©FORECASTING OF SPACE ENVIRONMENT PARAMETERS FOR SATELLITE AND GROUND SYSTEM OPERATIONS

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ABSTRACT

The E10.7 solar proxy has been developed to characterize the energy input into operational space physics models. The use of E10.7 in place of the 10.7-cm solar radio flux index, F10.7, has provided a significant improvement for solar-terrestrial models related to satellite operations that estimate satellite drag. Improvements in forecast E10.7 over forecast F10.7 are demonstrated. The first generation forecasting algorithms have been modified, taking into account new understanding of operational forecasting issues. Improvements are in the form of reduced 1-sigma uncertainties from 11% to 8% for the 3-day forecast. A second generation forecasting method is in development and is briefly described. Its improved algorithms will specify solar proxy variability on seven time scales, from nowcast and 72-hour forecast to 5 future solar cycle estimation based on physical as well as mathematical models. The improved forecast E10.7 proxy is produced by the SOLAR2000 model whose solar irradiance specification is compliant with the developing ISO draft standard CD 21348 for Determining Solar Irradiances.

BACKGROUND

First Generation Forecasting Methods for Satellite and Ground System Operations

Over the past two years, a first generation (FGen 1) solar irradiance forecasting capability has been developed. The "1" identifier for the forecast generation refers to the methodology of the forecast, i.e., the use of linear predictive mathematical techniques to extrapolate recent trends into the future. Generation 2 forecasting (FGen 2) will use forecast "seeds" from physical and mathematical models to ensure a physical basis for expected irradiance variations plus time series self-consistency between historical, nowcast, and forecast data.

FGen 1 capability and its application to space- and ground-based operational systems has been previously documented[1,2,3,4]. At the top level, the methodology of FGen 1 is based on the assumption of solar irradiance persistence over time scales of interest. For example, irradiance changes over a few days are governed principally by solar rotation effects and not active region evolution and decay. Table 1 outlines the algorithms for FGen 1. The algorithms differ between time scales, are described by Tobiska[4], and have been modified as described below and summarized in Table 2 (FGen 1x).

The FGen 1x algorithms start with the Viereck *et al.*[5] method for nowcast of a current Mg II value, e.g.,

$$\mathrm{EUV}_{\mathrm{Mg\ II\ proxy}} = 0.6\ \mathrm{Mg\ II}_{\mathrm{daily}} + 0.4\ \mathrm{Mg\ II}_{\mathrm{29\text{-}day\ avg.}}$$

The 72-hour through 4.5-month forecast is generated with an linear predictive technique assuming time-series stationarity where periodic episodes repeat themselves and are given in equation 1. This function computes future time-series values using a Pth order autoregressive model relating a forecasted value x_t of the time series $x = [x_0, x_1, x_2, \ldots, x_{t-1}]$, as a linear combination of P past values. The coefficients $\phi_1, \phi_2, \ldots, \phi_P$ are calculated such that they minimize the uncorrelated random error terms, w_t.

$$x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \cdots + \phi_P x_{t-P} + w_t \quad (1)$$

TABLE 1. GENERATION 1 ALGORITHMS FOR SOLAR INDICES' FORECAST

Time period	Product type	Algorithm
0 – 24 hours	nowcast	Viereck et al., 2001[5]
24 – 72 hours	forecast	autoregression using past 14 days
3 – 14 days	forecast	substitution of past 14 days with no smooth
14 – 28 days	forecast	substitution of past 28 days with 7-day smooth (convolution)
1 – 6 months	forecast	substitution of past 6 months with 30-day smooth (convolution)
1/2 – 11 years	forecast	substitution of past 11 years with 365-day smooth (convolution)
1 – 5 solar cycles	forecast	mean of five solar cycles

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TABLE 2. GENERATION 1X ALGORITHMS FOR SOLAR INDICES' FORECAST

Time period	Product type	Algorithm
-24 to 0 hours (current epoch)	nowcast	SET* linear prediction in equation 1
0 – 72 hours	forecast	SET* linear prediction in equation 1
3 – 14 days	forecast	SET* linear prediction in equation 1
14 – 28 days	forecast	SET* linear prediction in equation 1
1 – 4.5 months	forecast	SET* linear prediction in equation 1
4.5 – 6 months	forecast	substitution of past 6 months with 30-day convolutional smooth
1/2 – 11 years	forecast	substitution of past 11 years with 365-day convolutional smooth
1 – 5 solar cycles	forecast	mean of five solar cycles

*SET is the abbreviation for Space Environment Technologies.

The 6-month forecast uses the previous 6-month data convolved with a triangular function to smooth the day-to-day variability while the 11-year forecast uses the previous, smoothed 11-year data.

The definition of "nowcast" has been slightly modified in FGen 1x to indicate the period of time between –24 hours to the current epoch. Starting at 24 hours in the past, the input parameters that are required for model runs, i.e., the F10.7 and Mg II core-to-wing ratio data, have been operationally issued and will not change. However, at the current, "0" hour, epoch the solar conditions will have changed slightly and information has not yet been received to exactly define what the new parameter values are. Hence, an estimate made of the current conditions and the interpolation from known to unknown conditions during the past 24-hours constitutes a nowcast.

DISCUSSION

The SOLAR2000 Model Generates Forecast Proxies

SOLAR2000 is a collaborative project for accurately characterizing solar irradiance variability across the spectrum[1,6]. The overarching scientific goal of the SOLAR2000 project is to understand how the Sun varies spectrally and through time from the X-rays to the infrared wavelengths. A primary project task is to develop a full-disk proxy- and image-based empirical solar irradiance model that is valid in the spectral range of 1-10,000 nm for historical modeling and for forecasting throughout the solar system.

SOLAR2000 irradiance products are useful as fundamental energy inputs into planetary atmosphere models, for comparison with numerical/first principles solar models, and for modeling or predicting the solar radiation component of the space environment[2]. SOLAR2000 is compliant with the International Standards Organization (ISO) solar irradiance draft standard CD 21348.[7] Temporal and spectral information from the model expands the scope of our knowledge about the quiet and variable Sun, providing a comparative database for future studies of the Sun's changes and its envelope of variability[8]. SOLAR2000 represents an archive of information from multiple instruments, captured across many spacecraft and rockets, spectral bands, and periods of time. This archival aspect is a unique contribution of SOLAR2000 and fulfills two primary model purposes, i.e., to preserve a knowledge-bridge from historical measurements to first principles' representation of solar irradiances and to provide energetically self-consistent research and operational solar irradiances independent of passband binning. SOLAR2000 has been identified as an important element in meeting U.S. national operational space system requirements for space weather information and forecasting of the near-Earth space environment[9].

The SOLAR2000 operational grade model is developed for use in operations and forecast applications. It utilizes real-time solar irradiance proxy inputs of F10.7 for coronal emissions and Mg II core-to-wing ratio for chromospheric emissions between 2000-2003 and will use GOES-N EUV broadband data after 2004. It produces historical, nowcast, forecast, and high time resolution solar irradiances and proxies tailored for specific user requirements. These include the E10.7 index produced for empirical thermospheric and ionospheric models, the Qeuv thermospheric heating rate for aeronomy use, the Peuv EUV hemispheric power index complementing the auroral hemispheric power index, the Tinf which is the exospheric temperature for long-term climate change studies, the derived sunspot number, Rsn, for use by operational HF radio ray-trace algorithms, and the integrated solar spectrum, S, used for solar radiation pressure calculations related to spacecraft attitude control.

Comparison of Forecast F10.7 and E10.7

The forecast results between F10.7 and E10.7, where the latter uses the FGen 1x algorithms, are compared. There are two separate forecasts of F10.7 presented for the time frame of the first 200 days of 2001. This period, shown in Figure 1, was at the height of solar cycle 23 activity and the flux values were characterized by non-stationary behavior. During this time, NOAA Space Environment Center (SEC) and Space Environment Technologies (SET) separately forecasted the F10.7. In addition, SET forecasted the E10.7 which was derived from SET forecast F10.7 and Mg II used as inputs into the SOLAR2000 model. Forecasts were made for 1, 2, and 3 days for all three proxies (Figures 2, 3, 5, 7) and the forecasts were compared to the actual values on the appropriate days. In order to assess the forecast quality,

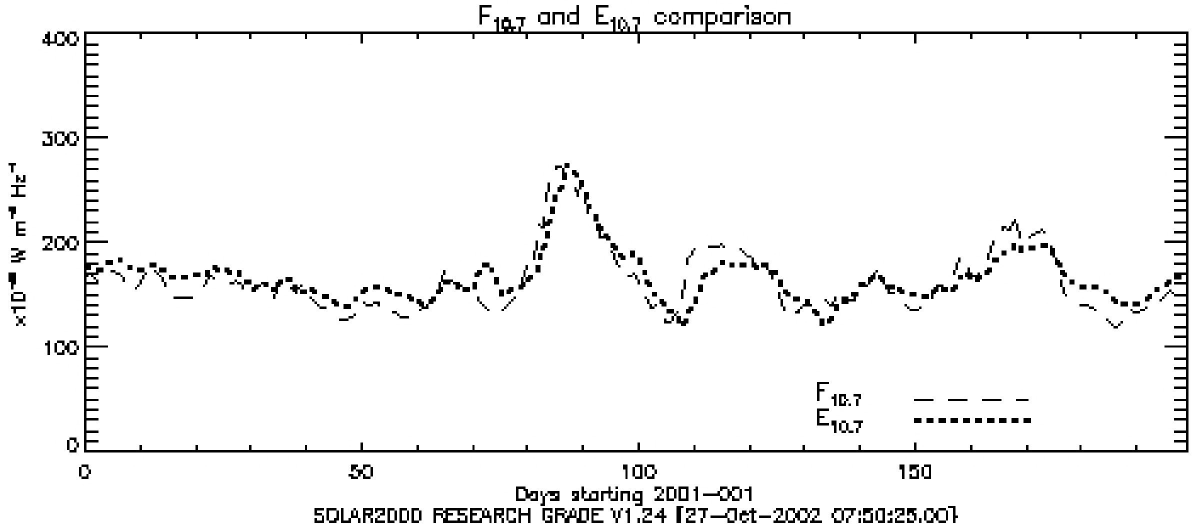

Figure 1. WDC observed F10.7 (dashed) and E10.7 (dotted) for the first 200 days of 2001.

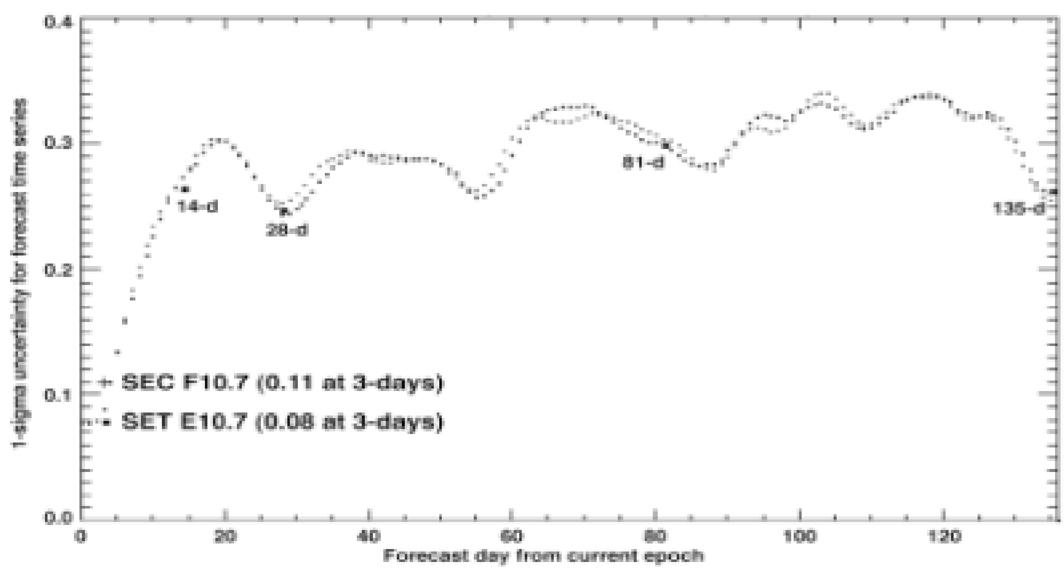

Figure 2. The forecast F10.7 1-sigma uncertainties out to 135 days (4.5 months or 5 solar rotations) based on.the first 200 days of 2001. Two different examples are shown using different "P" past values in the linear predictive algorithm. The 3-day forecast for SET E10.7 is 8% uncertainty and the SEC F10.7 forecast is 11% uncertainty.

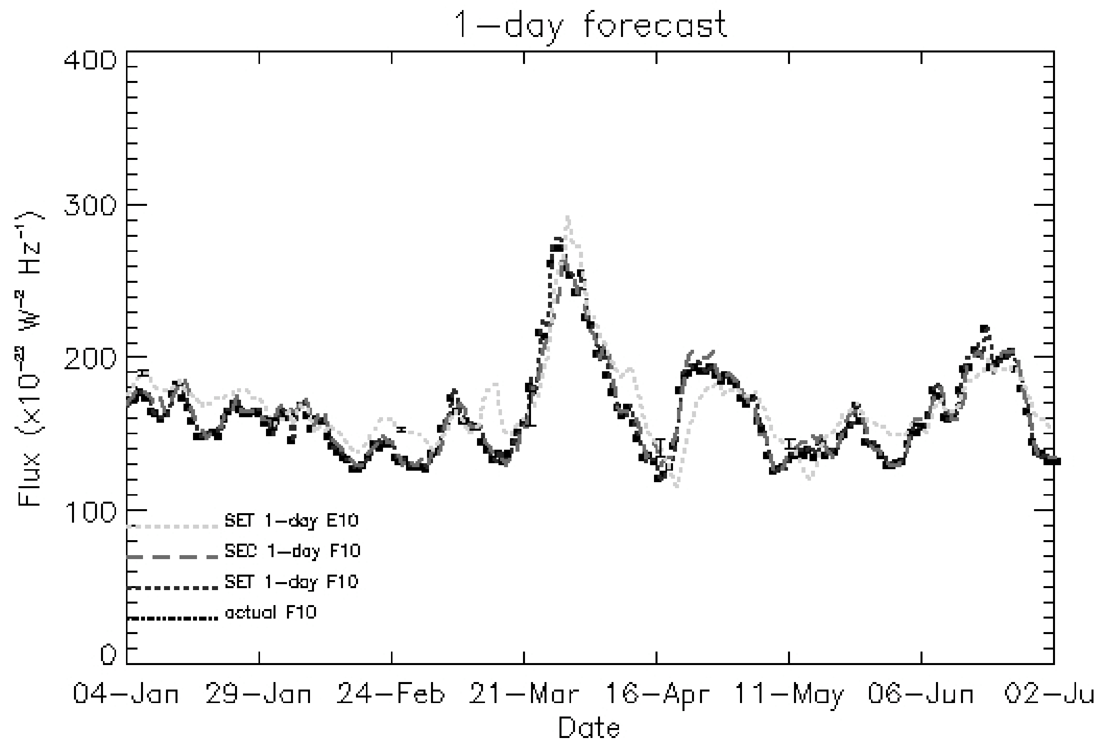

Figure 3. Time-series SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 1-day forecasts during each day of the first 200 days of 2001.

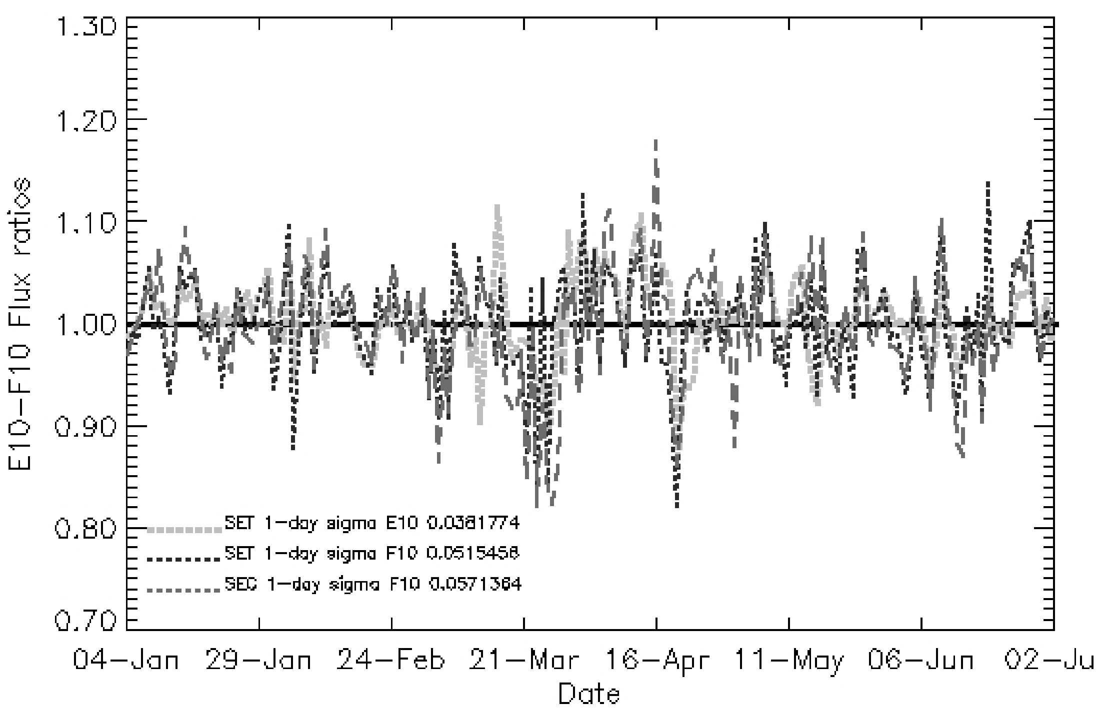

Figure 4. Ratio SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 1-day forecasts during each day of the first 200 days of 2001.

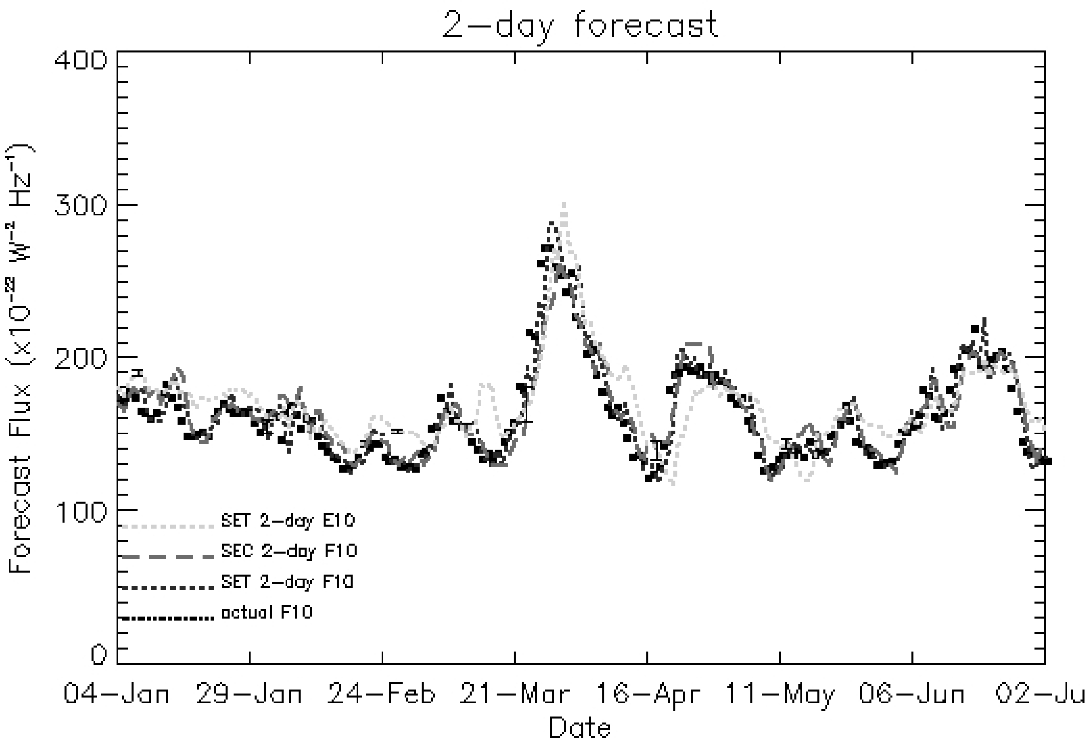

Figure 5. Time-series SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 2-day forecasts during each day of the first 200 days of 2001.

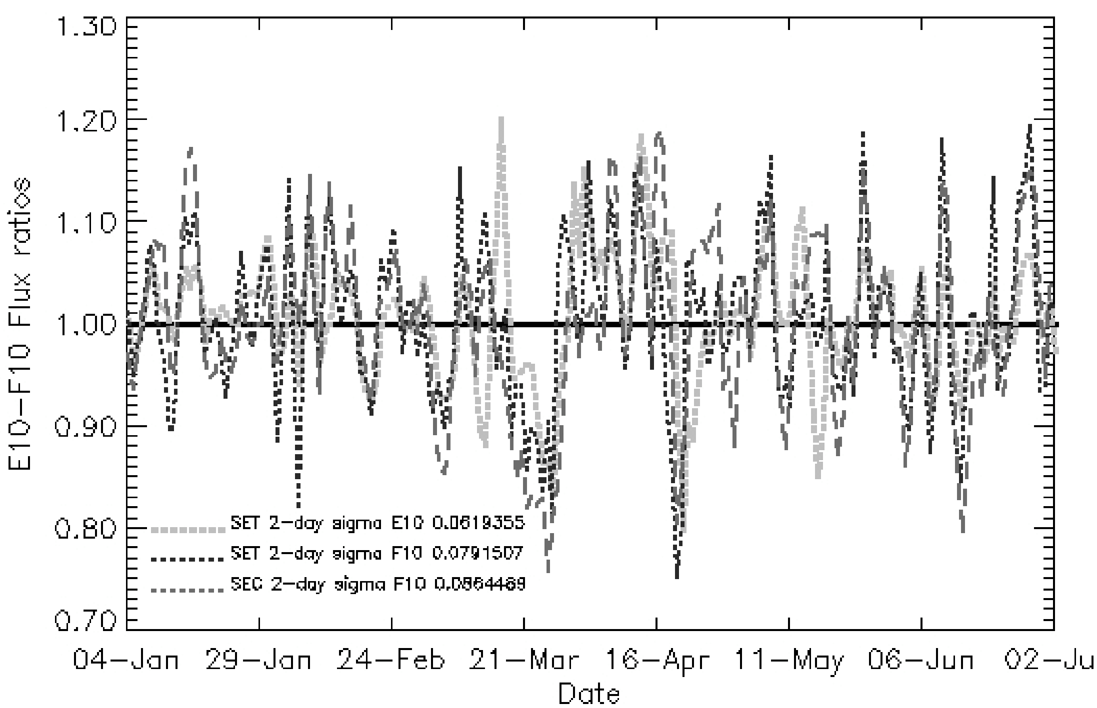

Figure 6. Ratio SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 2-day forecasts during each day of the first 200 days of 2001.

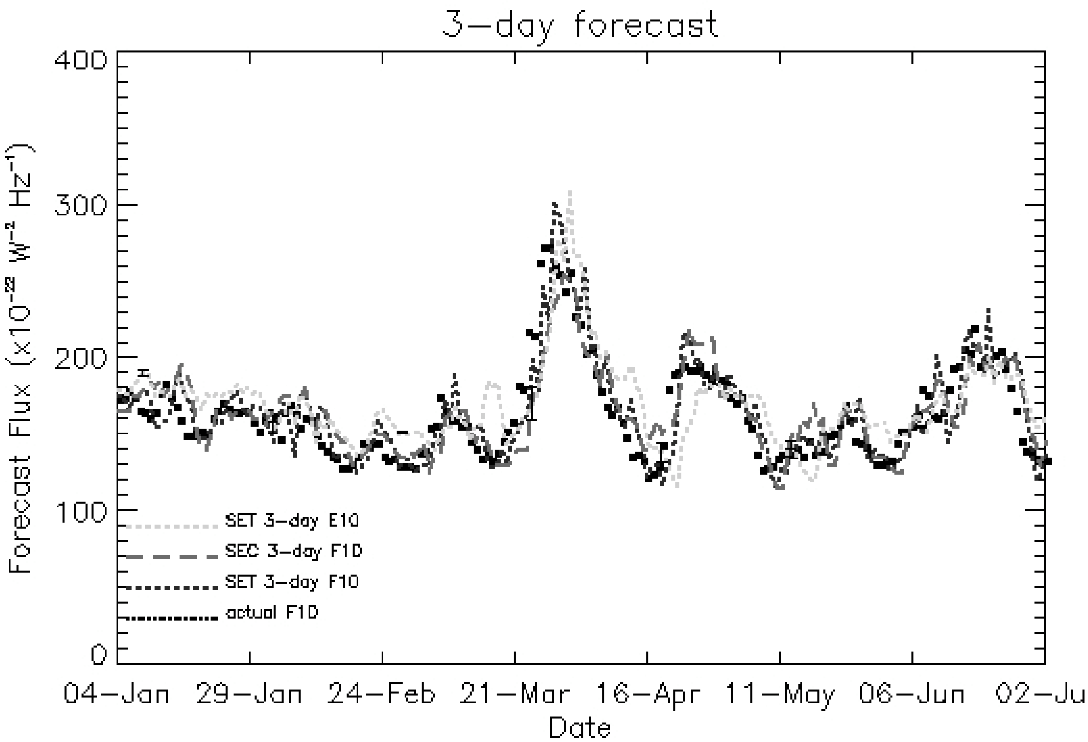

Figure 7. Time-series SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 3-day forecasts during each day of the first 200 days of 2001.

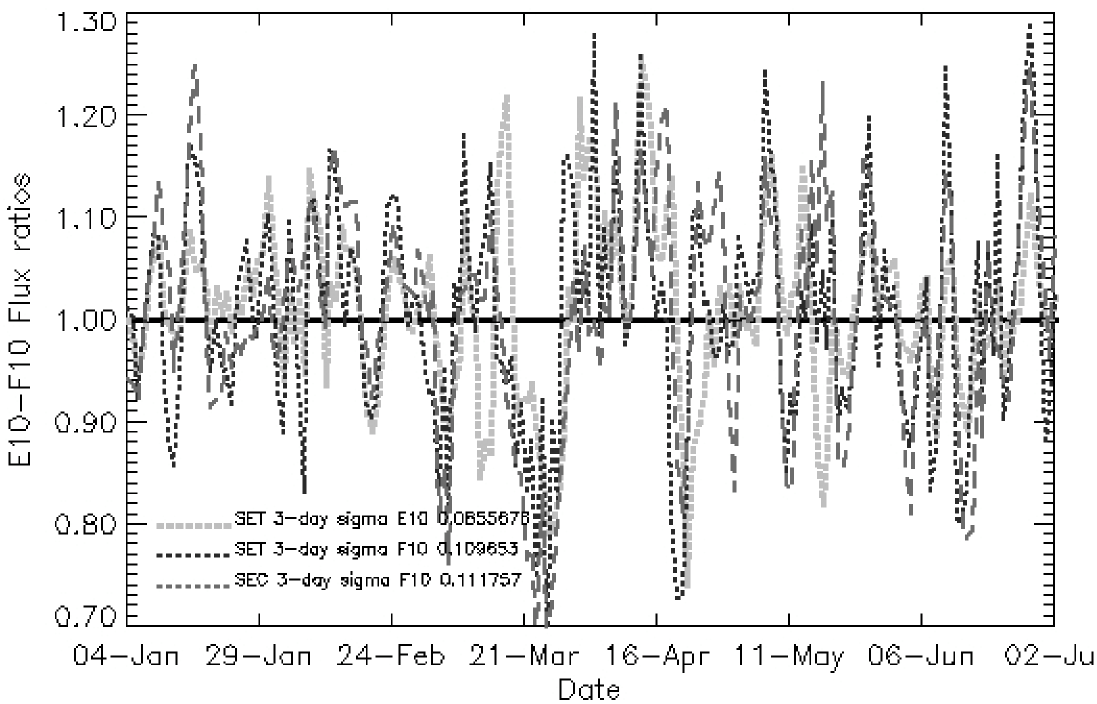

Figure 8. Ratio SET E10.7 (light gray) and F10.7 (dotted) are compared with NOAA/SEC F10.7 (dashed) for 3-day forecasts during each day of the first 200 days of 2001.

TABLE 3. SET AND SEC F10.7 FORECAST COMPARISON A (1-SIGMA ERROR*)

source	-24 to 0 hr	0-Day	0 to 24 hr	1-Day	24 to 48 hr	2-Day	48 to 72 hr	3-Day
SET E10	0.03662	0.03662	0.03818	0.04503	0.06194	0.05747	0.08557	0.06840
SET F10	n/a	0.05437	0.05155	0.06695	0.07915	0.08961	0.10965	0.11034
SEC F10	n/a	n/a	0.05714	0.07179	0.08645	0.09910	0.11176	0.11176

***example: 0.03662 = 3.662% error; shown graphically in Figure 9.**

TABLE 4. SET AND SEC F10.7 FORECAST COMPARISON B (1-SIGMA ERROR*)

source	proxy	Forecast day	1-sigma*	3-hr 1-sigma*
SET	E10	0-day	0.000000	0.0366210
SET	F10	0-day	0.000000	0.0543717
SET	E10	1-day	0.038177	0.0450289
SET	F10	1-day	0.051546	0.0669445
SEC	F10	1-day	0.057136	n/a
SET	E10	2-day	0.061936	0.0574719
SET	F10	2-day	0.079151	0.0896070
SEC	F10	2-day	0.086449	n/a
SET	E10	3-day	0.085568	0.0684007
SET	F10	3-day	0.109653	0.1103410
SEC	F10	3-day	0.111757	n/a

***example: 0.0366210 = 3.6621% error**

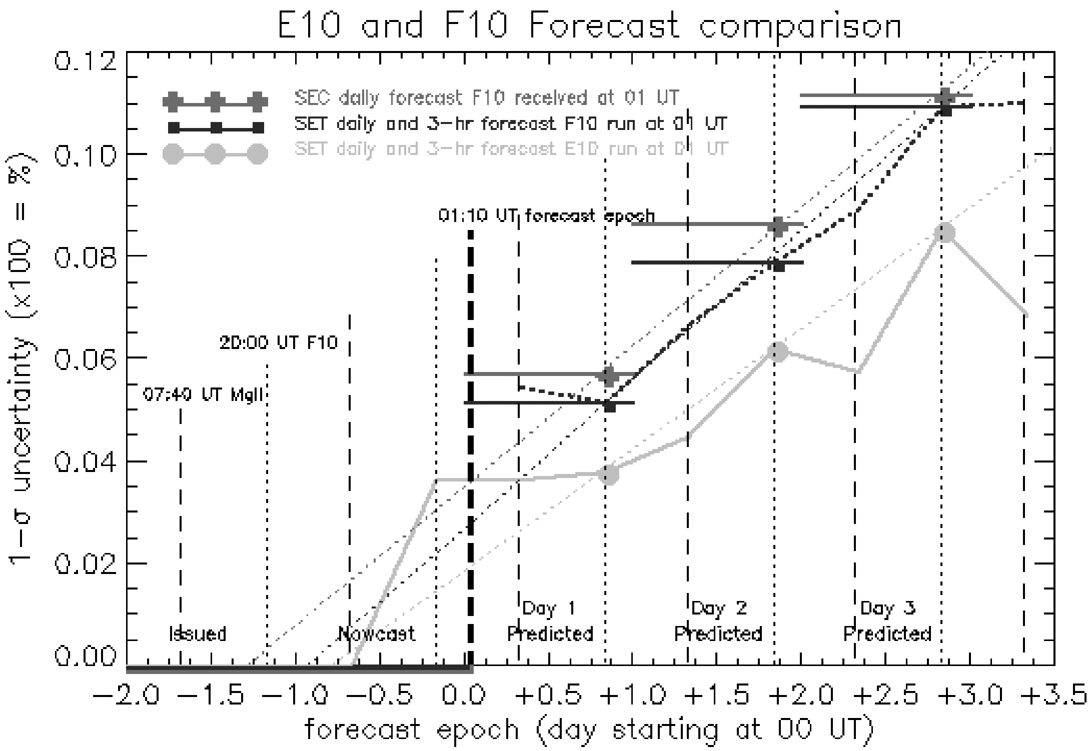

Figure 9. SET E10.7 (light gray dots) and F10.7 (black dots) are compared with NOAA/SEC F10.7 (dark gray pluses) 1-sigma uncertainties. Dotted lines are the interpolated uncertainties for each forecast epoch while the dots are the daily forecast uncertainties. The current epoch at "0.0" on the x-axis indicates the time at which a forecast was generated for the first 200 days of 2001. See Table 3 for numerical values.

the ratio of the forecast-to-data for each proxy covering the entire 200-day time series was created (Figures 4, 6, 8). From these time series ratios, the 1-sigma uncertainties were determined for 1-, 2-, and 3-day forecast cases. Tables 3 and 4 summarize the 1-sigma daily and 3-hourly uncertainties, respectively, for the SET FGen

1x method compared with the NOAA/SEC manual forecast method. The 1-sigma standard deviation of these time series ratios can be thought of as percentages of error and are shown in Figure 9.

Overall, the SET F10.7 forecast did slightly better than the SEC F10.7 forecast but the SET E10.7 forecast did signficantly better than either case of F10.7. Approximately 2/3 of the signal of E10.7 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 from tables 3 and 4 as well as from figure 9 that the SET F10.7 forecast improvement upon the SEC F10.7 forecast is achieved by lowering the uncertainty by approximately 0.5-1% while the E10.7 moves the uncertainty an additional 2% lower compared with the SEC F10.7.

Second Generation Forecasting Methodology

The second-generation, FGen 2, space weather operational forecasting activity now under development is characterized by algorithms ranging from image processing to solar dynamo theory. The algorithms start with the fundamental assumption of solar irradiance variability persistence at several unique time scales as shown in figure 10. However, by using 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.

A promising methodology for transferring past statistical variability into the future is the discrete wavelet transform (DWT). Figures 11 and 12 demonstrate the use of the DWT for irradiance forecasting. In general, a time series (top half of figure 11) can be represented by scales of variability in the DWT coefficients (link tick marks). If the past values already exist and future physical persistence "seeds" are created for the appropriate time scale, e.g., disk 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 over the entire time series, past and future, can contribute historical statistics to future forecasts (figure 12).

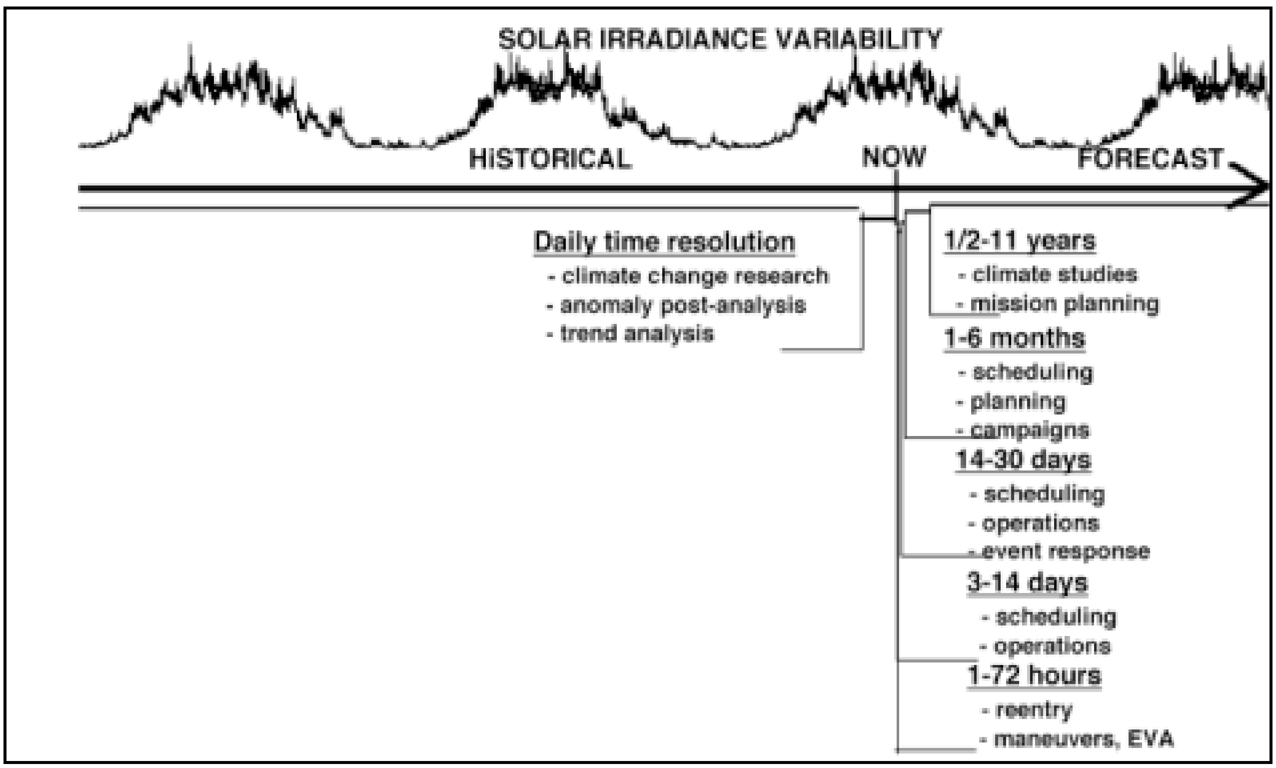

Figure 10. Applications of solar irradiance variability at seven unique time scales.

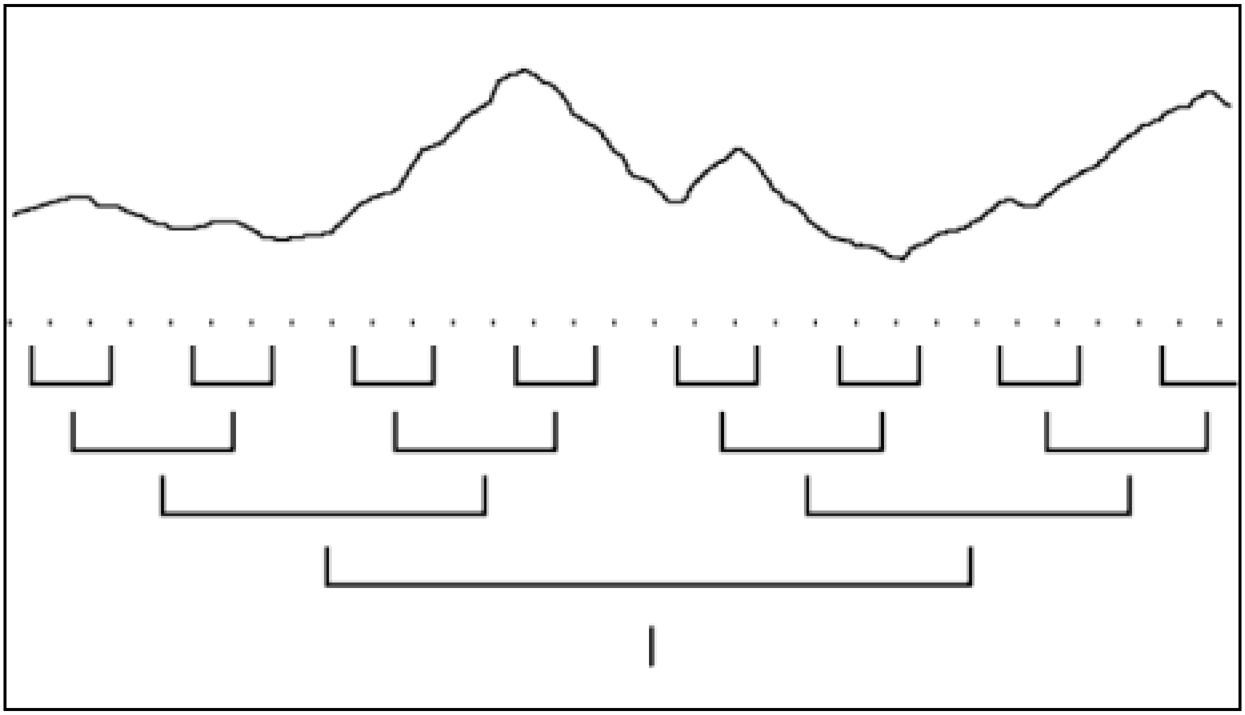

Figure 11. A time series (top half) as represented by increasing scales of variability in the DWT coefficients represented by linked tick marks for each coefficient pair.

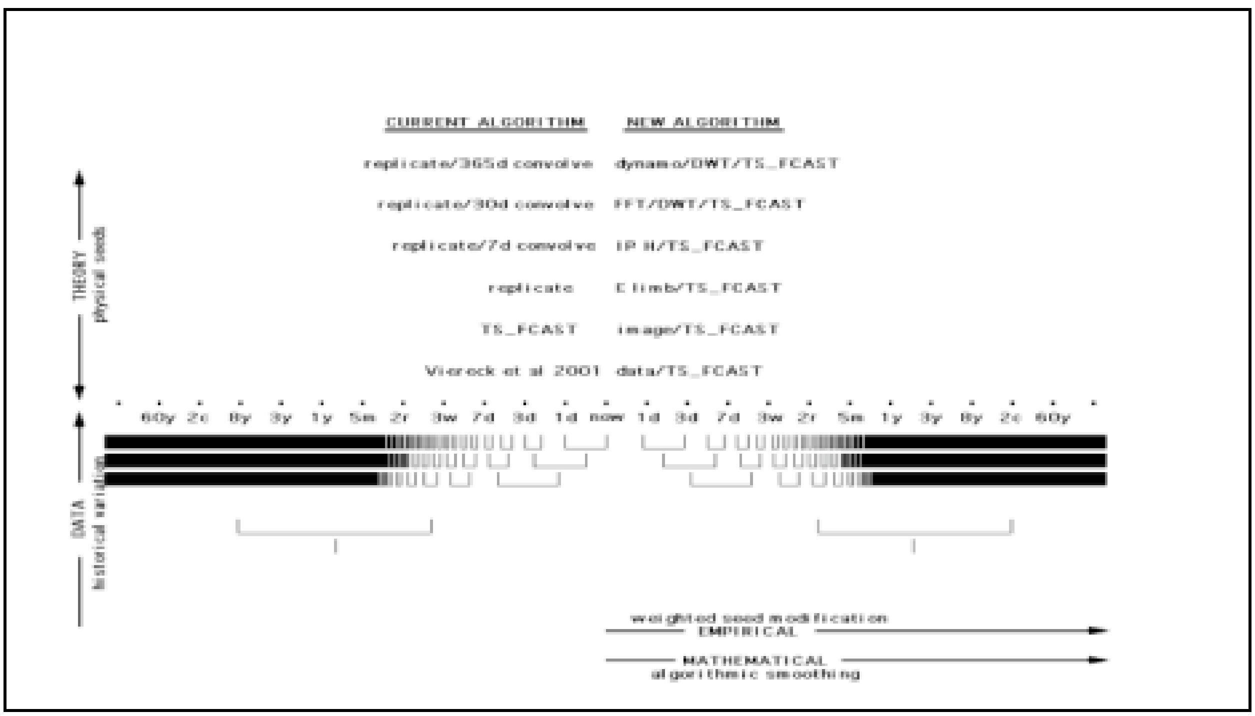

Figure 12. The DWT on a sliding time scale represents a next lower scale of variability into the future. New, “seed” algorithms are required for future physical irradiance specification. Time is represented exponentially in this figure centered on the current epoch, i.e., “now.”

CONCLUSIONS

A modified first generation forecasting algorithm (FGen 1x) has been developed that accounts for new understanding of operational forecasting issues. This includes a redefinition of the term "nowcast" to indicate the –24-hour to current epoch period and improved linear predictive techniques based on solar irradiance variability persistence. Improvements are in the form of reduced 1-sigma uncertainties from 11% (SEC F10.7) to 8% (SET E10.7) for the 3-day forecast.

A second generation forecasting method, FGen 2, is in development and is briefly described. Its improved algorithms will provide solar variability on seven time scales from nowcast and 72-hour forecast to 5 future solar cycles. The FGen 2 uses physical as well as mathematical models.

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All relevant documentation for SOLAR2000, along with the research grade SOLAR2000 IDL GUI application, can be downloaded from http://SpaceWx.com .

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