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SOLAR2000 irradiances for climate change research, aeronomy and space system engineering

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Abstract

Improvements to spectral and temporal solar irradiances are often based upon increasingly accurate and precise measurements as well as upon better understood physics. This paper reports on one example in an emerging trend for solar irradiance models that can be characterized as hybrid irradiance modeling. Empirical and physics-based modeling of irradiances are combined and take advantage of strengths within both methods to provide a variety of solar irradiance products to science and engineering users. The SOLAR2000 (S2K) version 1.24 model (v1.24) described in this paper has gone through 17 upgrades since it was originally released in 1999 as v0.10 and now incorporates three theoretical continua, 13 rocket spectra, and time series data from five satellites using 17 instruments. S2K currently produces six integrated irradiance proxies for science and engineering applications in addition to spectrally resolved irradiances in three common wavelength formats. Integrated irradiance proxies include the E10.7 integrated EUV energy flux, Q_{EUV} total thermospheric EUV heating rate, P_{EUV} hemispheric EUV power, T_∞ exospheric temperature, R_{SN} derived sunspot number, and S integrated spectrum. Besides three spectral wavelength and six integrated irradiance formats there are three time frames of historical, nowcast, and forecast irradiance products produced by four model grades. The Research Grade (RG) model is developed for aeronomical and climate change research, the Professional Grade (PG) model is developed for space system engineering applications, the Operational Grade (OP) model is developed for institutional and agency real-time operational space weather applications, and the System Grade (SY) model is developed for commercial operational and production applications. This report describes these model characteristics as well as the current state of operational irradiances which are now in the second release of a first generation forecast methodology. Forecast Generation 1x (FGen 1x) produces a 72-h forecast of E10.7 at high solar activity with 1-sigma uncertainties at the 8% level. All SOLAR2000 irradiance products from each of the versions, grades, and forecast generations are compliant with the ISO CD 21348 solar irradiance draft standard being developed as a standard method to specify all solar irradiances for use by space systems and materials users.

Keywords: SOLAR2000; Modeled solar irradiances; Solar proxies; Aeronomy; Space system operations; ISO CD 21348

1. Background

1.1. Motivations for improving solar irradiance spectral and temporal characterization

Because the full-disk solar spectrum is a foundation for understanding scattering and photoabsorption processes in Earth's atmosphere and ionosphere, it is important that an accurate, precise, and time-resolved spectral characterization is available. Solar irradiances vary with time and wavelength due to geometry and energy distribution processes on the Sun and their spatial, spectral, and temporal characteristics are primarily determined from measurements. Although the absolute accuracy and the precision of solar irradiances is continually being refined from space-based measurements, there are still spectral and temporal gaps in the measurement record.

In order to fill these gaps, especially in the Vacuum Ultraviolet or VUV ($200 > \lambda \geqslant 10$ nm) spectrum, rockets have been flown and reference spectra formed in the past five decades of space instrumentation (1946–1996). The VUV spectrum is important for space

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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, Examples of rocket-based reference spectra include the Air Force Geophysics Laboratory (AFGL) rocket spectra (using the YYDDD format) F74113, SC21REFW.EUVS, F79050N, F79226, and F79314 followed by the University of Southern California (USC) rockets on 1982-222, 1983-228, 1988-298, 1996-318 (SERTS) and the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) rockets on 1988-315, 1992-301, 1993-277, 1994-307.

While rocket measurements and reference spectra are still useful for particular days, generalized conditions, or satellite calibrations, temporally resolved irradiances were required for science campaigns and engineering design. Empirical models based on the satellite measurements started their development in the late 1970s where irradiance values parameterized through flux surrogates or proxies were created. Examples include SERF1 (Hinteregger et al., 1981; Hinteregger, 1985), Nusinov (1984), SERF2 (Tobiska and Barth, 1990), EUV91 (Tobiska, 1991), EUVAC (Richards et al., 1994), EUV97 (Tobiska and Eparvier, 1998), and SOLAR2000 (Tobiska et al., 2000).

However, by the late 1980s, several communities realized that more accurate and precise solar irradiance specification was needed at all spatial, spectral, and temporal resolutions. For example, the solar physics community, in Solar Dynamics Observatory (SDO) pre-mission literature, summarized their desire to know *what mechanisms drive the quasi-periodic 11-year cycle of solar activity, where do the observed variations in the Sun's total and spectral irradiance arise, and how do they relate to the magnetic activity cycles?* Another community, global climate change, concluded through the US National Research Council (NRC) Board on Global Change, Commission on Geosciences, Environment, and Resources National Academy of Sciences (1994), that "solar variations directly force global surface temperature, solar variations modify ozone and the middle atmosphere structure, solar variability effects in the Earth's upper atmosphere (and possibly) couple to the middle atmosphere and the biosphere, (but it is unknown if) solar variability effects in the Earth's near-space environment couple to the biosphere, (and) we need to improve our knowledge of the variable Sun to understand and predict solar influences on global change." By the mid-1990s, the satellite operations and the HF radio propagation communities wanted more accurate, precise, and temporally-resolved solar variability in integrated flux or solar flux proxies to run their operational atmospheric density systems for satellite drag and for ionospheric-based ray-trace models. The combined, emerging demand from these types of communities motivated the solar irradiance modeling community to re-evaluate the types of products it issued.

In a parallel development, it was broadly recognized that spectral variability precision can be significantly improved beyond measurements and empirical models by using empirical and physics-based modeling, either separately or in a hybrid fashion. An example of physics-based modeling includes the SunRISE spectral synthesis model (Fontenla et al., 1999; Fox et al., 2004) and an empirical/physics-based hybrid is the differential emission measure model NRLEUV (Warren et al., 2001). Beginning in model version 2, SOLAR2000 will also join the hybrid model ranks and this paper reviews the status of SOLAR2000 in its final stages as an empirical model.

From a space weather operations viewpoint, solar irradiance accuracy and precision have been improved by recent total solar irradiance (TSI) (Fröhlich and Lean, 1998) specification and spectral measurements (Woods et al., 2000a,b). Tobiska (2003) describes how this measurement knowledge has been transferred to operational solar irradiances. In a sense, the convergence of community pressures, on one hand, and the advances in measurements and modeling, on the other hand, have pushed breakthroughs in spectral and temporal solar irradiance specification. The emerging trend behind the breakthroughs is the formation of hybrid irradiance models that incorporate data with physics and that have energetically self-consistent irradiance formats which are useful for research, production design, or operations. It is the convergence of these pressures that is also demanding model and measurement harmonization and the section below related to an International Standards Organization (ISO) solar irradiance standard discusses this topic.

1.2. Climate change research and space weather: nomenclature and challenges

A note on space weather nomenclature is useful here. The shorter-term variable impact of the Sun's photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment that can adversely affect our technological systems is colloquially known as *space weather*. It includes, for example, the effects of solar coronal mass ejections, solar flares, solar and galactic energetic particles, as well as the solar wind, all of which affect Earth's magnetospheric particles and fields, geomagnetic and electrodynamical conditions, radiation belts, aurorae, ionosphere, and the neutral thermosphere and mesosphere. Some terms are acquiring specific meanings as a result of operational experience. The word *historical* is used in this report in relation to data that is well-measured or characterized earlier in time than 24 h in the past. The term *forecast*, i.e., a prediction based upon calculation as used by the space physics community, refers to the time frame starting at the current epoch and proceeding into the future. The phrase *current epoch* refers to the present instant in time as used in the reference sense by the astrodynamics community. The term *nowcast* is ill-defined but has become quite useful as it appropriately describes the period from 24 h in the past up to the current epoch in an operational sense. Because space weather products are now being created using coupled models that require many inputs, some of the input data has arrived in the past 24-h period while other data has not yet entered the operational system. Therefore, knowledge of a parameters' state in the 24-h period leading up to the current epoch utilizes both measured and estimated values. The term nowcast is useful for defining a longer time frame than the current epoch, for conveying the sense of the present, and for indicating that uncertainty still exists about the actual state. *Cadence* is used in this report as the shorthand description for an operational task that occurs on a fixed time interval with regularity.

Fundamental questions have been articulated by the solar physics community that reflect the interests of other scientific and engineering disciplines such as global climate change research and space systems engineering. For example, when will major geo-effective solar events occur, especially those affecting space and ground technological systems, and how accurate as well as reliable can forecasts be made of space weather parameters out to climatological conditions? Higher accuracy and precise solar irradiances useful for climate research and aeronomy are now measured by the NASA TIMED and SORCE missions. The characterization of variable solar spectral irradiances on multiple time scales will advance our understanding of how and why the solar spectral irradiance varies which will improve our capability of predicting its variability. Data from these missions and eventually from SDO, when combined into space physics models, help us to understand the geospace environment response to variations in the solar spectral irradiance and the impact on technological ground and space systems. These fundamental questions present challenges and one challenge is to operationally integrate these improved measurements with models to reliably forecast near-term geo-effective events out to climatological conditions.

The discussion below on improvements in SOLAR2000 v1.24 reports activities that address the operational integration challenge. A particular issue of this challenge, from a space weather perspective, is that space and ground systems require generalized solar irradiances to be translated into timely, accurate/precise historical, nowcast, and forecast products that are easily coupled with operational models. To meet space weather operational model requirements, we use guidance from the US National Space Weather Program Implementation Plan (NSWP, 2000). That document summarizes a collective effort to improve the understanding of the near-Earth space environment by encouraging the development of empirical and physics-based models to forecast and specify the environment. The end result of our work is leading to an operational and research tool for servicing space system engineering, aeronomy, and climate research users. We report on progress toward making SOLAR2000 that tool in the next sections. The solar irradiance products' applications, their users, and their users' needs have been described elsewhere (Tobiska et al., 2000, 2001).

1.3. Improvements to SOLAR2000 through version 1.24

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. SOLAR2000 is a tool for research and operations that is designed with these goals in mind. This evolving tool contributes to answering key solar physics and Earth climate change scientific questions, provides operational capabilities for space weather applications, and supports solar irradiance specification programmatic goals.

SOLAR2000 irradiance products are designed to be fundamental energy inputs into planetary ionosphere, atmosphere, and surface models. SOLAR2000, especially through the E10.7, Q_{EUV}, P_{EUV}, T_{∞}, R_{SN}, and S solar proxies, is a particularly useful tool to model and/or predict the solar radiation component of the space environment for space and ground systems using parameterized integrated irradiances based on spectrally resolved information. The v1.24 model characterizes solar irradiance variability across the soft X-ray and extreme ultraviolet spectrum through Lyman-alpha (121.6 nm). It produces energy flux and photon flux in the spectral range of 1–1,000,000 nm (1 nm–1 mm) for historical irradiances from February 14, 1947 through a few weeks before the current epoch. At wavelengths longer than Lyman-alpha, the vl.24 model uses the ASTM E-490 solar spectral standard. Across the spectrum, SOLAR2000 is compliant with the ISO CD 21348 solar irradiance draft standard.

1.4. Model upgrade and release convention

Regular and continuous upgrades to SOLAR2000 are occurring during the first half of the decade starting in 2000. These upgrades include additional spectral range variability (FUV, UV, VIS, IR), enhanced accuracy with the inclusion of new datasets and improved proxy regression algorithms, improved specification of the uncertainty in the irradiances, the development of nowcast and forecast irradiances along with the historical representations, and the development of new integrated irradiance proxies for user communities. The model has been upgraded 17 times between October 7, 1999 (v0. 10) (Tobiska et al., 2000) and September 11, 2002 (v1.24) through the publicly released S2K Research Grade (RG) model. S2K RG currently has over 400 registered users across 40 countries. The convention for the model grade designation is:

RG is Research Grade providing daily historical data on a platform-independent application;

PG is Professional Grade (formerly Contract Grade) providing daily historical, nowcast, and forecast data and analysis tools on a platform-independent application;

OP is Operational Grade providing daily historical, hourly nowcast, 72-h (3-h interval) forecast, and daily forecast data on a platform-independent operational server;

SY is System Grade (formerly Commercial Grade) providing historical, nowcast, forecast data in all time resolutions and with built-in analysis tools, accessible asynchronously/autonomously from a server or as a turn-key system.

While SOLAR2000 v1.24 is only variable in the XUV/EUV part of the spectrum, upgrades in progress include v2.00 FUV variability, v3.00 VIS/IR variability, and v4.00 physics-based model variability. The upgrades through v1.24 described here since the original SOLAR2000 paper (Tobiska et al., 2000) covers the two areas of data and code improvement. The versioning convention of *x. yz* for SOLAR2000 upgrade releases is:

x variability of the model's spectral range:

1 empirical XUV/EUV (1–122 nm);
2 empirical XUV–UV (1–420 nm);
3 empirical XUV–IR (1–2000 nm);
4 hybrid empirical and physics-based (1–1,000,000 nm);

y data improvement:

0 original 12 rocket observations (AFGL f74113, sc21refw, f79050n, f79226, f79314; USC 82222, 83228, 88298, SERTS_96; LASP nov_1988, 1992, 1993, 1994), one reference spectrum (ASTM E-490), four satellite datasets (SOLRAD, AEE monochromators, YOHKOH/SXT, SOHO/CDS), and three theoretical spectra (Avrett);
1 SOHO (SUMER, SEM, CDS accuracy in solar minimum short wavelengths);
2 SNOE, TIMED (SEE) and SDO (EVE) (accuracy in all spectra <200 nm);
3 UARS, TIM, and SIM (UV, VIS, IR accuracy);
4 ISS (SOL-ACES, SOLSPEC, TSI) (solar cycle upgrade to full spectrum);
5 GOES EUV and POES UV/VIS data (minutely time resolution); and

z code improvement and bug fixes:

0–9 new features, algorithm, and code improvements;
a minor bug fixes; and
b internal beta test version.

1.4.1. Data inclusion

The derivation data sets used through SOLAR2000 v1.24 and outlined in the above section include: theoretical He, H, and C continua emissions produced by E. Avrett (private communication, 1996) for active through quiet center-of-Sun conditions; the AFGL rocket spectra F74113 (Heroux and Hinteregger, 1978), SC21REFW.EUVS, F79050N, F79226, F79314 (H. Hinteregger private communication, 1985); the USC rocket broadband spectra on 1982-222, 1983-228, 1988-298 (D. Judge, private communication, 1995); the LASP rocket spectra on 1988-315, 1992-301, 1993-277, 1994-307 (T. Woods, private communication, 1995); the USC SERTS rocket spectrum on 1996-318 (D. Judge, private communication, 1998); the SOHO/CDS atlas (Thompson and Brekke, 2000) for 1998-113, 1998-141, 1998-173; the AE-E satellite data from 1977-182 to 1981-160 SC21OBSC.DAT (NSSDC archives); the revised SOLRAD-11 satellite data (F. Eparvier, private communication, 1996; Tobiska and Eparvier, 1998) from 1976-085 through 1979-265; the YOHKOH/SXT satellite data (L. Acton, private communication, 1999) from 1991-274 through 1999-243; the SOHO/SEM satellite data (D. Judge and D. McMullin, private communication, 2001) from 1996-001 through 1999-365; and the SNOE/SXP satellite data (S. Bailey, private communication, 2001) from 1998-070 through 1999-249.

In particular, beginning with the v1.15 release, the SOHO/SEM data from the central and first order daily average data sets greatly improved the multiple linear regression correlation coefficients for wavelengths less than 50 nm. Starting with v1.20 of the model, the SNOE data from the SXP_E1, SXP_E3, and SXP_E4 detectors significantly improved the soft X-ray (XUV) irradiances shortward of 26 nm. The model is calibrated to the designated primary data sets' absolute irradiance values (SNOE and SOHO/SEM in vl.24) while secondary data sets improve the relative day-to-day variability and/or the solar minimum and maximum values. The weighting functions for each data set used by the model's multiple linear regression algorithm are generated from the published instrumental uncertainties. The secondary data sets have less weight than the primary data sets and are absolutely scaled, within their 1-sigma uncertainty limits, to better match the absolute values of the primary data for improved regression results. The hierarchy of data sets in the derivation of SOLAR2000 v1.24 is the following and is based on absolute weighting. The ↥ character indicates that a data set on this line is reset to the absolute values represented by the data set on the line above it.

SDO/EVE (0.1–105 nm,)	primary spectral/temporal data set (2007–)
SORCE/TIM,SIM,SOLSTICE,XPS (1–2000 nm)	primary spectral/temporal data set (2003–)
└ **TIMED/SEE** (1–200 nm)	primary spectral/temporal data set (2002–)
└ GOES/EUV (1–122 nm)	primary temporal data set (2005–)
└ SNOE/SXP (2.0–6.0, 6.0–18.0, 18.0–27.0 nm)	primary spectral/temporal data set (1998–1999)
└ SOHO/SEM (1–50, 26–34 nm)	primary spectral/temporal data set (1996–1999)
└ sounding rockets (1–105 nm)	primary spectral data set (1974–1996)
└ SOHO/CDS (30.8–37.9, 51.3–63.3 nm)	secondary spectral data set (1998)
└ AE-E (16.8–102.6 nm)	secondary spectral/temporal data set (1977–1981)
└ SOLRAD-11 (1.8–3.0, 3.0–5.0 nm)	secondary spectral/temporal data set (1976–1979)
└ YOHKOH/SXT (2–3, 3–4 nm)	secondary spectral/temporal data set (1991–1999)

The S2K v1.24 derivation statistics indicates that the average correlation coefficient across all wavelengths is 0.97 with a range of correlation coefficients between 0.79 and 1.00. Figs. 1 and 2 demonstrate typical regressions using F10.7 as the coronal proxy (key = 2) and Lyman-alpha as the chromospheric proxy (key = 1). The average of all key values is 1.09, i.e., more chromospheric than coronal component in the photon flux of EUV emission from 1 to 105 nm. Fig. 3 shows the improvement in correlation coefficients from vl.05 to vl.24 due to new data inclusion.

1.5. Integrated solar irradiance proxies

With the release of v1.24, there are a total of six integrated flux irradiance proxies that are produced for the benefit of specific user communities. These proxies are provided in addition to the three spectral irradiance wavelength formats of 1 nm bins full spectrum from 1–1,000,000 nm, 39 EUV wavelength groups/lines from 1 to 105 nm, and 809 EUV lines from 1 to 105 nm. Each wavelength format is reported in three flux formats of energy (ergs $cm^{-2}\,s^{-1}$), photon (photons $cm^{-2}\,s^{-1}$), and SI units ($W\,m^{-2}$). The six v1.24 proxies are the E10.7 which is produced for empirical thermospheric and ionospheric model applications, the Q_{EUV} thermospheric heating rate created for comparative aikglow-derived versus solar-derived upper atmosphere heating, the P_{EUV} which is the EUV hemispheric power provided as a complement to the auroral hemispheric power index, the T_∞ which is the exospheric temperature and is useful for long-term climate change studies, the R_{SN} derived sunspot number for use by operational HF radio ray-trace algorithms, and the S integrated solar spectrum used for solar radiation pressure calculations related to spacecraft attitude control. The proxies are described in more detail in the next sections.

1.5.1. E10.7

E10.7 is the integrated extreme ultraviolet (EUV) energy flux (1–105 nm) at the top of the atmosphere reported in units of 10.7-cm radio flux, F10.7 ($\times 10^{-22}$ $W\,m^{-2}$ Hz^{-1}). There have been previous descriptions of the E10.7 proxy derivation, use, and validation (Tobiska et al., 2000, 2001, 2003). Operational E10.7, as a solar input into empirical thermospheric density models, is used for satellite operations to quantify satellite drag. In empirical ionospheric models it is used as a solar driver to help

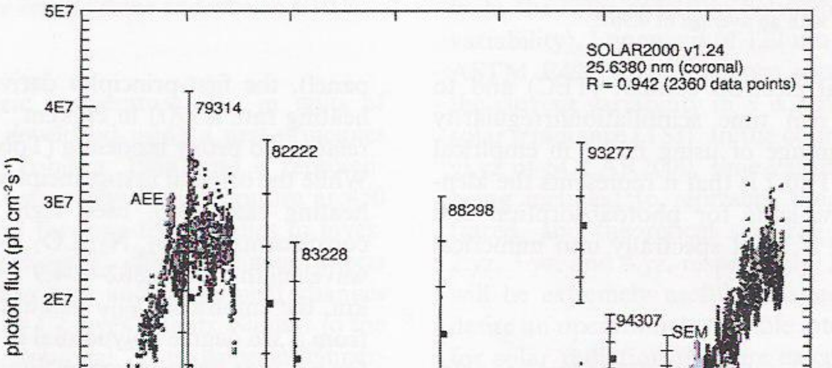

Fig. 1. S2K v1.24 regression plot for F10.7 and the 25.638 nm coronal line with time on the x-axis and photon flux (ph $cm^{-2}\,s^{-1}$) on the y-axis. Solid black dots are the S2K model values, error bar and large dots are rocket flights, light gray after 1998 is the SNOE data, medium gray after 1996 is the SOHO/SEM data, medium gray prior to 1980 is the AE-E data. With eight rockets and three satellite data sets in this derivation totaling 2360 data points, the regression coefficient was 0.94, mostly dominated by long-term trends across all the data sets.

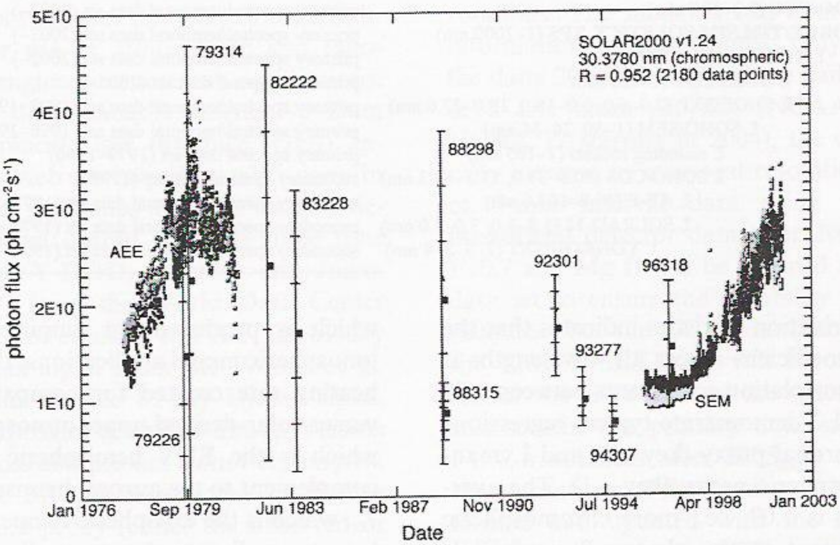

Fig. 2. S2K v1.24 regression plot for Lyman-alpha and the 30.378 nm chromospheric line with time on the x-axis and photon flux (ph $cm^{-2}\,s^{-1}$) on the y-axis. Solid black dots are the S2K model values, error bar and large dots are rocket flights, medium gray after 1996 is the SOHO/SEM data (central and first order), medium gray prior to 1980 is the AE-E data. With 10 rockets and three satellite data sets in this derivation totaling 2180 data points, the regression coefficient was 0.95, mostly dominated by long-term trends across all the data sets.

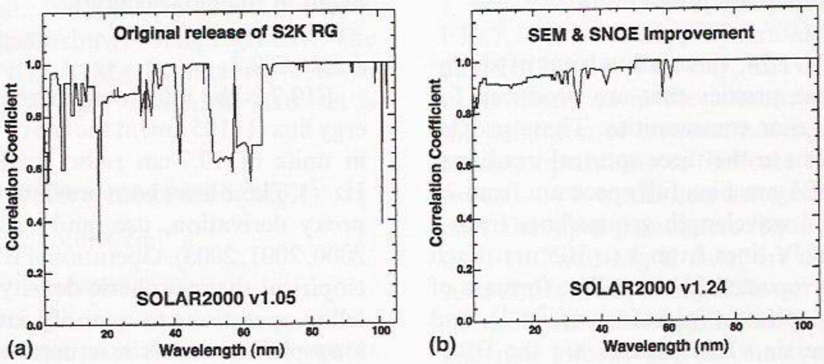

Fig. 3. Panel (a): SOLAR2000 v1.05 correlation coefficients by wavelength with an average of 0.928; panel (b): SOLAR2000 v1.24 correlation coefficients by wavelength with an average of 0.967.

characterize the total electron content (TEC) and to provide GPS near real time scintillation/irregularity knowledge. An advantage of using E10.7 in empirical models compared to F10.7 is that it represents the identical solar energy available for photoabsorption and photoionization that is input spectrally into numerical models.

1.5.2. Q_{EUV}

Q_{EUV} is derived from the time-dependent, t, solar heating of the thermosphere and is a function of EUV energy by wavelength, $I(\lambda, t)$, altitudinal heating efficiency, $\epsilon(\lambda, z)$, unit optical depth, $\tau(\lambda, z)$, absorption cross section of each neutral species, $\sigma_{\square}(\lambda$ and density of each species, $M_{\mathrm{i}}(z)$. These quantities, combined, become the constituent volume–heating rate in the thermosphere, $q_{\mathrm{i}}(\lambda, z, t)$. Integrated across all species (Fig. 4, left panel), wavelengths, (Fig. 4, right panel) and altitudes for a unit of time (total value reported in Fig. 4, left panel), the first-principles derived total thermospheric heating rate is $Q(t)$ in ergs $cm^{-2}\,s^{-1}$ and is described in relation to proxy modeling (Tobiska, 1988, 2000, 2001). While the original first-principles calculation of the daily heating rate, $Q(t)$, used eight neutral thermospheric constituents (O, O_2, N_2, CO_2, NO, He, H, and N), 809 wavelengths for 1.862–104.9 nm, and $z = 120 - 1000$ km, the empirical Q_{EUV} heating rate proxy was derived from a 3rd degree polynomial fit between $Q(t)$ and E10.7 for a 6-year period starting January 1, 1996 and ending December 31, 2001, i.e., the rise of solar cycle 23. Q_{EUV} is available on the same cadence as E10.7.

1.5.3. P_{EUV}

An EUV hemispheric power proxy, P_{EUV}, in units of Watts, has been developed and is complementary to the auroral hemispheric power index. It is designed for science research and operations. The SOLAR2000 model is run in the energy flux, $I(\lambda, t)$, mode

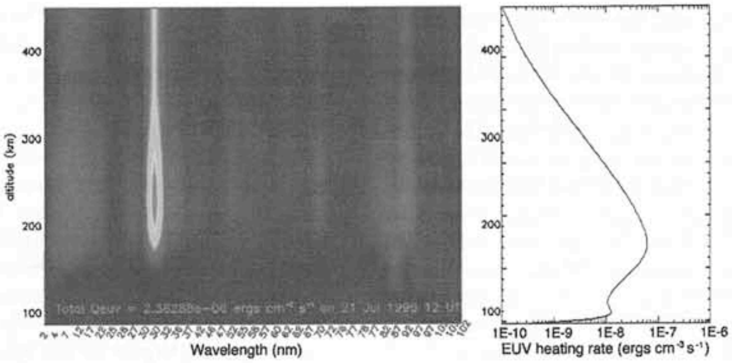

Fig. 4. Thermospheric volume EUV heating rate (left panel) as produced by the 1-D time dependent (1DTD) first principles atmospheric model as a function of wavelength and altitude. The integrated EUV heating rate across all wavelengths (right panel) by altitude shows the location of maximum EUV heating on a given date. The total daily heating rate from the EUV is integrated from these values and reported as $Q_{\rm EUV}$.

(ergs cm^{-2} s^{-1}) for 809 wavelengths and the flux values are summed across all wavelengths from 1 to 105 nm. This value is approximately 6 erg cm^{-2} s^{-1} for an average level of solar activity. If this solar energy is input across the disk of Earth, then a first-order number can be derived that is useful for comparison with the daily heating rates in the auroral oval. $P_{\rm EUV}$ is calculated in Eq. (1) to produce a value of 765 GW for 6 erg cm^{-2} s^{-1} energy flux.

$$P_{\rm EUV} = \pi R^2 \sum_{\lambda=1}^{105} I(\lambda, t)({\rm ergs\,s^{-1}}) \times (2.77 \times 10^{-11}\ {\rm W\,h\,erg^{-1}}) \times (3600\ {\rm s\,h^{-1}})\ {\rm W}, \quad (1)$$

where R is the Earth's radius of 6.378×10^8 cm. EUV heating is greater than auroral hemispheric power except during storm periods (D. Knipp, private communication, 2002). $P_{\rm EUV}$ is available on the same cadence as E10.7.

1.5.4. T_∞

A derived exospheric temperature, T_∞, in units of Kelvin (K), has been developed using a first-principles thermospheric model (Tobiska, 1988) and is representative of the neutral thermospheric temperature at 450 km. This value is useful for long-term studies to investigate potential anthropogenic climate change effects (cooling) in the thermosphere and subsequent changes to the ionospheric E and F2 layer heights. Similar to the $Q_{\rm EUV}$ calculation, the empirical T_∞ exospheric temperature proxy was derived from a 3rd degree polynomial fit between $T_{450}(t)$ and E10.7 for a 6-year period starting January 1, 1996 and ending December 31, 2001. T_∞ is available on the same cadence as E10.7.

1.5.5. R_{SN}

The $R_{\rm SN}$ proxy has been developed for operational use in ray-trace algorithms that historically use the Wolf sunspot number, R_z. $R_{\rm SN}$, dimensionless, is the derived sunspot number and, similar to the calculation of $Q_{\rm EUV}$, is derived from a 3rd degree polynomial fit between R_z and E10.7 for a 6-year period starting January 1, 1996 and ending December 31, 2001. $R_{\rm SN}$ differs from R_z during solar maximum conditions and does not reach the highest values of R_z, hence providing a capability for representing more accurately the variations in the ionosphere that derive directly from solar EUV photoionization. $R_{\rm SN}$ is available on the same cadence as E10.7.

1.5.6. S

The integrated solar spectrum, S, in units of W m^{-2}, is provided to researchers who desire the integrated spectrum variability relative to a reference, full solar spectrum. A description of the derivation, absolute value, and variation of S provided by SOLAR2000 is found in Tobiska et al. (2000, 2002a,b). In early versions of the SOLAR2000 model (vl.yz), the variability comes from the solar spectrum between 1 and 122 nm (EUV variability). Longward of 122 nm in the vl.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). In the course of upgrades beyond vl.yz of SOLAR2000, time-varying spectral models are being included to represent the ultraviolet, visible/infrared, and theoretical spectral variability in versions 2.yz, 3.yz, and 4.yz, respectively. 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. In v4.yz, a high spectral resolution of the Sun's irradiances will be provided for use in satellite imagery calibration. S is available on the same cadence as E10.7.

1.6. Historical, nowcast, and forecast irradiances

1.6.1. Historical

SOLAR2000 irradiances and proxies are used for both operational systems and for research. The S2K

Research Grade model produces daily historical irradiances and proxies for use in atmospheric and ionospheric scientific and engineering research applications. It is available via a downloadable Interactive Data Language (IDL) Graphical User Interface (GUI) application located at the web site http://SpaceWx.com. In addition to the spectral irradiance and flux formats described above, the model output provides three time formats including YYYY-DDD, calendar and Julian dates, the daily F10.7 from the World Data Center (WDC), either observed or adjusted to 1 AU, the 81-day F10.7, the daily Lyman-alpha from the Woods et al. (2000a) composite data set, the 81-day Lyman-alpha, and the six irradiance proxies described above. Version 1.24 provides irradiances and proxies from February 14, 1947 through July 31, 2002. It creates the irradiances using the F10.7 coronal proxy (either the observed or adjusted values, i.e., there are two separate versions of S2K) and the Lyman-alpha chromospheric proxy which is the Woods' composite five solar cycle set through June 23, 2001 followed by the NOAA 16 Mg II core-to-wing ratio data (Mg II) scaled to Lyman-alpha (Viereck and Puga, 1999; Viereck et al., 2001; the ftp data is available at http://sec.noaa.gov/ftpdir/sbuv/NOAAMgII.dat). The relationship between NOAA Mg II data reported in these references and the Woods' composite data set is given in Eq. (2).

$$\text{Lyman-alpha} = (-30.239579 + 128.09029 \times \text{MgII}) \times 1\text{e}11 \text{ photons cm}^{-2}\,\text{s}^{-1}. \quad (2)$$

1.6.2. Nowcast

Nowcast irradiances and proxies, using the operational NOAA 16 SBUV Mg II data for the chromospheric proxy from Eq. (2) and the 20 UT observed F10.7 for the coronal proxy, are provided by the S2K Operational Grade model vl.24 located at NOAA Space Environment Center (SEC) in Boulder, Colorado (http://sec.noaa.gov/spacewx/). Fig. 5 demonstrates the current E10.7 (gray bars) compared with the 20 UT observed F10.7 (dashed line) for the current epoch (nowcast) and the previous 54-days, i.e., two solar rotations. The model is run hourly and, although the information content changes only twice per day using the daily 20 UT F10.7 and the daily Mg II (NOAA 16), or a few times per day (NOAA 16 combined with NOAA 17 starting in 2004), the cadence will dramatically increase in temporal resolution with the inclusion of 5-min interval data using the GOES-N EUV broadband detector data after 2005. At that time, the F10.7 and Mg II will be retained as a redundant proxy data set to ensure the capability of calculating the irradiances but the GOES data, absolutely calibrated to the TIMED/SEE data, will become the primary data set for the EUV part of the spectrum. The Mg II will still remain the primary data set for calculating the FUV irradiances after 2005. In addition to graphical representations of the irradiances, nowcast data files are located and updated with the same hourly cadence at SEC's anonymous FTP server http://sec.noaa.gov/ftpmenu/lists/spacewx.html. The files located at that site of "E10.7 nowcast data", "Solar spectral data", and "Validation of today's E10.7 data" provide the nowcast E10.7 with ±1-sigma values, the full solar spectrum at 1 nm resolution, and comparative nowcast data of F10.7, F10.7 81-day, Lyman-alpha, Lyman-alpha 81-day, E10.7, E10.7 81-day, and *S*.

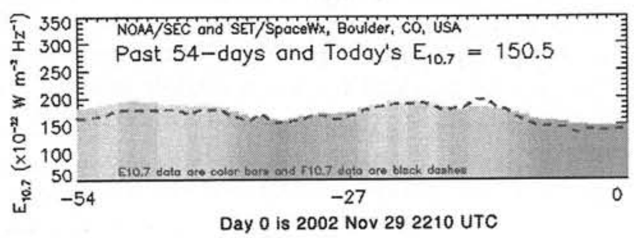

Fig. 5. The current E10.7 (gray bars) compared with the 20 UT observed F10.7 (dashed line) for the current epoch (nowcast) at day 0 and the previous 54-days, i.e., two solar rotations.

As described in the nomenclature discussion above, the definition of nowcast has been slightly modified in current operations to indicate the period of time between −24 h to the current epoch. Starting 24 h in the past, the input parameters required for model runs, i.e., the F10.7 and Mg II data, are already operationally issued and will not change. However, at the current epoch "0" hour the solar conditions will have changed slightly and new information has not yet been received to exactly define what the new proxy values are. Hence, an estimate made of the current conditions, and the interpolation from known to unknown conditions during the past 24-h, constitutes a nowcast.

1.6.3. Forecast

Forecast and high time resolution irradiances and proxies are provided operationally via the Space Environment Technologies (SET) server for government and commercial customers. The first (current) Forecast Generation algorithm is denoted FGen 1x 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. Tobiska (2003) provides a descriptive overview of this type of forecast.

For example, with FGen 1x, the forecasts for next 72-h are produced on a 3-h cadence and synchronized with the release of the NOAA/SEC and US Air Force Kp and ap geomagnetic indices. Recent comparisons between the SET and SEC forecasts of F10.7 and E10.7 are shown in Fig. 6 for the time frame covering the first

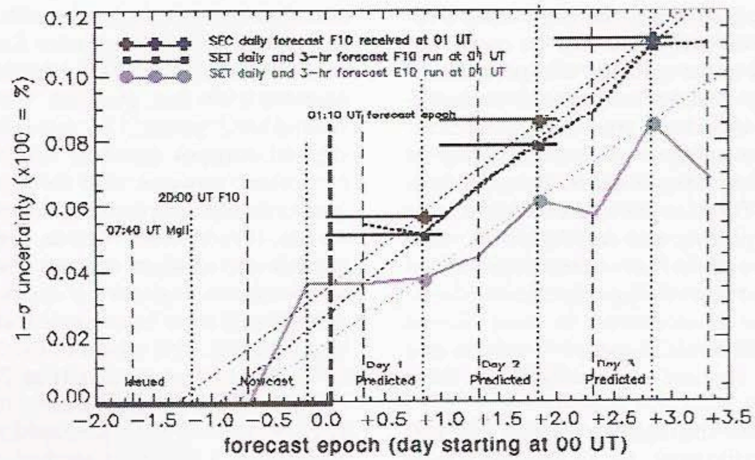

Fig. 6. SET E10.7 (light gray dots) and F10.7 (black dots) are compared with NOAA/SEC F10.7 (dark gray pluses) 1-sigma uncertainties. Dotted lines are the interpolated uncertainties for each forecast epoch while the dots are the daily forecast uncertainties. The current epoch at "0.0" on the x axis indicates the time at which a forecast was generated every 3 h for the first 200 days of 2001.

200 days of 2001. This period was at the height of solar cycle 23 activity and the flux demonstrated non-stationary behavior. During this time, SEC and SET separately forecasted the F10.7. In addition, SET forecasted the E10.7 which was derived from SET forecasts where F10.7 and Mg II were used as inputs into the SOLAR2000 model. Forecasts were made every 3 h for 1–3 days for all three proxies and the forecasts were then compared to the actual values on the appropriate days. In order to assess the forecast quality, the ratio of forecast to actual data for each proxy, covering the entire 200-day time series, was created. From these time series ratios, the 1-sigma uncertainties were determined for 1-, 2-, and 3-day forecast cases. The 1-sigma standard deviation of these time series ratios can be thought of as percentages of error and are the values shown in Fig. 6. Overall, the SET F10.7 forecast slightly improved upon the SEC F10.7 forecast but the SET E10.7 forecast significantly improved upon either case of F10 7. Approximately 90% of the E10.7 calculation is based upon the Mg II proxy which has less variability than F10.7. This translates into less uncertainty and that advantage is carried over into the derivation of E10.7. It can be seen in Fig. 6 that the SET F10.7 forecast improvement upon the SEC F10.7 forecast is achieved with lowered uncertainty of approximately 0.5–1% while the E10.7 moves the uncertainty an additional 2% lower.

Space Environment Technologies also provides forecast irradiances for longer timescales out to the next solar cycle and beyond. Tobiska (2003) describes these forecasting activities in more detail. Improvements to forecasting beyond FGen 1x are being developed for FGen 2, also described in this reference.

1.7. The draft ISO solar irradiance standard CD 21348

The International Standards Organization (ISO) Committee Draft (CD) 21348 draft International Standard, "Process for Determining Solar Irradiances", can be viewed at the "ISO irradiances" link at http://SpaceWx.com. Tobiska and Nusinov (2000) describe the evolution and details of this draft standard. It specifies all representations of solar irradiances and is applicable to measurement sets, reference spectra, empirical models, and theoretical models that provide solar irradiance products. Its purpose is to provide a standard method for specifying all solar irradiances for use by space systems and materials users.

Because knowledge of solar irradiance spectral and temporal characteristics is fundamental to the understanding of a wide variety of physical processes and technical issues, and because solar irradiances have been reported in a variety of formats, standardization of solar irradiance specification is important for ease of international and interdisciplinary use. With a common, standard format of SI units for solar irradiances, community-specific formats will not necessarily disappear but will become useful to wider disciplines. Standardization of solar irradiances enables suppliers and users of solar products to exchange information with common, understandable formats. Solar irradiance products derived from measurements and/or models are frequently reported to space systems users and a common format enables easy, rapid exchange of information. Examples of solar irradiance products include spectral and time series intensities, surrogates or proxies intended to represent solar irradiances, and solar images with spectral content.

A fundamental concept behind the draft solar irradiance standard assumes that there will be continued technical improvements in the accuracy and precision of ground-based and space-based measurements as instruments use new detectors, filters, and computer hardware/software algorithms. Improved understanding of the physical processes occurring at the Sun also leads to improved irradiances. There is the expectation of continual change in the reporting and calculation of reference spectra, empirical, and first-principles models and it is likely that there will be an evolving solar standard user community. Given new developments in these diverse areas, the draft solar irradiance standard is written as a robust document to support and encourage these changes.

Robustness is achieved through the content and format of the draft standard. First, the draft solar irradiance standard does not specify one measurement set, one reference spectrum, or one model as a single standard. Second, to encourage continual improvements in solar irradiance products, the solar irradiance standard is a process-based standard. This means that as one develops a solar irradiance product, he or she follows a reporting process which results in self-compliance with the standard.

Because the draft standard is process-based, i.e., no specific product is selected as the standard, and because the scientific and engineering communities require some type of detailed solar irradiance specification for their-separate activities, a parallel activity is in progress to provide a published volume of measurement sets, reference spectra, and models that certify compliance with this standard. It is anticipated that a volume will be published as part of a special 2004 COSPAR session and that the volume will contain adequate material to satisfy the solar science, space systems, and materials users communities.

2. Conclusion

There are strong motivations for improving solar irradiance spectral and temporal characterizations for climate change, aeronomy, and space system engineering applications. Improvements have traditionally included more accurate and precise measurements, reference spectra, empirical, and physics-based models. At present, a new trend of hybrid models is emerging that combines the best of empirical and physics-based models to provide a wide variety of solar irradiance products for science and engineering users.

As part of this development, the SOLAR2000 model has gone through 17 upgrades since it was first released in 1999. Additional data sets have been added so that the vl.24 model incorporates three theoretical continua, 13 rocket spectra, and time series data from five satellites that combine 17 instruments. S2K also produces six integrated irradiance proxies for a wide variety of science and engineering applications, including E10.7 integrated EUV flux, Q_{EUV} EUV heating rate, P_{EUV}, EUV hemispheric power, T_{∞} exospheric temperature, R_{SN} derived sunspot number, and S integrated spectrum. Historical, nowcast, and forecast irradiances and integrated irradiance proxies are produced by the Research Grade, Professional Grade, and Operational Grade models for climate change research, aeronomy, and space system engineering applications. Substantial improvements have been made through Forecast Generation 1x of the S2K model to the 3-day forecast, resulting in 8% 1-sigma uncertainties at 72-h for E10.7.

SOLAR2000 is compliant with the ISO CD 21348 solar irradiance draft standard that is being developed to provide a standard method for specifying all solar irradiances for use by space systems and materials users.

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