I_F(t - \Delta t_i + f) \) where \( f > \Delta t_i \). The 10 day forecast, for example, is

\[
I_F(t + 10) = x_0 + x_1[I_O(t - \Delta t_1 + 10) - I_d] + x_2[I_O(t - \Delta t_2 + 10) - I_d] + x_3[I_O(t - \Delta t_3 + 10) - I_d] + I_d
\]

We use equations (6), (7), and (8) to forecast the \( Mg \ II \) and \( F_{10.7} \) solar activity indices and then determine the corresponding EUV spectra using the NRLSSI model (the 2C and 3C models give essentially identical results for these short time scales). Figure 11 compares changes in total EUV irradiance (0–120 nm) observed by SEE, \( \Delta I_{\text{SEE}} \), with the changes forecast using NRLSSI, \( \Delta I_{\text{NRLSSI}} \) (with the forecast \( Mg \ II \) and \( F_{10.7} \) proxy inputs) for forecast days \( f = 1 \), 5, and 10 ahead of the time \( t = 0 \) of the forecast. The two time series compared are \( \Delta I_{\text{SEE}} = I_{\text{SEE}}(f) - I_{\text{SEE}}(0) \) and \( \Delta I_{\text{NRLSSI}} = I_{\text{NRLSSI}}(f) - I_{\text{NRLSSI}}(0) \).

A measure of the accuracy of the EUV irradiance forecast is the root mean square error, defined as follows by Wilks [1995]:

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (\Delta I_{\text{NRLSSI}}^k - \Delta I_{\text{SEE}}^k)^2}
\]

The accuracies of 1 to 10 day forecasts of the total EUV irradiance shown in Figure 12 are evaluated by averaging the daily forecast and observed deltas (shown in Figure 11) over the epoch of the TIMED mission, expressed as percentages of the average observed values. The average error of the EUV forecasts obtained with the third-order autoregressive model over the entire period from 2002 to 2009 increases from \( \sim 2\% \) for the 1 day forecast to \( \sim 8\% \) for the 10 day forecast.

Figure 11. Changes in total solar EUV irradiance, \( \Delta I \), observed by SEE are compared with forecast changes (a) 1 day, (b) 5 days, and (c) 10 days ahead of the day of the forecast. The forecasts were made by inputting to the NRLSSI model the \( Mg \ II \) and \( F_{10.7} \) solar activity indices forecast using third-order autoregressive algorithms with a training window of 162 days.
forecast. The autoregressive forecasts are more accurate than forecasts accruing from either persistence (in which the forecast for each day in the training interval equals that of the current day, i.e., $I_p(t)$) or from climatology (in which the forecast for each day equals the mean value in the training interval, i.e., $I_c$). Note that these accuracies refer to the change in the EUV irradiance; there is additional uncertainty associated with the irradiance absolute value.

4.2. Solar Cycle 24 Forecasts

[38] The NWS SWPC also forecasts levels of solar activity in upcoming solar cycles using a variety of techniques, including statistical tools, numerical models, and physical understanding [Hathaway, 2009]. The statistical tools harness the recurrence patterns of solar activity and solar rotation [Hathaway et al., 1999]; the numerical models describe this behavior; and the physical understanding utilizes knowledge of the dynamo, active region evolution and magnetic flux transport by rotation, diffusion, and meridional flow [Dikpati et al., 2006].

[39] Initial estimates (issued in April 2007) were ambiguous as to whether cycle 24 would be of higher or lower than average strength (D. Biesecker et al., http://www.swpc.noaa.gov/SolarCycle/SC24/PressRelease.html, 2007), but subsequent studies [Wang and Sheeley, 2009; Hathaway, 2009] have favored lower levels. In September 2009, the SWPC issued a revised forecast (http://www.swpc.noaa.gov/SolarCycle/SC24/index.html) for peak cycle 24 sunspot numbers of 90 ± 10 in mid-2013 (with equivalent $F_{10.7}$ of 141 ± 9 10$^{-22}$ W m$^{-2}$ Hz$^{-1}$). Correspondingly, the total EUV irradiance during cycle 24 shown in Figure 13 is expected to increase in the range of 40% (according to the 2C model) to 80% (according to the 3C model) from the 2008 minimum. These estimates are obtained by extrapolating the relationships with sunspot numbers of the total EUV irradiance calculated by the 2C and 3C models during past cycles using forecasts for sunspot numbers in cycle 24 issued by the SWPC.

5. Discussion

5.1. Absolute Irradiance Scale

[40] Absolute uncertainties in the SEE irradiance at launch (in 2002) are in the range of 10% to 20% (1σ [Woods et al., 2005]) as determined from extensive preflight calibration and characterization at the NIST. Subsequent in-flight calibrations with five NIST-calibrated instruments on rockets (at the times indicated in Figure 1) and regular solar measurements using alternative optical elements with a lower duty cycle provide long-term sensitivity tracking at a level of a few percent per year. Uncertainties in SEE observations during solar minimum (August 2008, 6.5 years later) are therefore of the order of 23% to 33%. Least certain are the observed spectral irradiances at wavelengths less than 27 nm.

Figure 13. Reconstructions of the total EUV irradiance (0–120 nm) using the 2C and 3C models are shown daily during solar cycle 23 and projected into cycle 24, using forecasts of future sunspot numbers. The shading reflects uncertainty in the sunspot forecast.
as a consequence of radiometric difficulties in calibrating the broadband observations by SEE’s XPS photometers, which necessitates the use of solar atmosphere models in the reduction algorithm [Woods et al., 2008].

[41] SEE solar minimum irradiances in individual 1 nm bins can differ from the NRLEUV quiet Sun spectrum by more than 100% (Figure 8), especially in bins in which the solar flux is low, presumably because of scattered light in the SEE EGS. Differences between SEE and NRLEUV2 irradiances in 1 nm bins exceed 50% (an approximate upper value for their combined uncertainties) in more than a quarter of the 119 bins between 0 and 120 nm. A recent rocket observation of solar spectral irradiance made by the newly developed, higher-resolution EUV Variability Experiment (EVE) [Woods et al., 2010] agrees better with NRLEUV2 [Chamberlin et al., 2009].

[42] On the basis of the comparisons of 10 nm wavelength bands during solar minimum (Figure 8), the SEE absolute scale is ~20% higher than that of NRLEUV2 in the 0–40 nm wavelength region, but lower by 13% in the 40–80 nm region and lower by 20% in the 80–120 nm region, differences that are within the combined uncertainties of the SEE and NRLEUV2 uncertainties (Table 1). GUVI Q_EUV derived using the newly measured Young et al. [2010] photoelectron impact excitation cross section is consistent with SEE Q_EUV (Figure 9). This suggests that the NRLEUV absolute scale is too low in the wavelength region 0–45 nm, with the caveat that the uncertainty in GUVI Q_EUV is likely large (30% to 70%).

5.2. Irradiance Variability Amplitudes

[43] EUV irradiance variations associated with the ~27 day solar rotation can be as large as 30% at wavelengths near 100 nm and 100% at wavelengths near 10 nm during high solar activity. SEE observations of the wavelength–dependent amplitudes and temporal structure of the rotational modulation (as shown in Figures 6 and 7) is considered to be well characterized, since instrumental changes are relatively modest over the time span of the Sun’s rotation, and since both the 2C and 3C models replicate the observations.

[44] Validating SEE’s observed solar cycle spectral irradiance variations that range from 100% (near λ = 100 nm) to >400% (near λ = 10 nm) is far more difficult. Direct validation is not available, because independent, overlapping EUV 1 nm spectral irradiance observations are lacking during the TIMED mission. If SEE’s measurement repeatability is 2% per year, then observed solar cycle amplitudes (from February 2002 to August 2008) in excess of ±13% are strictly real. In this case, solar cycle amplitudes (Table 1 and Figure 5) in the total EUV irradiance (0–120 nm) and in the 0–40, 40–80 and 80–120 nm bands are, respectively, 140 ± 30%, 180 ± 40%, 50 ± 20%, and 90 ± 30%.

[45] Instrumental effects related to various causes are known to affect the SEE irradiances, in addition to larger than expected scattered light. For example a scale adjustment in mid-September 2004 in SEE version 10 data, relative to version 9, accounts for abrupt degradation due to contamination when SEE was pointed downward during a safe mode of the TIMED spacecraft. If the differences between the SEE observations and the 2C model are entirely instrumental, the solar cycle amplitudes in the total EUV irradiance (0–120 nm) and the 0–40, 40–80, and 80–120 nm bands are 80%, 90%, 60%, and 60%, respectively. Indeed, the spectral shape of the third component’s strength (Figure 7c) is somewhat similar to that of the logarithmic solar spectrum (Figure 3), with the highest incident fluxes requiring the largest third component, consistent with the concept that the strongest solar emission produces the largest degradation of instrument sensitivities, some of which may be unaccounted for in the SEE observations. Note that adopting the scale of the NRLEUV2 spectrum (instead of that observed by SEE) alters the solar cycle amplitudes somewhat (to 60%, 80%, 60%, and 50%, respectively, for these four bands) because it redistributes the flux among different 1 nm wavelength bins, each of which varies by different amounts.

[46] The Q_EUV derived from the GUVI observations of the disk and limb dayglow provide independent validation of the larger solar cycle variations that SEE observes at wavelengths <45 nm and also provide further confirmation that 2C-type proxy models can underestimate solar cycle variations [Woods et al., 2000]. GUVI also employs in-flight sensitivity tracking by periodic observations of known stellar fluxes, with estimated uncertainty of 10%, and its observations compare well with simultaneous dayglow observations by the Special Sensor Ultraviolet Spectral Imager (SSUSI) on the DMSP F–16 satellite. Furthermore, the solar cycle changes in SEE spectral irradiances converted to photon units and summed into two broadband (0–45 nm and 28–34 nm) are generally consistent with independent measurements made by SEM on SOHO [Judge et al., 1998]. The assumed third component may therefore indicate a real source of solar variability in addition to the active regions and network contributions already encapsulated in the Mg II and F_10.7 indices, at least in this short wavelength spectral region.

[47] If such a source of solar EUV irradiance variability is indeed present, its wavelength dependence (Figure 7) is sufficiently complex to make reliable identification difficult. This postulated third component is present mainly in coronal emissions at EUV wavelengths less than 40 nm. In the region 40 to 80 nm, where the flux–weighted average temperature of the quiet Sun in 1 nm bins [obtained from Warren et al., 2001] is typical of transition region emissions (0.5 to 5 × 10^5 K), the additional third component that Woods et al. [2000] surmised is not evident. To add to the confusion, the larger solar cycle variations that SEE observes in cooler emissions (10^4 to 10^5 K) in the 80–120 nm range support the need for a third model component, although independent validation is unavailable from other observations.

[48] Conceptually, the spectral region 40–80 nm, which the 2C model adequately reproduces, may be dominated by Ambrold et al.’s [2008] first elementary spectrum, the region 0–40 nm, which is composed mainly of hotter coronal emissions and is modeled better by the 3C model, by the third elementary spectrum, and the 80–120 nm region by the second elementary spectrum of the cooler chromosphere. However, since the three elementary spectra are derived directly from SEE observations, the extent to which instrumental effects may have (inadvertently) contributed to this designation is unclear.

[49] Taking into account the lack of direct validation and incomplete understanding that precludes unequivocal differentiation among the 2C and 3C models and the SEE and NRLEUV2 absolute scales, estimates of solar cycle amplitudes and their uncertainties are obtained by averaging all
four models. In this case (Table 1), solar cycle amplitudes of
the 0–120, 0–40, 40–80, and 80–120 nm bands are, respec-
tively, 100 ± 30%, 120 ± 60%, 60 ± 20%, and 80 ± 40%, where
the uncertainties are the 1σ standard deviations of the four
models.

6. Summary

[50] The Mg II and F10.7 solar activity indices are used to
reconstruct daily solar EUV irradiance changes during the
past five solar cycles and annual changes since the Maunder
Minimum, as well as to forecast future changes, using param-
eterizations of these indices with the irradiance observed by
SEE on TIMED from 2002 to 2009. The parameterizations
characterize the wavelength‐dependent variability observed
during successive solar rotations, with maximum peak-to-
valley amplitudes (in October 2003) in excess of 100% at
wavelengths <10 nm, decreasing to ~30% for EUV wave-
lengths near 100 nm.

[51] A two component (2C) model, constructed by scaling
the rotational modulation of the Mg II and F10.7 indices to
longer time scales, underestimates the increase at solar cycle
23 maximum relative to solar activity minimum that SEE
observes at all wavelengths shorter than 40 nm and longer
than 80 nm. For the wavelength band 0–40 nm, the solar cycle
amplitude is 180% in SEE observations and 90% in the
2C model. For the wavelength band 40–80 nm, the solar cycle
amplitude is 50% in SEE observations and 60% in the
2C model. For the wavelength band 80–100 nm, the solar
cycle amplitude is 90% in SEE observations and 60% in the
2C model. Since the observed solar cycle changes are
determined with uncertainties of 20–40%, these differences
suggest that the 2C model is inadequate for parameterizing
EUV irradiance variations at some wavelengths. To enable
better reproduction by proxy parameterizations of the entire
spectrum variability, a 3C model is developed by including
a third component which is obtained by scaling the smoothed
Mg II index. The 3C model better reproduces the solar cycle
changes that SEE observes.

[52] The nature of the third component is obscure. The
good agreement of SEE irradiance summed over the band 0
to 45 nm with the total EUV flux needed to produce the ter-
restrial FUV dayglow measured by GUVI and with inde-
pendent SEM observations argues in favor of a solar origin
for the long‐term component, at least at wavelengths less
than 45 nm. However, the similarity of the spectral structure
of the third component with logarithmic spectral irradiance,
such that larger energy fluxes require larger long‐term com-
ponents, suggests that undetected instrumental changes may
nevertheless be contributing, since instrument sensitivity
is known to be exposure‐related.

[53] Short‐term EUV irradiance changes can be forecast on
time scales of 1 to 10 days with average uncertainties of
2% to 10%, respectively, by combining parameterizations of
EUV irradiance variability in terms of Mg II and F10.7 with
autoregressive algorithms that forecast each of these two
indices. Using the SWPC forecast for cycle 24, we estimate
peak levels of total EUV irradiance 40% to 80% above
current solar minimum levels. Although speculative, we sug-
gest that the total EUV irradiance was reduced in the range of
25% (2C model) to 46% (3C model) in the Maunder Minimum
relative to the cycle 23 minimum.

[54] Future measurements made by SEE in the ascending
phase of cycle 24, concurrently with those by EVE on the
recently launched Solar Dynamics Explorer (SDO), will pro-
vide invaluable new knowledge of solar irradiance variability
amplitudes and mechanisms and of instrument sensitivity
changes in space missions. The SEE and EVE instruments
overlap at different phases of their mission degradation his-
tories. Increasing solar activity in cycle 24 will provide a
stringent test of their respective sensitivity tracking algo-
rithms, since declining (or level) irradiances as solar activity
increases points with high probability to unresolved instru-
mental sensitivity degradation. The EVE measurements will
also provide independent observations with which to test the
2C and 3C models derived from the SEE data.

[55] Acknowledgments. NASA and ONR funded this work. Harry
Warren made available the NRL/EUV2 quiet Sun solar spectrum. The
NRLSSI model is available on the LISIRD and SOLARIS web sites.
[56] Philippa Browning thanks Rodney Viereck and another reviewer
for their assistance in evaluating this paper.

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G. F. Eparvier and T. N. Woods, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, 1234 Innovation Dr., Boulder, CO 80303, USA.

J. L. Lean, Space Science Division, Naval Research Laboratory, Code 7605, 4555 Overlook Ave., SW, DC 20375, USA. (judith.lean@nrl.navy.mil)

R. R. Meier, Department of Physics and Astronomy, George Mason University, MS 3F3, 4400 University Dr., Fairfax, VA 22030, USA.