

New developments in solar irradiance proxies for operational space weather

W. Kent Tobiska

Space Environment Technologies/SpaceWx Division, Pacific Palisades, CA USA
ktobiska@spacenvironment.net

Abstract. Six new solar proxies have been developed in the past two years in support of a second-generation forecasting capability. These proxies help characterize the energy input into operational space physics models. In addition to hourly-to-daily forecasts that produce a full solar spectrum used in numerical atmospheric and ionospheric models relevant to climatological studies, the E10.7 index is produced for empirical thermospheric and ionospheric model applications. New proxies include the Q_{eu} thermospheric heating rate for comparative use in airglow-derived versus solar-derived upper atmosphere heating, the P_{eu} which is the EUV hemispheric power as a complement to the auroral hemispheric power index, and the T_{inf} which is the exospheric temperature applicable to long-term climate change studies. Additionally, a derived sunspot number, R_{sn}, 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 are now provided. The second-generation forecasting will include higher cadence solar input information beyond daily flux values such that solar flare characterization will be possible. The second-generation forecasting also will incorporate improved algorithms ranging from wavelet transforms to solar dynamo theory in order to specify solar variability on eight time scales from historical and nowcast to 72-hour forecast through 5 solar cycle estimation.

1. Operational space weather and the requirement for new proxies

Over the past decade, there has been a growing awareness in space- and ground-system operations of the phenomena of space weather, i.e., the short-term variable impact of the Sun's photons, solar wind particles, or magnetic field upon the Earth. It is also during this period that scientific knowledge about the Sun's effects upon the Earth has progressed to the point where space weather operational systems, deriving from space physics research models, now exist. These systems are increasingly able to mitigate risks from the space environment. More importantly, the input data sources required to drive the models supporting these systems are now sufficiently mature so as to enable forecast capabilities with quantifiable uncertainties.

Several types of space environment models, e.g., solar irradiance, upper atmosphere density, ionosphere (including data fusion, convection, and ray-trace), solar wind, solar particles, and magnetosphere, are growing examples in the chain of linked operational applications. These models individually require inputs from either ground- or space-based data streams that are continuous, robust, and reliable. In first-generation forecasting algorithms, automated linkages between models still tend to be cumbersome or non-existent and the forecasts themselves are either nowcasts (current 24-hour period) or first-order extrapolations of solar phenomena based on the assumption of persistence. In general, because most of these operational models come from legacy algorithms that are already in place, their inputs have used first-order proxy representations of solar photons, particles, and fields to represent solar inputs. The cadence is often daily input which results in coarse time resolution.

It is with the transition to second-generation forecasting, i.e., with the introduction of improved forecasting algorithms and higher time cadences to better represent the dynamic variability of the Sun-Earth connection, that the need for custom-designed proxies has increased. New proxies are being designed for unique applications to better translate new knowledge of the Sun and Earth interactions into existing operational systems.

2. Development of an EUV energy flux, 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 ($\square 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$). There have been

previous descriptions of the E10.7 proxy derivation, use, validation, and comparison of predictions to actual data [Tobiska *et al.*, 2000; Tobiska, 2001; Tobiska, 2002a; Tobiska, 2002b]. 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 characterize the total electron content (TEC) and provide GPS near real time scintillation/irregularity knowledge. An additional benefit of using E10.7 in empirical models is that it represents the identical solar energy available for photoabsorption and photoionization that is input spectrally into numerical models.

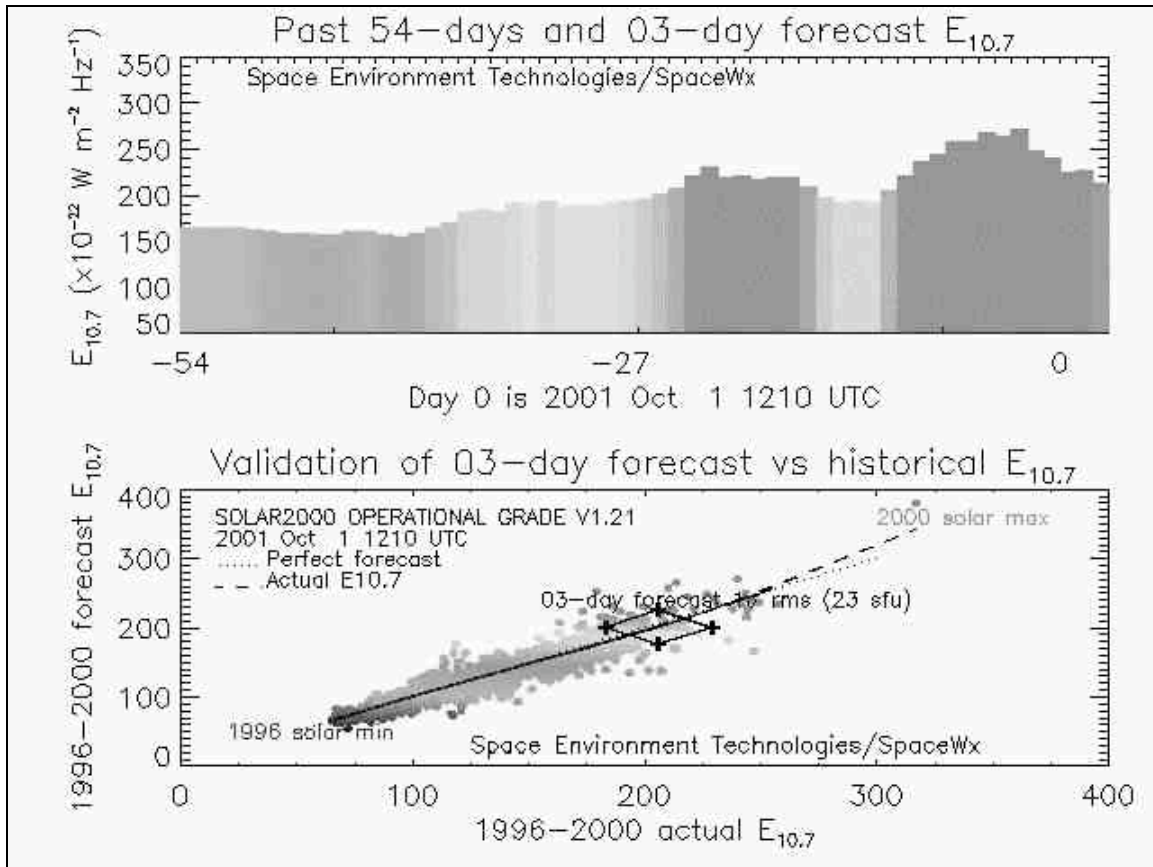


Figure 1: The 3-day forecast solar irradiance proxy E10.7 shown with the previous two solar rotations (54 days) (top panel) and against historical solar cycle 23 values (bottom panel).

E10.7 is available on a wide range of time scales. Daily research grade E10.7 is provided for historical periods prior to the current epoch back to 1947. Operational E10.7 is generated as a daily nowcast value through NOAA Space Environment Center and commercially every hour with high time resolution on 3-hourly time centers to 72 hours, then daily into the next five solar cycles (figure 1). After the transition to second-generation forecasting in 2004, E10.7 will be produced with a 5-minute cadence to capture soft X-ray and EUV flare activity.

3. Development of a thermospheric heating rate, Q_{euv}

The time-dependent, t , solar heating of the thermosphere is a function of EUV energy by wavelength, $I(\lambda, t)$, altitudinal heating efficiency, $\eta(\lambda, z)$, unit optical depth, $\tau(\lambda, z)$, absorption cross section of each neutral species, $\sigma_i(\lambda)$, and density of each species, $M_i(z)$. These quantities, combined, become the constituent volume-heating rate in the thermosphere, $q_i(\lambda, z, t)$. Integrated across all species, wavelengths, and altitudes for a unit of time, the first-principles derived total thermospheric heating rate is $Q(t)$ in $\text{ergs cm}^{-2} \text{s}^{-1}$ and is described in relation to proxy modeling [Tobiska, 1988; Tobiska *et al.*, 2000; Tobiska, 2001].

While the original first-principles calculation of the daily heating rate, $Q(t)$, used 8 neutral thermospheric constituents (O, O₂, N₂, CO₂, NO, He, H, and N), 809 wavelengths for $\lambda = 1.862$ to 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. Figure 2 demonstrates the comparison between $Q(t)$ and Q_{EUV} for this time period with a correlation coefficient of 0.99. Q_{EUV} is available on the same cadence as the daily E10.7.

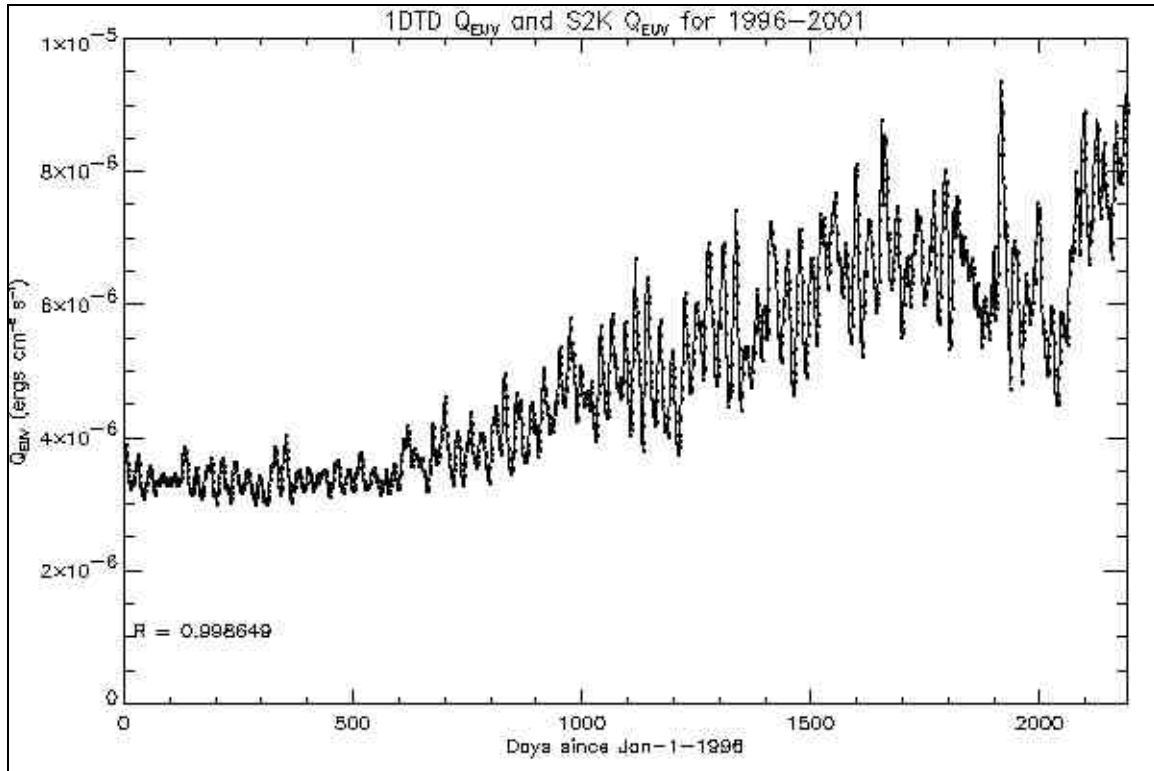


Figure 2. Comparison of $Q(t)$ and Q_{EUV} for January 1, 1996 through December 31, 2001 during the rise of solar cycle 23. The 3rd degree polynomial fit coefficient of regression is 0.99.

4. Development of an EUV hemispheric power, $Peuv$

An EUV hemispheric power, $Peuv$, in units of Watts, has been developed for science research and operations that is complementary to the auroral hemispheric power index. The SOLAR2000 model is run in the energy flux, $I(\lambda, t)$, mode ($\text{ergs cm}^{-2} \text{s}^{-1}$) for 809 wavelengths and the flux values are summed across all wavelengths from 1–105 nm. This value is approximately $6 \text{ erg cm}^{-2} \text{ s}^{-1}$ 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. $Peuv$ is calculated in equation 1 to produce a value of 765 GW for $6 \text{ erg cm}^{-2} \text{ s}^{-1}$ energy flux.

$$Peuv = \pi R^2 \int_{\lambda=1}^{105} I(\lambda, t) (\text{ergs s}^{-1}) \pi (2.77 \times 10^{-11} \text{ W-hr erg}^{-1}) \pi (3600 \text{ s hr}^{-1}) \text{ W} \quad (1)$$

where R is the Earth's radius of 6.378×10^8 cm. In general, the EUV heating is larger than the auroral hemispheric power except during storm periods. $Peuv$ is available on the same cadence as the daily E10.7.

5. Development of a derived exospheric temperature, $Tinf$

A derived exospheric temperature, $Tinf$, 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 poten-

tial anthropogenic climate change effects (cooling) in the thermosphere and subsequent changes to the ionospheric E and F2 layer heights. Similar to the Q_{euv} calculation, the empirical T_{inf} 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. Figure 3 demonstrates the comparison between $T_{450}(t)$ and T_{inf} for this time period with a correlation coefficient of 0.99. T_{inf} is available on the same cadence as the daily E10.7.

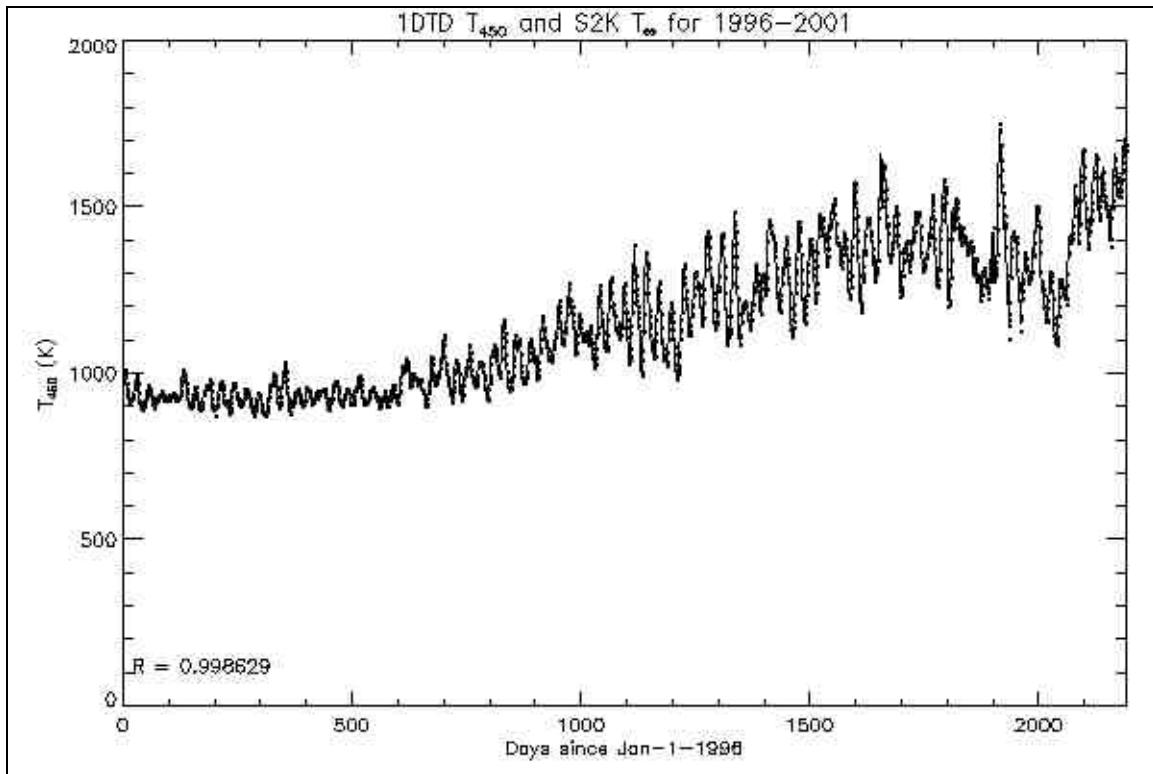


Figure 3. Comparison of $T_{450}(t)$ and T_{inf} for January 1, 1996 through December 31, 2001 during the rise of solar cycle 23 using a 3rd degree polynomial fit.

6. Development of a derived sunspot number, R_{sn}

The ionosphere is created and affected by incident solar EUV radiation and the processes of ion and electron loss due to neutral constituent chemical reactions, ionospheric electrodynamics, and ion drag from thermospheric wind. Natural variability in these physical processes causes changes in electron density profile with altitude including the location of the electron layer peak. This, in turn, affects the ability to reflect high frequency (HF) radio signals from the ionosphere by users such as aircraft or ground transmitters.

HF 3 – 30 MHz radio signals are capable of long-distance, over-the-horizon propagation as a result of signal bounce off ionospheric layers. The one- or multi-hop calculation of a signal bounce off the ionospheric E and F2-regions can be performed with ray-trace algorithms. Since the radio signal is reflecting off ionized layers, the ability to reflect is dependent upon the space-weather modulated electron density within the various layers of the ionosphere.

A new proxy has been developed for operational use in ray-trace algorithms that historically use the Wolf sunspot number, R_z . R_{sn} , dimensionless, is the derived sunspot number and, similar to the calculation of Q_{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. Figure 4 compares R_z with R_{sn} for the five solar cycles (18-23). R_{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_{sn} is available on the same cadence as the daily E10.7.

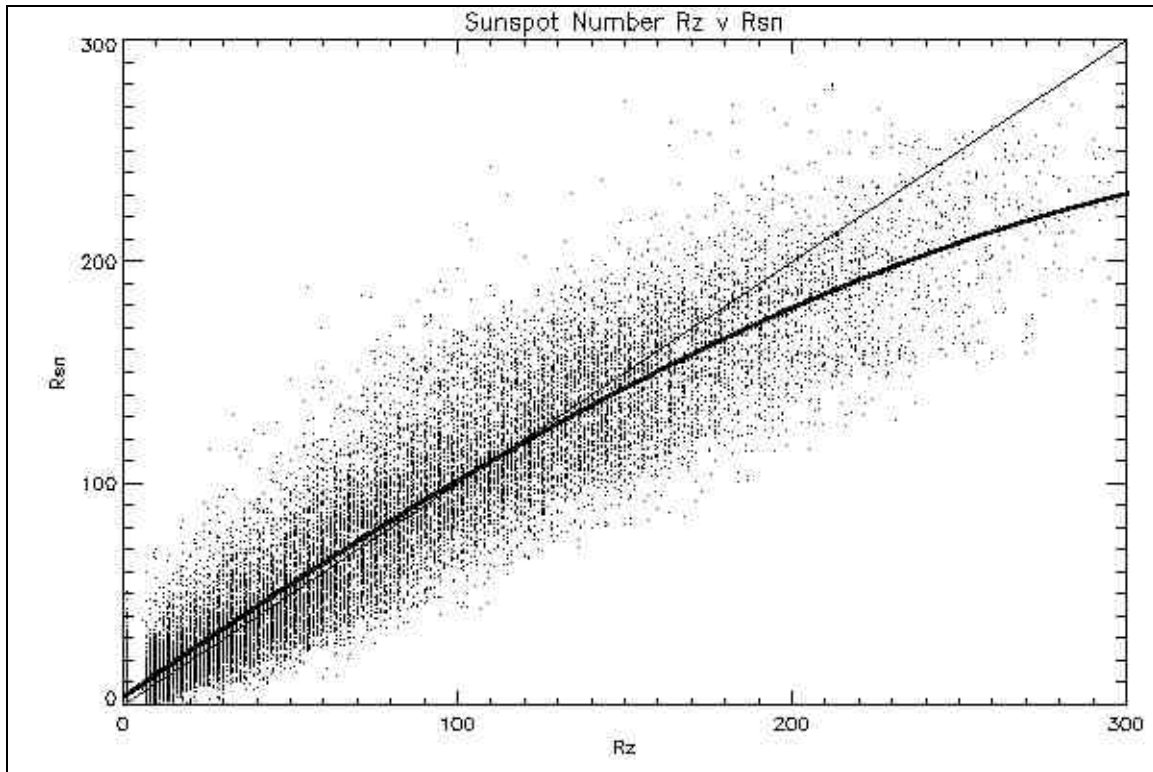


Figure 4. R_z compared with R_{sn} for the five solar cycles 18-23. The light line is the unity line (slope = 1) while the heavy line is the fit of R_{sn} to R_z . High R_z values during active solar conditions are not necessarily reflected in high solar EUV irradiance emissions that lead to photoionization and changes to the ionosphere.

7. Development of an integrated solar spectrum, 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], Tobiska [2002c], Tobiska [2002d] and in the SOLAR2000 model "Readme" file. In the early versions of the SOLAR2000 model (v1.yz), the variability comes from the solar spectrum between 1–122 nm (EUV variability). The upgrade version nomenclature of vx.yz denotes spectral range of model variability (x), major data inclusion (y), and additional application and/or bug fixes (z). Longward of 122 nm in the v1.yz model, a solar reference spectrum (ASTM E490) is used. Hence, the current variability in S is not the same as the total solar irradiance (TSI). In the course of upgrades beyond v1.yz of SOLAR2000, time-varying spectral models will be 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 satellite imagery calibration use. Figure 5 shows the integrated solar spectrum from SOLAR2000 v1.21 demonstrating variability from the 1-122 nm range due to the coronal and chromospheric input proxies. S is available on the same cadence as the daily E10.7.

8. Second-generation operational space weather forecasting

The second-generation space weather operational forecasting activity is characterized by the development of improved algorithms incorporating image processing to solar dynamo theory. The algorithms continue to use the fundamental assumption of persistence of solar irradiance variability at several unique time scales [Tobiska *et al.*, 2000] as shown in figure 6. However, by using

tailored proxies for specific applications, new solar inputs with higher time resolution, and mathematical tools to combine the statistics of recent variability with the physical persistence at different time scales, it is possible to improve solar irradiance forecasting uncertainties. Improvements are transferred into the six new proxies described above since they are derived from the underlying model that will incorporate the improvements. A promising methodology for transferring past statistical variability into the future is the discrete wavelet transform (DWT). Figures 7 and 8 demonstrate the use of the DWT for irradiance forecasting. In general, a time series (figure 7) can be represented by scales of variability in the DWT coefficients. If physical persistence “seeds” are extended into the future at the appropriate time scale, e.g., image analysis for 1-7 days, solar east limb image analysis for 7-14 days, farside solar Lyman-alpha backscatter from interplanetary hydrogen for 14-28 days, scale or periodicity information from transforms of the evolution of active regions for 1-6 months, and solar dynamo theory for solar cycle time frames, then the DWT on a sliding temporal scale can represent a next lower scale of variability into the future (figure 8).

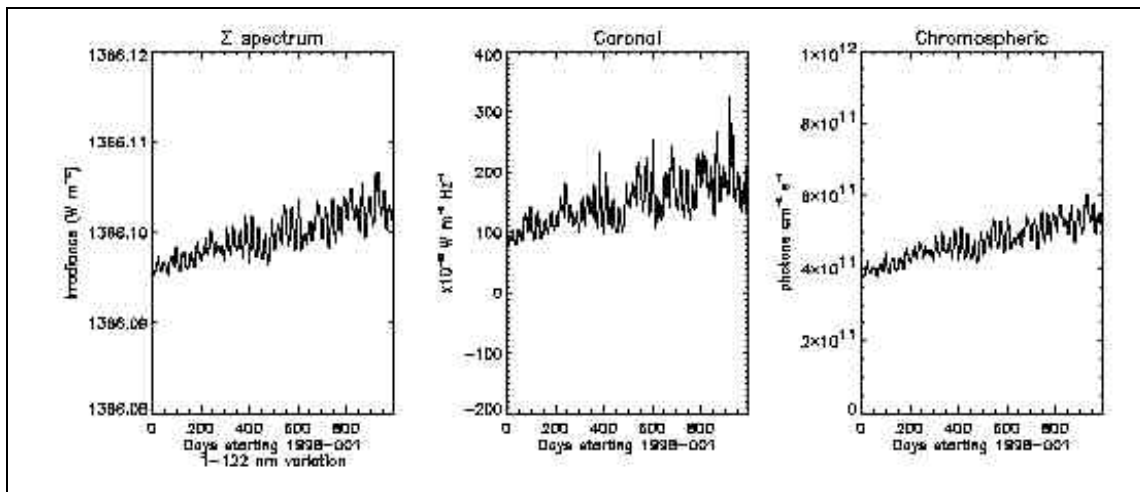


Figure 5. The integrated solar spectrum in SI units with variability from the 1-122 nm range compared with the coronal and chromospheric input proxies in their own units for 1000 days starting January 1, 1998 during the rise of solar cycle 23.

9. Conclusion

Six new solar irradiance proxies are described that will aid in second-generation space weather forecasting. These include the E10.7 energy flux, the Qeuv thermospheric heating rate, the Peuv EUV hemispheric power, the Tinf exospheric temperature, the Rsn derived sunspot number, and the S integrated solar spectrum. In the transition to second-generation forecasting, these proxies will convey tailored solar irradiance information to specific models using higher time resolution and greater fidelity to representing the physical and statistical variability of solar irradiances. Although persistence of irradiance variability on seven identified time scales will remain an underlying assumption in forecasting, new mathematical tools such as discrete wavelet transforms will help translate past historical information into the future.

10. Acknowledgements

Support for this work has been provided by the NASA TIMED contract NAS5-97179 (UCB SPO 000028766), by the NASA LWS contract NASW-01006, by the NASA LWS contract NAS8-01117, by the NATO EST.CLG 975301 collaborative travel grant, and by the NOAA/SEC-SET CRADA. Documentation for the SOLAR2000 research grade model and a downloadable software application for running the model is available from <http://SpaceWx.com>.

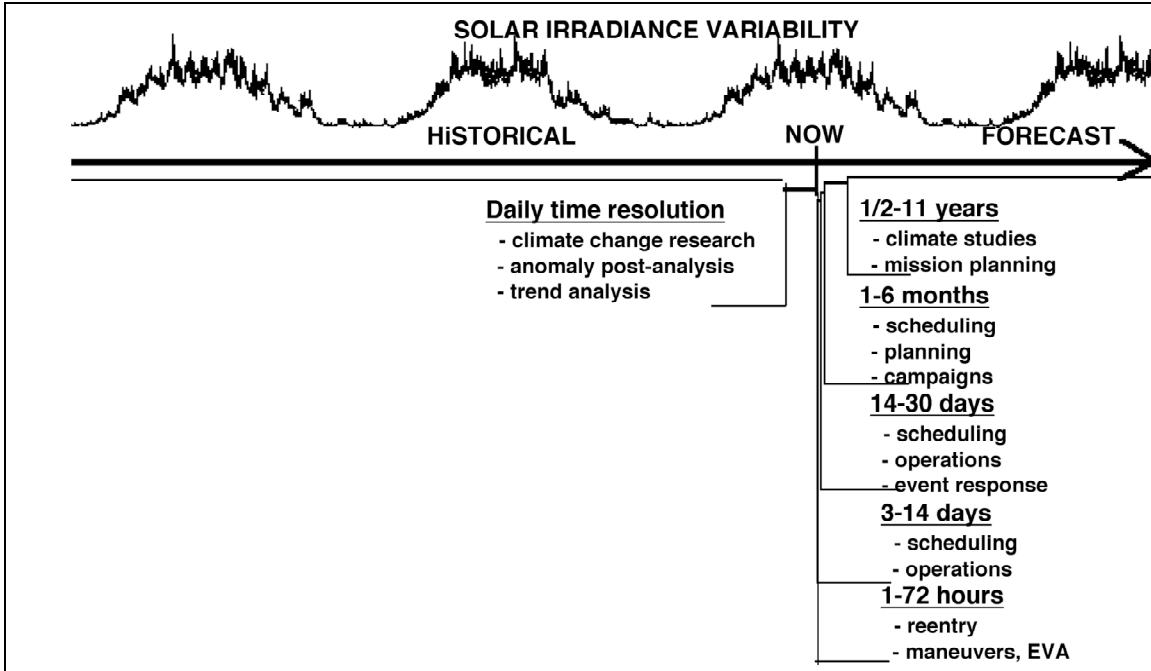


Figure 6. Applications of solar irradiance variability at seven unique time scales.

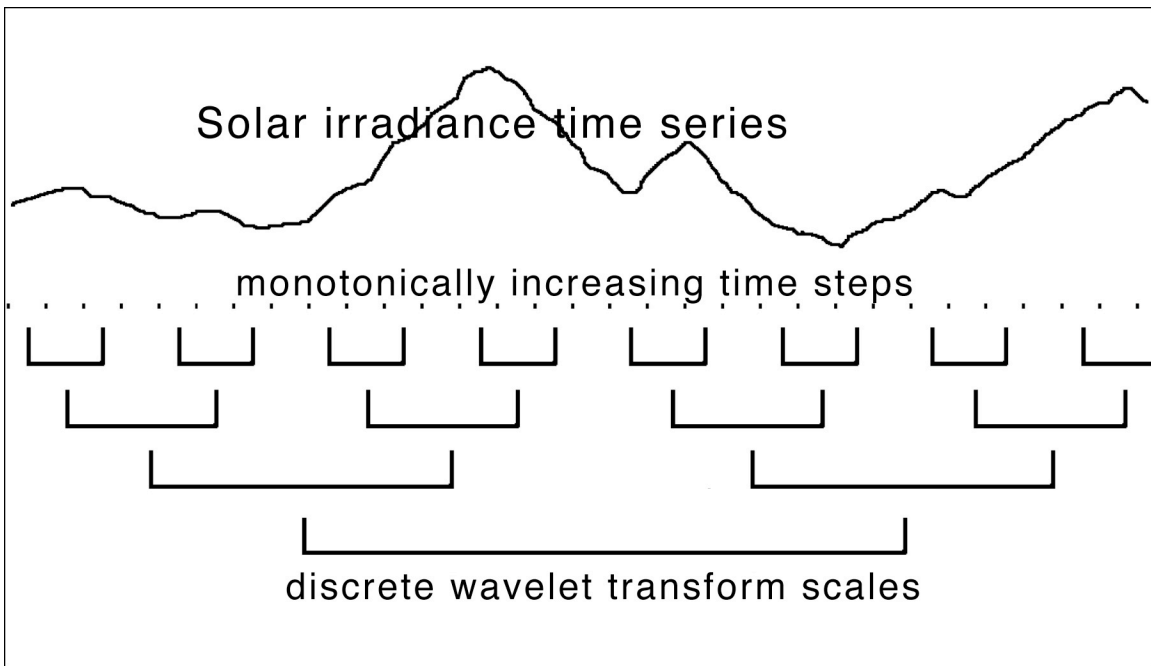


Figure 7. The generalized case of a solar irradiance time series in monotonically increasing time steps as represented by scales of variability in the DWT coefficients.

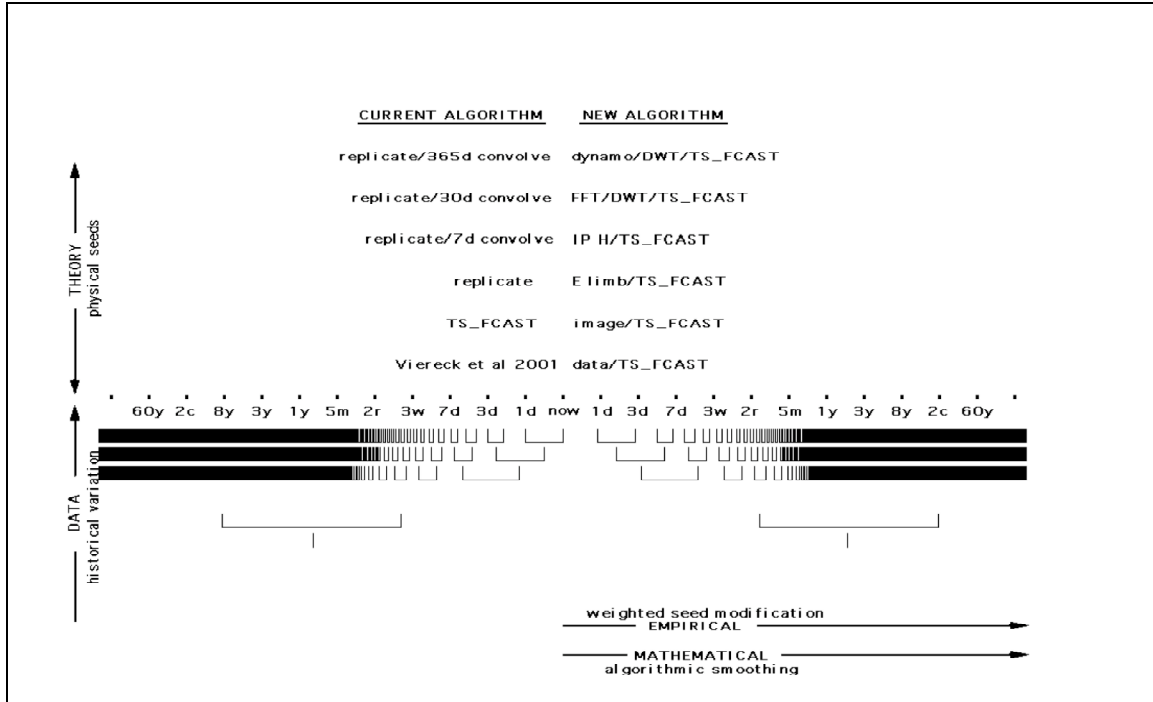


Figure 8. The DWT on a sliding time scale represents a next lower scale of variability into the future. New “seed” algorithms are required for future physical irradiance specification (right side of figure from “now”). Time is represented exponentially and centered on the current epoch, “now,” with historical information to the left and future information to the right.

11. References

Tobiska, W.K., A Solar Extreme Ultraviolet Flux Model, Ph.D. thesis, Univ. of Colorado, Boulder, 1988.

Tobiska, W.K., T. Woods, F. Eparvier, R. Viereck, L. Floyd, D. Bower, G. Rottman, and O.R. White, The SOLAR2000 empirical solar irradiance model and forecast tool, *J. Atm. Solar Terr. Phys.*, **62**, (14), 1233-1250, 2000.

Tobiska, W.K., Validating the Solar EUV Proxy, E10.7, *J. Geophys.Res.*, **106**, A12, 29969-29978, 2001.

Tobiska, W.K., Forecast E10.7 for Improved Low Earth Orbit Satellite Operations, *J. Spacecraft Rock.*, in press, 2002a.

Tobiska, W.K., Forecasting of space environment parameters for satellite and ground system operations, *J. Spacecraft Rock.*, submitted, 2002b.

Tobiska, W.K., Reply, *J. Geophys. Res.*, **107**, A2, SIA 5 1-2, 2002c.

Tobiska, W.K., Variability in the Solar Constant from Irradiances Shortward of Lyman-alpha, *Adv. Space Res.*, **29** (12), 1969-1974, 2002d.