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New developments in SOLAR2000 for space research and operations

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Abstract

The SOLAR2000 (S2K) project provides solar spectral irradiances and integrated solar irradiance proxies for space researchers as well as ground- and space-based operational users. The S2K model currently represents empirical solar irradiances and integrated irradiance proxies covering the spectral range from the X-rays through the far infrared and has evolved through 23 version releases since October 1999. Variability is provided for time frames ranging from 1947 to 2052. The combination of variability through multiple time periods with spectral formats ranging from resolved emission lines through integrated irradiance proxies is a unique feature that provides researchers and operational users the same solar energy for a given day but in formats suitable for their distinctly different applications. We report on new developments in the SOLAR2000 version 2.24 model. There are several models and reference spectra now included in SOLAR2000 including the S2K extreme ultraviolet (EUV) irradiance model provided by Tobiska (S2K: 1–121 nm), the vacuum ultraviolet (VUV) model provided by Woods (VUV2002: 1–420 nm), and the ASTM-E490 reference spectrum (122–1,000,000 nm). Improved model accuracy in the XUV–EUV spectral regions is obtained with the inclusion of the new TIMED SEE version 7 dataset. We report on integrated irradiance products including some revisions to previously reported proxies, $E_{10.7}$, Q_{EUV}, P_{euv}, T_∞, R_{SN}, and S, and an introduction to seven new integrated irradiance proxies. They include E_{1_40}, $XE_{10.7}$, X_{b10}, X_{hf}, $X_{10.7}$, E_{SRC}, and E_{SRB}. The Schatten solar dynamo model output is included in the S2K Operational Grade model and provides forecast proxies out to five solar cycles. The SOLAR2000 Research Grade (RG) model provides historical irradiances and proxies for space research and is freely available, via web download, to users of any platform through the use of an IDL virtual machine (VM) graphic user interface (GUI) application. The SOLAR2000 Professional Grade (PG), Operational Grade (OP), and System Grade (SY) models provide historical, nowcast, and forecast irradiances and proxies, including in high time resolution, for ground- and space-based operations; these fee-based applications are available to operational users on any platform through an IDL VM GUI application (S2K PG: daily values), server access (S2K OP: daily plus high time resolution), and rack-mount turn-key (S2K SY: daily plus high time resolution linked with a system of models) configurations. All SOLAR2000 model versions and grades are compliant with the ISO standard 21348 "Space environment (natural and artificial) – process for determining solar irradiances."

Keywords: SOLAR2000; Solar irradiance model; XUV; EUV; FUV; UV

1. Background

1.1. Motivations for improving solar irradiance spectral and temporal characterization

The solar soft X-ray or XUV ($0.1 \leqslant \lambda < 10$ nm) and vacuum ultraviolet or VUV ($10 \leqslant \lambda < 200$ nm) spectral irradiance range (cf. the new ISO 21348 spectral range definitions in Tobiska and Nusinov, 2005) is particularly important for space system engineering, aeronomy, and climate change research since these wavelengths deposit their energy in the thermosphere, mesosphere, and stratosphere as well as create the ionosphere. Because solar spectral irradiances are a foundation for understanding scattering and photoabsorption processes in atmospheres and ionospheres, it is important to provide user communities with accuracy, precision, and time-resolution in solar irradiance

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products. Previous reports (Woods et al., 2004; Tobiska, 2004) have reviewed and outlined solar XUV and VUV irradiance characterization by rockets, satellites, and models through 2002. For operations affected by space weather, solar irradiance product accuracy and precision have already begun to be transferred to operational solar irradiances (Tobiska, 2002a, 2003a,b) and this paper describes further progress in that direction. Between 2002 and 2004 there have been significant changes in space systems operations and space physics that are relevant to solar XUV and VUV irradiance specification. For example, Earth thermospheric mass density specification has improved by nearly an order of magnitude at the current epoch through the high accuracy satellite drag model (HASDM) project (Storz et al., 2002), the global assimilative ionospheric model (GAIM) (Schunk et al., 2004; Scherliess et al., 2004; Wang et al., 2004; Hajj et al., 2004) has reached new maturity at a prototype demonstration level, and aeronomy from Venus to Saturn is actively being studied. These activities require accurate and precise solar irradiances and integrated irradiance proxies. The requests by these user communities for improved irradiance products are combined with more accurate XUV and VUV irradiance measurements beginning in 2002 made by solar instruments on the TIMED and SORCE missions, with the development of the International Standards Organization (ISO) solar irradiance standard 21348, and with improved solar irradiance modeling techniques over the past decade through EUVAC (Richards et al., 1994), SunRISE (Fontenla et al., 1999; Fox et al., 2004), NRLEUV (Warren et al., 2001), and SOLAR2000 (Tobiska et al., 2000). Together, all these factors provide strong motivations for continuing the effort to make improvements in solar irradiance products.

1.2. Definitions for and uses of solar spectral and temporal irradiances and proxies

One particular focus for SOLAR2000 model development is to provide a common irradiance product platform for space physics (aeronomy and climate change studies) and for space weather (operational atmosphere and ionosphere systems as well as mission planning and materials testing) users. Whether an irradiance product is a historical solar maximum reference spectrum at high spectral resolution or the forecast time series of an integrated irradiance proxy such as $E_{10.7}$, the total energy content across a given spectral range is the same and its heritage is traceable to measurements and modelling that includes quantifiable uncertainties (Tobiska et al., 2000).

Several terms used in this paper have acquired specific definitions through operational experience (Tobiska, 2004). We review some of those definitions and introduce additional definitions. *Time states* that are relevant to space physics and space weather data, including solar irradiance products, are *past, present*, and *future*. A key element in defining the time state of a data set is knowledge of the *current epoch* which refers to the present instant in time as used by the astrodynamics community. Past data that are well characterized and that represent times earlier than 24 h relative to the current epoch are either called *historical* or *previous* data depending upon whether they represent operational *enhanced* or *core data streams*. Operational data has the quality of redundancy where, for risk mitigation purposes, alternative methods exist to represent the same types of information. The flow of these data from producers to users and their applications is called a data stream. Enhanced data contains enriched information content such as high temporal, spectral, and spatial resolution or reduced uncertainty. Core data, on the other hand, contains fundamental information that, given the absence of enhanced data, can represent the climatology or statistics of a physical system. The terms *nowcast* or *current* describe the operational period from 24 h in the past up to the current epoch, again depending upon whether they are enhanced or core data streams, respectively. The terms *forecast* or *predicted* indicate a prediction based upon calculation; they refer to the time frame starting at the current epoch and proceeding into the future for enhanced or core data streams, respectively. As shorthand in this paper, we use the enhanced data stream terms historical, nowcast, and forecast to represent the three time state domains for solar irradiance products. Fig. 1 demonstrates the relationship between time states and data streams. *Cadence* describes the time interval of a repetitious operational task, e.g., daily, hourly, minutely data production, and Fig. 2 shows the relationship between time states and cadence with their associated uncertainty.

Examples of SOLAR2000 historical daily irradiance product space physics users include: (a) aeronomers (neutral atmosphere and ionosphere) studying Venus, Earth, and Mars; (b) heliospheric researchers; (c) investigators of long-term climate change effects in the terrestrial mesosphere and thermosphere; (d) long-term satellite orbit decay analysts. Examples of SOLAR2000 irradiance product space weather users include: (a) NOAA Space Environment Center (SEC) which provides nowcast daily irradiances for public release; (b) other US Government agencies' operations centers using forecast high time resolution irradiance products for the calculation of thermospheric and ionospheric effects; (c) national and international commercial aerospace organizations flight dynamics groups using forecast daily irradiances for low-Earth orbit satellite atmospheric drag calculations; (d) NASA Moon and Mars projects using forecast daily solar cycle irradiances for mission planning related to astrodynamics and materials charging (spacecraft surface and lunar dust photoionization); (e) other NASA science missions using operational recent historical and nowcast daily irradiances for Level 3 science data processing (reporting of calibrated data in geophysical units). We describe next the improvements to SOLAR2000 v2.24 that benefit these space physics research and space weather operational systems users.

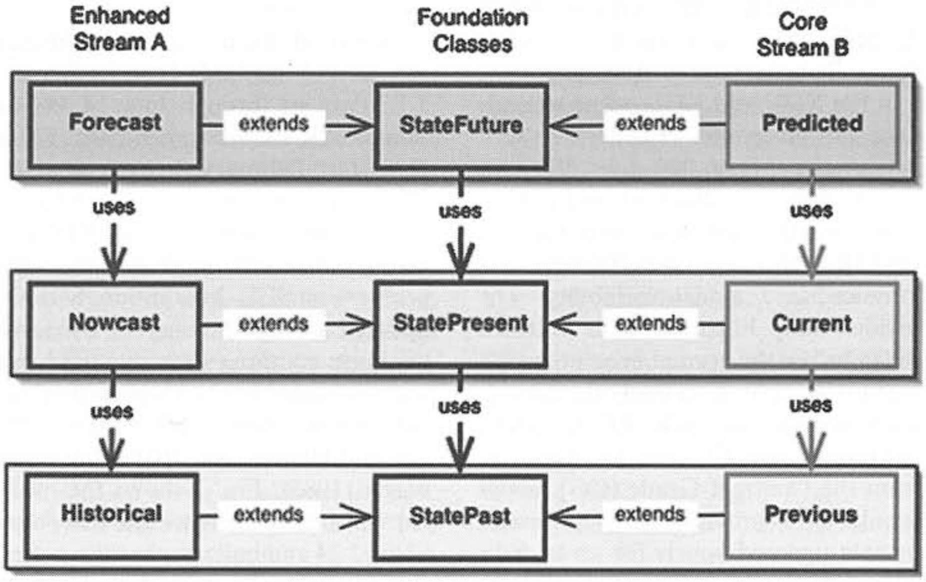

Fig. 1. Time states related to data streams for operational space weather, including solar irradiances products.

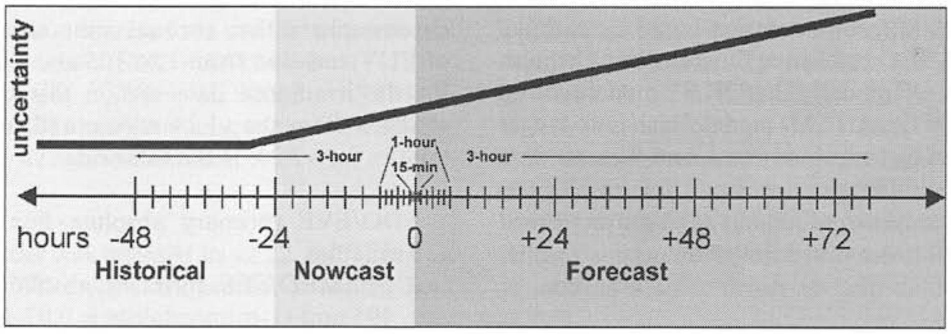

Fig. 2. Cadences and uncertainty for three operational space weather enhanced data stream time states.

2. Recent improvements to SOLAR2000 through version 2.24

While the overarching scientific goal behind developing SOLAR2000 modeled solar irradiances is to understand how the Sun varies spectrally and temporally from X-ray through radio wavelengths, a research and operational objective has been to enable SOLAR2000 irradiance products to link easily and accurately with other applications. A special feature of other space physics and space weather applications is that they are often written in legacy software and require specific types of solar irradiance information inputs. In order to provide transparent use of increasingly accurate and precise solar irradiance products for models that have been written in legacy code, SOLAR2000 spectral irradiances are provided in a variety of formats between February 14, 1947 and dates into 2052. Tobiska (2004) reported on six integrated irradiance products, i.e., $E_{10.7}$, Q_{EUV}, P_{EUV}, T_{∞}, R_{SN}, and S, in addition to the spectral irradiance, I_{λ}, formats of energy (erg cm^{-2} s^{-1}) and photon (photons cm^{-2} s^{-1}) flux as well as SI unit (W m^{-2}) irradiance. Wavelength bins (spectral sampling) are reported on a 1 nm $\Delta\lambda$ wavelength grid for the full spectrum of 1–1,000,000 nm (1 nm to 1 mm) as well as 867 bins of approximately 0.1 nm $\Delta\lambda$ for the soft X-ray and extreme ultraviolet (XUV: $0.1 \leqslant \lambda < 10$ nm and EUV: $10 \leqslant \lambda < 121$ nm) spectral ranges and 39 wavelength groups and bins (discrete lines and 5 nm bins) for a legacy 1–105 nm template. In this paper, we briefly summarize the previous six integrated irradiance products and introduce seven new ones. We also describe improvements to the Research Grade (RG), Professional Grade (PG), Operational Grade (OP), and System Grade (SY) models that are useful for specific user communities. With S2K v2.24, we also declare compliance with the ISO 21348 solar irradiance standard for the first time.

2.1. Version 2.24 major upgrades

This section reports major upgrades to SOLAR2000 between v1.24 (Tobiska, 2004) and v2.24. A detailed explanation of each upgrade is available as part of the "About S2K" file that is embedded within the actual model GUI application. The SOLAR2000 (S2K) versioning convention of *x.yz*, the upgrade philosophy, and the model grade description is provided in Tobiska (2004). As a summary, S2K vl.yz is variable in the XUV and EUV, v2.yz extends the variability into the far ultraviolet (FUV: $122 \leqslant \lambda < 200$ nm), the middle ultraviolet (MUV: $200 \leqslant \lambda < 300$ nm), the near ultraviolet (NUV: $300 \leqslant \lambda < 400$ nm), and to blue light (420 nm), v3.yz extends the variability into the VIS ($380 \leqslant \lambda < 760$ nm) and IR ($760 \leqslant \lambda < 1{,}000{,}000$ nm), and v4.yz incorporates physics-based model variability. The S2K RG model provides daily historical data with an approximate 3-month lag before the current epoch through a platform independent GUI application freely downloadable from http://www.SpaceWx.com. S2K RG currently has over 400 registered users across 40 countries. The S2K PG model evolved from the Contract Grade (CG) model which is no longer available. It provides daily historical, nowcast, and forecast data updated hourly for up to 4018 consecutive days (1 solar cycle) as well as Continuous Wavelet Transform (CWT) analysis tools on a fee-based platform-independent GUI application. The S2K OP model provides daily historical, hourly nowcast, 72-h (3-h interval) forecast, and daily forecast data from a contract-based operational server; both NOAA SEC and Space Environment Technologies (SET) run S2K OP models. The S2K SY model evolved from the Commercial Grade (CM) model which is no longer available. It provides historical, nowcast, and forecast data with minutely to daily (or user specified) time resolutions and is part of a larger system of models as a contract-based distributed network or as a turn-key system.

2.1.1. Upgrade 1

SOLAR2000 was upgraded from v1.24 to contain variability from the XUV–EUV into the FUV, MUV, NUV and blue light (1–420 nm) starting with v2.21. In the wavelength region between 0.1 and 121 nm, there are two options of models that can be used, i.e., either S2K EUV or VUV2002 provided by T. Woods (private communication, 2002). The HI Lyman-α spectral irradiance ($121 \leqslant \lambda < 122$ nm) is additionally available as one of the two driver proxies to the model. Prior to June 24, 2001 the Woods et al. (2000a) composite 5-cycle Lyman-α data set calibrated to the UARS Lyman-α is used. Beginning June 24, 2001 the regression value of Lyman-α calculated from the NOAA SBUV Mg II core-to-wing ratio (CWR) data set provided by Viereck and Puga (1999) and Viereck et al. (2001) is used. The regression algorithm is given in Eq. (1). From 122 to 420 nm, the VUV2002 model is used exclusively while above 420 nm, the ASTM E-490 reference spectrum is used. VUV2002 uses the daily $F_{10.7}$ as the proxy to model UARS FUV and UV irradiances and is based on the VUV reference spectra published by Woods and Rottman (2002).

$$\text{Lyman-}\alpha = [-30.24 + (128.09) \times (\text{Mg II}_{\text{NOAA SBUV CWR}})] \times 10^{11} \ (\text{photons cm}^{-2}\ \text{s}^{-1}) \quad (1)$$

2.1.2. Upgrade 2

A second major upgrade in the v2.yz model is the incorporation of the TIMED SEE (Woods et al., 2000b) version 7 L3 data set through June 14, 2004 as part of the derivation of S2K EUV between 1 and 120 nm. The TIMED SEE data start February 8, 2002 (2002-039 or JD 2452314.0). The SEE data includes the XPS (0.1–34 nm) and EGS (27–194 nm) detector data. XPS have been replaced, in SEE v7, with the SORCE XPS data due to a filter wheel problem on SEE. In addition, SOHO SEM data have been updated through January 14, 2003. All satellite, rocket, and reference continua data sets used in the model derivation are now scaled to the absolute level of the SEE data in each ~0.1 nm wavelength bin on the SC21REFW format (Heroux and Hinteregger, 1978; Hinteregger et al., 1981; Hinteregger, 1985). Fig. 3 shows the multiple linear regression correlation coefficients plotted against wavelength for S2K v2.24 and indicate that the overall range of correlation coefficients is 0.73–0.97 while the average correlation across all wavelengths is 0.95. Using $F_{10.7}$ as the coronal proxy (key = 2) and Lyman-α as the chromospheric proxy (key = 1), the average of all key values is 1.096, i.e., more chromospheric than coronal component in the photon flux of EUV emission from 1 to 105 nm. The scaling hierarchy for the irradiance data sets in this derivation has been changed from the v1.24 release and, using revised uncertainties for v2.24, is the following:

SDO/EVE (primary absolute flux data set, not yet available)
  |_TIMED/SEE (primary absolute flux data set, 1–195 nm) (1-σ uncertainty = 0.07–0.55);
    |_GOES/EUV (primary time-resolved data set, not yet available);
    |_SNOE (primary data set 2.0–6.0, 6.0–18.0, 18.0–27.0 nm) (1-σ uncertainty = 0.15);
    |_SEM (1–50, 26–34 nm) (1-σ uncertainty = 0.40);

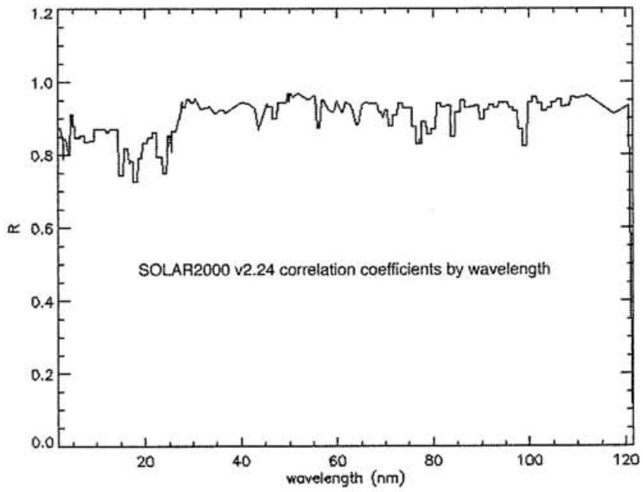

Fig. 3. S2K v2.24 correlation coefficients by wavelength for XUV and EUV (ISO 21348) spectral ranges.

|_YOHKOH (2–3, 3–4 nm) (1-σ uncertainty = .50);
|_AE-E (16.8–102.6 nm) (1-σ uncertainty = 0.35);
|_SOLRAD (1.8–3.0, 3.0–5.0 nm) (1-σ uncertainty = 0.30);
|_sounding rockets (wide range of 1-σ uncertainties but generally = 0.35).

2.1.3. Upgrade 3

A third upgrade is in the operation of the model which has been changed in two ways. Starting with v2.23, a user is no longer required to purchase an interactive data language (IDL) software license in order to run the model. Research Systems, Inc. (RSI) manufactures IDL and has provided an IDL 6.0 (or higher) virtual machine (VM) that is freely downloaded from the RSI web site http://www.rsinc.com. Once the IDL VM is installed on a user's machine, the S2K RG model can be run with the following command line typed in the X-terminal window: idl -vm=solar2000_rg_vm.sav. This capability has made S2K widely available to users who were previously unfamiliar with or unable to purchase IDL. S2K also runs directly within IDL if a user chooses that method of operation. A feature that has been added to S2K v2.23 and higher is an option for a user to run combinations of models: (a) S2K + ASTM490 (1–121 + 122–1,000,000 nm); (b) S2K + VUV2002 + ASTM490 (1–121 + 122–420 + 421–1,000,000 nm); (c) VUV2002 + ASTM490 (1–420 + 421–1,000,000 nm).

2.1.4. Upgrade 4

The S2K PG model was released in v2.22 and, using an internet link with a 56K modem connection or higher, Java 1.4 or higher installed, and either IDL 5.6 or higher or IDL 6.0 VM installed, an operational user on any type of platform is able to access, from the SET server, hourly irradiance product forecasts out to 137 days (4.5 months or five solar rotations) from the current epoch. The inexpensive service is internationally accessible 24/7/365, is compliant with ISO 21348, and is available through the http://www.SpaceWx.com web site.

2.2. Integrated irradiance proxies

In addition to the six previously described (Tobiska, 2004) integrated irradiance products, i.e., $E_{10.7}$, Q_{EUV}, P_{EUV}, T_∞, R_{SN}, and S, there are seven new integrated irradiance proxies that we introduce here. They include E_{1_40}, $XE_{10.7}$, X_{b10}, X_{hf}, $X_{10.7}$, E_{SRC}, and E_{SRB}. All 11 proxy descriptions are given next and summarized in Table 1.

2.2.1. $E_{10.7}$

We note that $E_{10.7}$ is the integrated EUV energy flux, $E(t)$, (erg cm^{-2} s^{-1}) for $\Delta\lambda = \lambda_2 - \lambda_1$, where $\lambda_1 = 1$ nm and $\lambda_2 = 105$ nm, at the top of the atmosphere and reported in units of 10.7-cm radio flux, $F_{10.7}$ ($\times 10^{-22}$ W m^{-2} Hz^{-1}). Eq. (2) provides the conversion between $E(t)$ and $E_{10.7}$ in S2K v2.24. There have been previous descriptions of the $E_{10.7}$ proxy derivation, use, and validation (Tobiska et al., 2000; Tobiska, 2001). Operational $E_{10.7}$, as a solar input into empirical thermospheric density models, is used for satellite operations to calculate satellite drag (Tobiska, 2003a,b). In empirical ionospheric models it is used as a solar driver to help characterize parameters

Table 1
Summary of SOLAR2000 proxies

Proxy	Description	Application	Release version
$E_{10.7}$	Integrated XUV-EUV energy from 1 to 105 nm reported in 10.7 cm solar flux units	Empirical thermospheric density and ionospheric models that use 10.7 cm solar flux inputs	1.03
S	Integrated solar spectrum	Research and operations that use a variable total solar irradiance	1.03
Q_{EUV}	Total volume thermospheric heating rate	Aeronomy usage for comparison between UV airglow and solar irradiances	1.20
R_{SN}	Derived sunspot number	HF propagation ray-trace algorithms that historically use the International Sunspot Number	1.20
T_∞	Exospheric temperature	Comparison with Jacchia exospheric temperatures	1.21
P_{EUV}	XUV-EUV hemispheric power	Aeronomy usage for comparison with Joule and particle precipitation heating	1.23
E_{1_40}	Integrated XUV-EUV energy from 1 to 40 nm	Aeronomy usage for comparison between UV airglow and solar irradiances	2.21
$XE_{10.7}$	Integrated XUV-EUV energy from 1 to 40 nm reported in 10.7 cm solar flux units	Aeronomy usage for comparison between UV airglow and solar irradiances	2.25
X_{b10}	XUV 0.1–0.8 nm 24-h background irradiance index	Operational flare evolution prediction	–
X_{hf}	XUV 0.1–0.8 nm hourly flare irradiance index	Operational flare evolution prediction	–
$X_{10.7}$	$X_{b10} + X_{hf}$ reported in 10.7 cm solar flux units	Comparison of XUV 0.1–0.8 nm variability with 10.7 cm flux	–
E_{SRC}	Integrated Schumann–Runge continuum energy from 125 to 174 nm	Lower thermosphere energy contribution to atmospheric density	–
E_{SRB}	Integrated Schumann–Runge band energy from 175 to 204 nm	Mesosphere and stratosphere energy contribution to atmospheric density	–

such as long-term trends of terrestrial f_oF_2 (Danilov, 2003) and 27-day topside plasma densities (Rich et al., 2003) as well as Martian peak electron densities (Breus et al., 2004) and daily variability (Martinis et al., 2003). While several investigations have shown that $E_{10.7}$ and $F_{10.7}$ are comparable in terms of accuracy and 1-σ deviations when input into thermospheric density models (Tobiska, 2001; H. Koinuma, private communication, 2003; F. Marcos, private communication, 2004; Pardini et al., 2005; Bowman, private communication, 2005), advantages of using $E_{10.7}$ in empirical models compared to $F_{10.7}$ are that: (a) it physically represents the actual solar energy available for photoabsorption and photoionization; as measurements and modeling become more accurate, the improved physics can be easily represented through $E_{10.7}$; (b) for operations, $E_{10.7}$ is produced at a higher cadence and finer time resolution which includes effects such as flares; (c) for aerospace contractual obligations, $E_{10.7}$ is compliant with ISO 21348. When $E_{10.7}$ or similar solar proxies do not do as well as $F_{10.7}$ in legacy code, this indicates the need for improving integrated irradiance proxies' accuracy, for creating specialized proxies relevant to specific altitude regimes or dominant species, and for improvements to legacy code such as atmosphere density models in their temperature and fitting formulations.

$$E_{10.7} = -122.7 + 110.0 \times E(t) + (-13.41) \times E(t)^2 + 0.79 \times E(t)^3 (\times 10^{-22}\ \mathrm{W\ m^{-2}\ Hz^{-1}}). \quad (2)$$

2.2.2. Q_{EUV}

Q_{EUV} is the total volume thermospheric heating rate that has been summed over height from 120 to 450 km and wavelength from 1 to 105 nm in units of erg cm^{-2} s^{-1} and derived from EUV energy flux photoabsorbed by seven neutral species' characterized by altitudinal concentrations, cross-sections, and heating efficiencies. It is useful for aeronomy research as well as climate change studies and it's derivation has been described in previous work (Tobiska, 1988, 2001; Tobiska et al., 2000). In S2K v2.24, Q_{EUV} is calculated from Eq. (3)

$$Q_{EUV} = (2.45 \times 10^{-6}) + (-3.35 \times 10^{-10}) \times E_{10.7} + (2.22 \times 10^{-10}) \times E_{10.7}^2 + (-4.72 \times 10^{-13}) \times E_{10.7}^3\ (\mathrm{erg\ cm^{-2}\ s^{-1}}). \quad (3)$$

2.2.3. P_{EUV}

P_{EUV} is the EUV hemispheric power proxy in units of gigaWatts (GW) and complements the auroral hemispheric power index. Knipp et al. (2004) have used P_{EUV} to illustrate the relationship between EUV, Joule heating, and particle precipitation heating over solar cycle time scales. In S2K v2.24, P_{EUV} is calculated from Eq. (4)

$$P_{EUV} = \pi \times (6.38 \times 10^8)^2 \times E(t) \times (2.77 \times 10^{-11}) \times 3600.0\ (\mathrm{GW}). \quad (4)$$

2.2.4. T_∞

T_∞, the dayside subsolar point exospheric temperature at 450 km in units of Kelvin (K), was originally introduced in v1.21 where it was empirically set to the absolute levels of the Jacchia 1970 nighttime minimum exospheric temperatures. Starting with v2.21 the empirical scaling was removed. In S2K v2.24, T_∞ is calculated from Eq. (5). T_∞ is still consistent with the Jacchia 1970 nighttime minimum exospheric temperatures and the average daily relationship for six years from January 1, 1996 to December 31, 2001 (solar minimum to maximum) between T_∞ and the Jacchia value was used to derive Eq. (6). It is useful for long-term studies investigating potential anthropogenic climate change effects (cooling) in the thermosphere and subsequent changes to the ionospheric E and F2 layer heights

$$T_\infty = 752.34 + 1.01 \times E_{10.7} + 0.03 \times E_{10.7}^2 + (-6.02 \times 10^{-5}) \times E_{10.7}^3\ (\mathrm{K}) \quad (5)$$

$$T_\infty \approx T_{\mathrm{exosphere\ (J70)}} \times 1.3\ (\mathrm{K}). \quad (6)$$

2.2.5. R_{SN}

R_{SN}, dimensionless, is the operational derived sunspot number proxy for use in HF radio propagation ray-trace algorithms that historically use the International Sunspot Number, R_z. R_{SN} differs from R_z during solar maximum conditions and does not reach the highest values of R_z; this provides a capability for more accurately representing the ionosphere variations that derive directly from solar EUV photoionization. In S2K v2.24, R_{SN} is calculated from Eq. (7)

$$R_{SN} = -93.0 + 1.55 \times E_{10.7} + (-0.002) \times E_{10.7}^2 + (-8.99 \times 10^{-8}) \times E_{10.7}^3\ (\mathrm{dimensionless}). \quad (7)$$

2.2.6. S

S is the integrated solar spectrum from 1 to 1,000,000 nm in units of W m^{-2} and is provided to researchers who desire the integrated spectrum variability relative to a reference, full solar spectrum. The derivation, absolute value, and variation of S have been described previously (Tobiska et al., 2000; Tobiska, 2002b,c) and the variability in SOLAR2000 v2.24 comes from the solar spectrum between 1 and 420 nm. Longward of 420 nm in the v2.yz model, the ASTM E490 solar reference spectrum is used. Hence, the current variability in S is not the same as the total solar irradiance (TSI) and there is only modest variability in the TSI due to irradiance deficit from sunspots. In v3.yz, this spectrum will be extremely useful for space systems' users who desire an operational, variable integrated solar spectrum for solar radiation pressure calculations on spacecraft.

2.2.7. E_{1_40} and $XE_{10.7}$

E_{1_40} is a new integrated solar irradiance product that was provided starting with S2K v2.21. It is the integrated

EUV energy flux between 1 and 40 nm and is useful for aeronomical studies of UV airglow. It has units of erg $cm^{-2} s^{-1}$ for $\Delta\lambda = \lambda_2 - \lambda_1$, where $\lambda_1 = 1$ nm and $\lambda_2 = 40$ nm, and is provided as part of the *s2k_output.txt* file. An interesting feature of E_{1_40} appears when it is converted into an equivalent $F_{10.7}$, $XE_{10.7}$ (Eq. (8)), and is compared to satellite drag data from low ($i = 36°$, satellite 1616, 410 km reference altitude) and high ($i = 77°$, satellite 4122, 400 km reference altitude) inclination low-Earth orbiting satellites for solar maximum to minimum time scales (January 1, 1990 to December 31, 1996) (F. Marcos, private communication, 2004). One finds that it consistently correlates well with drag-derived density. Figs. 4 and 5 demonstrate the correlation using S2K v2.24 daily observed values where all data for periods of $A_p > 7$ have been excluded in order to isolate quiet geomagnetic conditions and focus on the solar variability component. These results are consistent with the fact that between 180 and 450 km, where these satellites spend much of their perigee time, the dominant species is atomic oxygen, O. The majority of the 1–40 nm solar energy heats atomic oxygen which has its unit optical depth throughout this altitude region. E_{1_40} and $XE_{10.7}$ better capture this region's variability compared with $E_{10.7}$ which mixes longer wavelength energy deposited in lower altitudes dominated by other species.

$$XE_{10.7} = -0.20 + 53.42 \times E_{1\_40} \ (\times 10^{-22}\ \mathrm{W\ m^{-2}\ Hz^{-1}}). \tag{8}$$

2.2.8. X_{b10}, X_{hf}, and $X_{10.7}$

Solar spectral irradiances shortward of 31 nm, i.e., XUV ($0.1 \leqslant \lambda < 10$ nm) and some EUV ($10 \leqslant \lambda < 31$ nm) irradiances, are the dominant source of 180–450 km altitude thermospheric heating and Fl and F2 ionospheric layer photoionization. These spectral irradiances are mostly absorbed by atomic oxygen which is the dominant species in this altitude region at most levels of solar activity. Wavelengths in this spectral range are highly variable during solar flares and, at the shortest wavelengths, can increase by up to two orders of magnitude in a few minutes from flare start to flare peak. Even though NOAA SEC provides a flare estimate (P. Bornmann, SPD presentation, June 2000), there has not been a consistent method for operational solar XUV and EUV flare spectral, magnitude, and duration estimation although the geoeffectiveness of these characteristics on short time scales is significant.

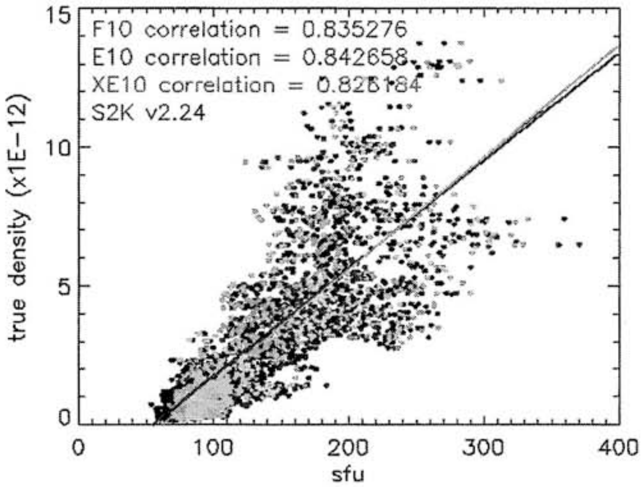

Fig. 4. Correlation for S2K v2.24 $E_{10.7}$, $XE_{10.7}$, and $F_{10.7}$ with satellite 1616 true density ($i = 36°$, $A_p < 7$,410 km, reference altitude).

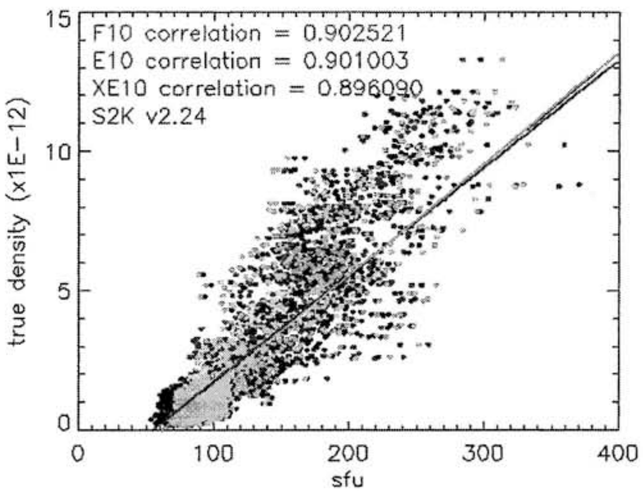

Fig. 5. Correlations for S2K v2.24 $E_{10.7}$, $XE_{10.7}$, and $F_{10.7}$ with satellite 4221 true density ($i = 77°$, $A_p < 7$, 400 km, reference altitude).

Space weather users can use knowledge of flare spectral characteristics, magnitude, and duration once a flare has started. As the operational beginning of a capability that provides this information, we introduce here three new integrated irradiance indices, X_{b10}, X_{hf}, and $X_{10.7}$. These indices help provide spectral flare estimation in the XUV and EUV through the creation of electron temperatures and emission measure that can be used in models like Mewe, CHIANTI, and APEC.

In order to provide flare magnitude and duration once it has started, we have developed a prototype flare model using the correlation between dX_{hf}/dt, flare magnitude, and duration. The time rate of change of X_{hf}, dX_{hf}/dt, is obtained after separating the X_{b10} background so that the actual flare start time, rise phase, and decay shape can be determined. This topic will be described in a separate paper.

The two new indices are formed by using high time resolution data that are operationally available. Among the shortest wavelengths of the XUV are the 0.1–0.8 nm irradiances measured by the GOES-series spacecraft and reported every minute by NOAA SEC. The 0.1–0.8 nm band, $XUV_{0.1-1.8}$, is a combination of continuum and lines (free-free bremsstrahlung, free-bound recombination, and two photon emission) dominated by $T > 10^6$ K hot corona emission coming from heated plasma in closed magnetic loops within active regions (Mewe, 1972; Kato, 1976; Mewe and Gronenschild, 1981; Aschwanden, 1994). Since these irradiance measurements, as reported, are a combination of flaring and non-flaring sources, our first task is to separate the flare and non-flare components to create flare indices that are geoeffectively relevant.

The long-standing X-ray background index, X_b, was originally developed (Bouwer et al., 1982; Bouwer, 1983) as a method of estimating the non-flaring $XUV_{0.1-0.8}$ background. We have long noticed that this index is unsatisfactory for removal of flare information since it is calculated using the lowest of three 8-h window mean values in a day and it has been inconsistently preserved in historical archives. Taking the mean value over the relatively long 8-h time frame enables flares to contaminate any of the three selection windows. In place of X_b, we have developed two new X-ray indices. The first, X_{b10}, is the $\log_{10}$ (unitless) number representing the lowest daily decile of the reported GOES $XUV_{0.1-0.8}$ minutely data (Eq. (9)). One-hour of minutely $XUV_{0.1-0.8}$ data is collected and the value of the lowest decile is saved. Over the course of a 24-h period, the lowest of the 24 decile values is selected as the X_{b10} background value. The resulting X_{b10} index provides the best removal of flare effects we have found. Physically, it represents the $T \approx 10^6$ K coronal emission that gradually evolves on active region time scales. It is distinct from the solar 10.7-cm radio flux ($F_{10.7}$ index) which is created in the cooler, $T \approx 10^4$ K transition region. For comparison and for use of X_{b10} in legacy code that only uses $F_{10.7}$, we have generated an equivalent $F_{10.7}$, i.e., $X_{10.7}$, (units of $\mathrm{W\,m^{-2}\,Hz^{-1}}$) using X_{b10} through Eq. (10) that is valid for $X_{b10} \geqslant 237$

$$X_{b10} = 100\,\log_{10}(XUV_{0.1\text{-}0.8} \times 10^{10})\ \text{(dimensionless)}, \quad (9)$$

$$X_{10.7} = -285.0 + (1.20) \times X_{b10}\ (\times 10^{-22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}). \quad (10)$$

A scatter plot comparison between $F_{10.7}$ and $X_{10.7}$ is shown in Fig. 6; the figure indicates that $X_{10.7}$, which is created every few minutes covering the previous hour, can be used as a general surrogate for $F_{10.7}$ that is produced 3 times per day. The fact that the optically thin $X_{10.7}$ has differences with $F_{10.7}$ is exactly the feature one desires to capture since the objective is to model $T \approx 10^6$ K coronal emissions and not transition region emission captured by $F_{10.7}$.

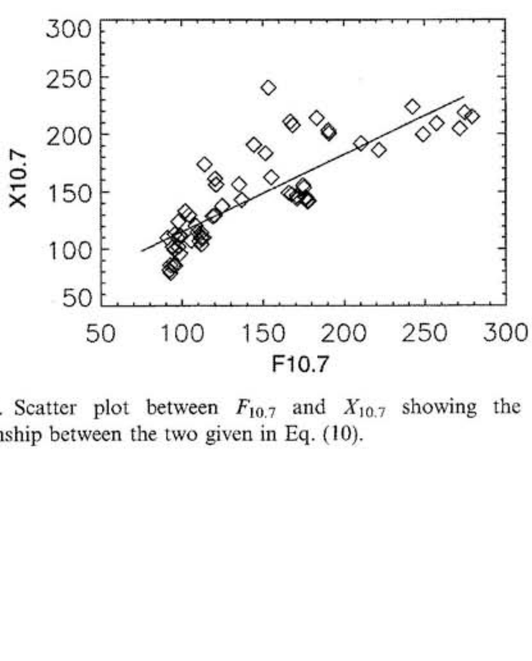

Fig. 6. Scatter plot between $F_{10.7}$ and $X_{10.7}$ showing the general relationship between the two given in Eq. (10).

The second index, X_{hf}, is the $\log_{10}$ (unitless) number representing the difference between the daily (previous running 24-h) X_{b10} background value that is created hourly and the median of the $XUV_{0.1-0.8}$ measurements each hour. This index provides a good estimate of $T \approx 10^6$ K or $T \approx 10^7$ K hot coronal flare activity. Fig. 7 (top panel), shows the $XUV_{0.1-0.8}$ measurements each hour for the 2-month period of October 1 to November 30, 2003 during major flares. NOAA SEC flare classes are listed on the right-hand side of the panel. The Fig. 7 (bottom panel) shows X_{b10} and X_{hf} separated from each other.

Fig. 8 (top panel), shows the maximum electron temperature, T_e, calculated from XUV flare relationships studied by Garcia (1994a,b) and Feldman et al. (1996) who have found empirical, linear relationships in log-linear space that provide flare maximum temperature in MK and emission measure in $\mathrm{cm^{-3}}$ based on the log value of the $XUV_{0.1-0.8}$ data. Eq. (11) is used to generate the Fig. 8 (top panel) and is modified from Feldman et al. (1996) to use operational X_{b10} and X_{hf} while Eq. (12) is reproduced directly from Feldman et al. (1996). The bottom panel of Fig. 8 compares the hourly F_{10x}, $E_{10.7}$, $F_{10.7}$, and $XE_{10.7}$ for the October 1 to November 30, 2003 flare period

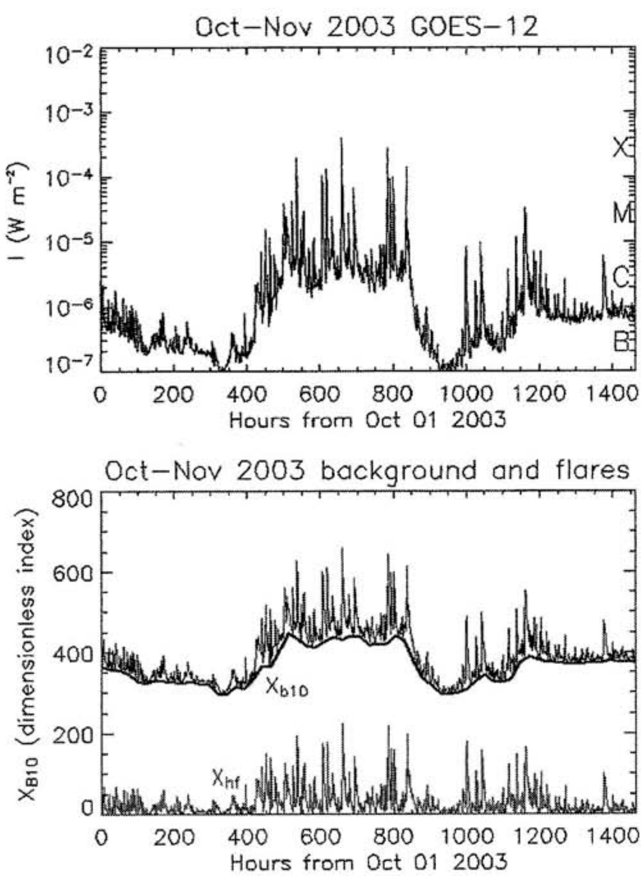

Fig. 7. (Top panel) $XUV_{0.1-0.8}$ measurements each hour for the two 2-month period of October 1 to November 30, 2003; (bottom panel) the hourly X_{b10} and X_{hf} shown combined (highest values) and separately (dark line and gray lowest values).

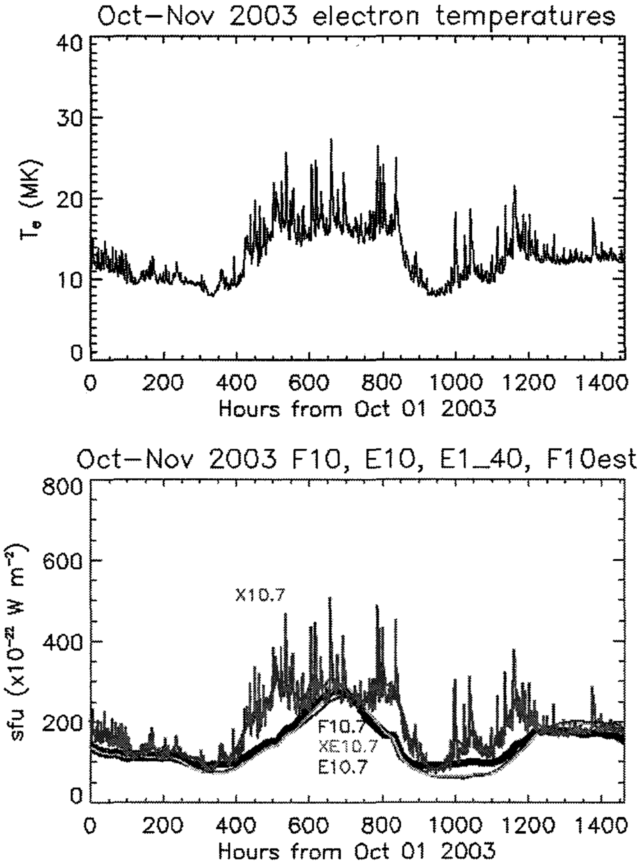

Fig. 8. (Top panel) Electron temperatures (T_e) each hour for the 2-month period of October 1 to November 30, 2003; (bottom panel) the hourly $X_{10.7}$, $E_{10.7}$, $F_{10.7}$ and $XE_{10.7}$.

$$T_e = 48.65 + 5.41 \times \{-0.54 + [0.01 \times (X_{b10} + X_{hf}) - 10]\} \text{ (MK)}, \quad (11)$$

$$\text{EM} = 1.7 \times 10^{0.137T_e + 46.0} \text{ (MK)}. \quad (12)$$

Both maximum electron temperature, T_e, and emission measure, EM, are used by the CHIANTI code, for example, to provide XUV–EUV spectral irradiances during flares.

In summary, our operational method (flare quicklink at http://SpaceWx.com) captures and predicts XUV and EUV flares on short time scales for use by space weather operations. We produce previous hour X_{b10} and X_{hf} indices from the GOES $XUV_{0.1-0.8}$ measurements every 2 min. By doing this we remove background contamination of the flares and retain pristine flare information. This allows us to accurately determine the flare rate of change parameter dX_{hf}/dt which is then used as the input for our flare model. The resulting 6-h prediction of X_{hf} provides a flare peak magnitude and timing as well as flare duration information. When combined with the underlying background, X_{b10}, predicted T_e and EM are created. These two predicted quantities can then be used to calculate XUV and EUV spectral irradiances for a running 6-h period. The operational results will be presented in a separate paper.

2.2.9. E_{SRC} and E_{SRB}

Two new indices are in the early stages of development for use in improved operational neutral atmosphere density specification. E_{SRC} and E_{SRB} are the integrated energy flux, initially in units of erg cm^{-2} s^{-1} but possibly to be transformed into other units, of the Schumann–Runge continuum (SRC: 125–174 nm) and Schumann–Runge band (SRB: 175–240 nm) spectral irradiances.

The motivation for producing these indices is to better characterize, for operations, our understanding of the coupling between solar irradiance energy deposition and atmospheric dynamics. We now realize that new parameterizations are needed to capture the effects of how gravity waves, planetary waves, winds, tides, and inter/intra-hemispheric circulation patterns are coupled with, or are driven by, solar energy. On one hand, the X_{b10} and X_{hf} indices help us understand the effects over very short time scale changes (minutes to hours) that solar X-ray flares have upon the ionosphere D-, E-regions and the mesosphere, lower thermosphere. On the other hand, a similar method of capturing the stratospheric and mesospheric solar irradiance forcing that couples with atmospheric dynamics is needed. We anticipate that E_{SRC} and E_{SRB} will be a start in providing this information. In addition, we are studying and parameterizing medium-term changes (days) in winds, tides, and global circulation that are forced by solar SRC, SRB, and X_{b10} energy deposited in the mesosphere/thermosphere. The physical processes we are trying to understand, which may result in new operational indices, include the heating or ionization of mesospheric/thermospheric molecular oxygen and the related dynamical expansion, possibly time-lagged, that results in increased densities in the thermosphere. A related topic of study that these new parameters can be applied to is the onset of rapid upward, meridional, or zonal winds that may affect hemispheric circulation and, hence, thermospheric densities. The new E_{SRC} and E_{SRB} indices should directly assist in these studies.

2.3. Historical, nowcast, forecast irradiance products

2.3.1. Historical

Historical SOLAR2000 irradiances and integrated irradiance proxies are used for both operational systems and for research. They are regularly updated and the current archive location for data, up to approximately 3-months prior to the current epoch, is at http://www.SpaceWx.com on the "Products" link. We are working with NOAA NGDC to establish a permanent archive for solar irradiance products.

2.3.2. Nowcast

Nowcast irradiances and proxies are provided by the S2K OP model v1.24 located at NOAA SEC in Boulder, CO (http://www.sec.noaa.gov/spacewx/) and at SET. SET is upgrading the S2K OP at NOAA SEC and SET to the most current version in 2005–2006. The SET web site http://www.SpaceWx.com provides a graphical update of the current $E_{10.7}$ compared with the 20 UT observed $F_{10.7}$ for the previous 54-days (two solar rotations), the current epoch (nowcast), and the next 24-h forecast. Nowcast data files are located and updated with an hourly cadence at SECs anonymous FTP server http://www.sec.noaa.gov/ftpmenu/lists/spacewx.html. The files located there, *$E_{10.7}$ nowcast data, Solar spectral data*, and *Validation of today's $E_{10.7}$ data*, provide the nowcast $E_{10.7}$ with ± 1-σ values, the full solar spectrum at 1 nm resolution, and comparative nowcast data of $F_{10.7}$, $F_{10.7}$ 81-day, Lyman-α, Lyman-α 81-day, $E_{10.7}$, $E_{10.7}$ 81-day, and S.

Although the model is run hourly, the information content changes only twice per day using the daily 20 UT $F_{10.7}$, and the daily (NOAA 16) Mg II CWR, or a few times per day (NOAA 16 combined with NOAA 17 starting after 2005). The cadence will dramatically increase in temporal resolution with the inclusion of 5-min data using the X_{b10} and X_{hf} proxies in 2005 and the GOES-N EUV broadband detector data after 2006. SET will continue to use the $F_{10.7}$, and Mg II CWR as redundant proxy data sets to ensure a capability for calculating the irradiances. However, the GOES-N data, when operationally available and absolutely calibrated to the TIMED SEE data, will become a primary data set for the EUV part of the spectrum. The Mg II CWR will still remain a primary data set for calculating FUV and UV irradiances after 2005–2006.

2.3.3. Forecast

Forecast and high time resolution irradiances as well as proxies are provided operationally via the Space Environment Technologies (SET) server for government and commercial customers. The first and current *F*orecast *Gen*eration algorithm is denoted FGen 1× and primarily relies on linear predictive techniques for forecasting. The fundamental assumption of persistence in solar irradiances at time scales of interest is the basis for the forecast techniques and Tobiska (2002c, 2003a,b) provide a descriptive overview of this type of forecast.

The Schatten solar dynamo model (Schatten et al., 1978; Schatten, 2003) output has been incorporated into the S2K OP v2.24 model and provides forecast proxies out to five solar cycles. These data are provided to users who desire long-term, solar cycle time scale predictions of the solar irradiances. The Schatten model provides three proxies that can drive SOLAR2000 and they include a coronal index ($F_{10.7}$ units), a chromospheric index (Mg II CWR units), and a photospheric index (%dS units). The proxies are provided on 6-month time intervals (first half or second half of a year) starting 6 months from the current epoch and extend through approximately five solar cycles (50 years). Fig. 9 shows the Schatten solar dynamo model output included in the S2K OP prediction for coronal (top panel) and chromospheric (bottom panel) proxies at the epoch starting June 19, 2004. The discontinuity at

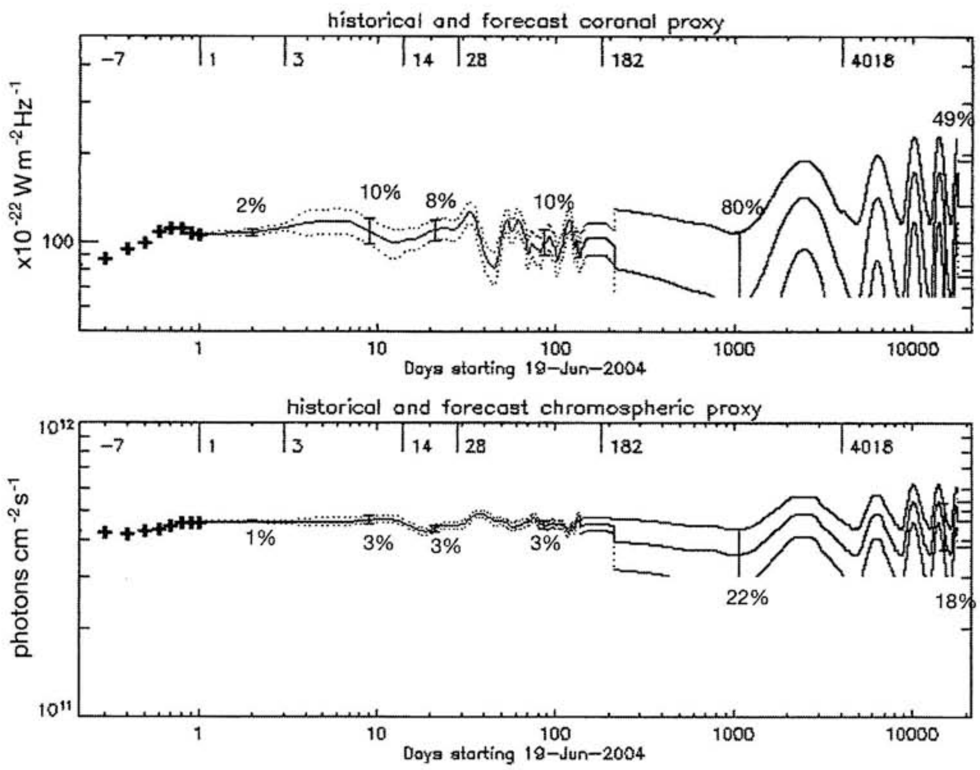

Fig. 9. Schatten solar dynamo model output included in the S2K OP prediction for coronal (top panel) and chromospheric (bottom panel) proxies. The vertical numbers in both panels associated with the error bars are the 1-σ percentage uncertainties on forecast days 2, 9, 21, 85, 1060, and 14841.

6-months is being removed in the next S2K OP model release (late 2005), FGen 2, using continuous wavelet transforms.

3. ISO 21348 compliance

The International Standards Organization (ISO) International Standard (IS) 21348 "Space environment (natural and artificial) – process for determining solar irradiances" can be viewed in draft form at the "ISO solar standard" link at http://www.SpaceWx.com. Tobiska and Nusinov (2000, 2005) describe the evolution and details of this standard. It specifies the process for determining all representations of solar irradiances, including the use of empirical or hybrid models such as SOLAR2000 that provide solar irradiance products and solar irradiance proxies.

The process used for determining solar irradiances reported herein is compliant with ISO International Standard 21348 "Space environment (natural and artificial) – process for determining solar irradiances". The SOLAR2000 empirical/hybrid model products (irradiance, spectral irradiance, and integrated irradiance proxies), starting with v2.24, have ISO 21348 type 3 and type 5 designations and provide total solar irradiance information, solar integrated irradiance proxies, and values for the solar irradiance spectral categories from 1 to 1,000,000 run (soft X-rays into radio wavelengths).

SOLAR2000 reports irradiances in SI units of W m^2 as well as conversions to community-useful units of energy (erg cm^2 s^1) and photon (photons cm^2 s^1) flux. Values are reported through a graphical user interface (GUI) interactive data language (IDL) application computer run of the model; numerical values are located in the *s2k_output.txt* ASCII file and JPEG files are produced for the GUI figures. Either 1 astronomical unit (1 AU) adjusted (adj.) or Earth-observed (obs.) GUI applications of SOLAR2000 are available. Spectral sampling (wavelength bin, $\Delta\lambda$) is reported in each model run depending upon the option that the user selects.

4. Conclusion

The solar XUV, EUV, and VUV spectral irradiance ranges are important for space system engineering, aeronomy, and climate change research since irradiances in these wavelengths deposit their energy in the thermosphere, mesosphere, and stratosphere as well as create the ionosphere. These solar spectral irradiances are a foundation for understanding scattering and photoabsorption processes in atmospheres and ionospheres, it is important to provide user communities with accuracy, precision, and time-resolution in solar irradiance products. Between 2002 and 2004 there have been significant changes in space systems operations and in space physics that are relevant to solar XUV and VUV irradiance specification and these include improved Earth thermospheric mass density specification, GAIM maturity, Venus to Saturn aeronomy studies, accurate XUV and VUV irradiance measurements by TIMED SEE, and the ISO solar irradiance standard 21348 development. These have been motivating factors for providing improvements in solar irradiance products.

We introduce operational definitions of solar irradiance products in this paper including: (a) *time states* of *past, present*, and *future* data; (b) *current epoch, historical* or *previous, nowcast* or *current*, and *forecast* or *predicted* data; (c) operational *enhanced* or *core data streams*; (d) *cadence*. In addition, user groups of solar irradiance products and applications are described.

We describe research and operational objectives for developing SOLAR2000 irradiance products to enable their linkage with other legacy code applications. We review six formats of integrated irradiance products, i.e., $E_{10.7}$, Q_{EUV}, P_{EUV}, T_{∞}, R_{SN}, and S in addition to the spectral irradiance, I_{λ}, and introduce seven new ones including E_{1_40}, $XE_{10.7}$, X_{b10}, X_{hf}, $X_{10.7}$, E_{SRC}, and E_{SRB}. There have been four major upgrades to SOLAR2000 from v1.24 to v2.24 and these: (a) provide spectral variability from the XUV/EUV through the FUV/UV; (b) incorporate the TIMED SEE v7 data set as part of the derivation of S2K EUV; (c) provide user flexibility through the IDL 6.0 virtual machine (VM) used by the S2K model so users can run the model on any platform; (d) allow an operational user to access the SET server hourly cadence, daily time resolution irradiance product forecasts out to 137 days (4.5 months or five solar rotations) from the current epoch with the S2K PG model. Historical, nowcast, and forecast improvements to S2K are described and, for the first time, SOLAR2000 irradiance products are compliant with ISO 21348.

Acknowledgments

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