The MSFC Solar Activity Future Estimation (MSAFE) Model

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I. Introduction

The Natural Environments Branch at Marshall Space Flight Center (MSFC) provides solar cycle forecasts for NASA space flight programs and the aerospace community. These forecasts provide future statistical estimates of 13-month smoothed international sunspot number (SSN), solar radio 10.7 cm flux (F10.7), and the geomagnetic planetary daily index, *Ap*. The purpose of the forecasts is to provide future solar index values for input to various space environment models. For example, many thermosphere density computer models used in spacecraft operations, orbital lifetime analysis, and the planning of future spacecraft missions require as inputs the F10.7 and *Ap*.

The solar forecasts date back to the beginnings of NASA's Skylab program in the early 1970's. Solar forecasts were critical as inputs to calculating Skylab's orbital lifetime and eventual reentry. Solar forecasts were also required for the initial International Space Station (ISS) orbital altitude mission design for assembly and orbital reboost (Space Station Program Natural Environment Definition for Design NASA SSP 30425, 1993). Currently, the ISS program trajectory planning team uses the MSFC Natural Environments Branch's monthly solar forecasts for altitude reboost planning. The forecasts also support MSFC projects involving mission lifetime studies.

Solar forecasts are generated each month and provided on the Natural Environments Branch's solar webpage at https://sail.msfc.nasa.gov/. The current solar forecast is updated by executing the branch's solar forecast computer program referred to as the MSFC Solar Activity Future Estimation (MSAFE) model. The forecasted solar indices represent the 13-month smoothed values consisting of a best estimate value stated as a 50 percentile statistical value along with 95 and 5 percentile cumulative frequency bounds or approximately ± 2 standard deviations (SD). Although the observed indices are on time scales of days, the MSAFE model is not able to calculate forecasts of the indices on temporal scales such as daily or monthly. Users of the forecasts understand the highly variable nature of the observed indices and thus the limitations of being able to provide forecasts on those scales.

II. MSAFE Model

A. Input Data

The MSAFE model uses the historical and the latest month's observed solar and geomagnetic indices to provide estimates for the balance of the current solar cycle. The historical sunspot data consists of the 13-month smoothed SSN at monthly intervals since 1755 (beginning of cycle 1) until present. The historical and latest observed SSN are obtained from the World Data Center, Sunspot Index and Long-term Solar Observations, Royal Observatory of Belgium in Brussels.

The F10.7 historical data consists of 13-month smoothed observations at monthly intervals since 1947 and were obtained from the Solar Radio Monitoring Program, Space Weather Canada. The dataset also contains reconstructed values from 1755 to 1947. The reconstructed values were obtained by using a correlation relation between the F10.7 and SSN calculated by regressing the observed 13-month smoothed F10.7 from 1947 to 1978 with the associated 13-month smoothed SSN record.

The historical *Ap* data record consists of the 13-month smoothed observations at monthly intervals from 1932 to present. The data were obtained from the Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences. The dataset was extended back to 1884 by reconstructing the *Ap* using the 13-monthed smoothed magnetic character figure (Ci) data. The reconstructed data were calculated by correlating the 13-month smoothed Ci with the 13-month smoothed *Ap* from 1932 to 1963.

B. Solar Index Prediction Algorithm

The solar indices prediction algorithm of MSAFE uses a regression method referred to as the MSFC Lagrangian Linear Regression Technique (MLLRT) (Niehuss et al. 1996). The MLLRT is a modification of the linear regression method applied by McNish and Lincoln (1949). The algorithm uses a mean cycle of 132 months calculated by averaging the previous cycles at each time interval of the associated smoothed datasets. Each of the previous cycles are interpolated to 132 time intervals using a Lagrangian interpolation technique which stretches and contracts each cycle to the average cycle length before averaging.

The mean cycle is used in the calculation of deviations between the mean cycle and each of the previous cycle's values at the current month's observation and at the next prediction month. The deviations are used to find regression coefficients to predict future observations in the current cycle. Thus, if the current month's solar index measurement is at time interval m, then the next month's solar index prediction at m+1 is given by

$$R_{m+1} = \overline{R}_{m+1} + C_m \Delta R_m , \qquad (1)$$

where R_{m+1} is the predicted solar index, $\overline{R}_{m+1}$ is the mean cycle value at time m+1, ΔR_m is the solar index deviation from the mean cycle for the current month, and C_m is the regression coefficient (see Fig. 1). The regression coefficients are calculated by minimizing the sum of the squared differences (least squares method) of the linear regression of the deviations at m+1 with the deviations at time interval m. The slope of the regression line is thus C_m and is given by

$$C_m = \sum_{i=1}^{N} \Delta R_{m,i}\, \Delta R_{m+1,i} \Big/ \sum_{i=1}^{N} \Delta R_{m,i}^2 \ , \tag{2}$$

where N is total number of solar cycles in the indices dataset. The predictions for months greater than m+1 uses (1) and (2) recursively to predict the next month's value throughout the cycle. The prediction uncertainty bounds of 95 and 5 percent are based on cumulative frequency distributions of the differences between the observed and predicted solar index values obtained from applying the MLLRT to the historical solar cycle data (cycles 1-23) in the same manner as in the current cycle prediction.

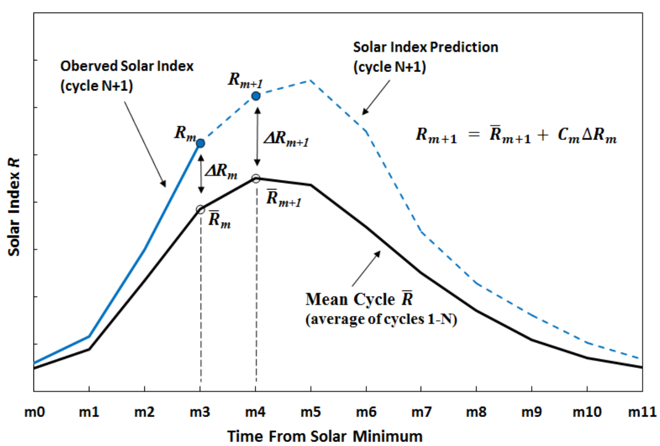

Figure 1. Graphical depiction of the parameters used in equations (1) and (2) in the text.

C. Example Forecast

Solar forecasts for a new cycle are generally made after two to three smoothed index values are observed after solar minimum to allow the cycle trend to establish. Because of the time lag in calculating the 13-month smoothed values, this will imply that the new cycle will have been under way for approximately 9 months.

An example of forecasts made early in the current cycle for SSN, F10.7, and *Ap* are shown in Fig. 2. The forecasts were made in Sept. 2009 beginning with the third smoothed observed value since the start of cycle 24 in Dec. 2008. Also shown in Fig. 1 are the actual observed index values observed since the time of the forecasts. In addition, the mean cycles for each of the indices are shown that were used in the calculation of the forecasts using (1) and (2) recursively.

As seen from Fig. 2, the SSN and F10.7 forecasts indicate a smaller than average solar cycle. This is confirmed by the actual data observations made since the forecast. The forecasts for these two solar indices does fairly well in capturing the overall trend of the cycle, however, the forecasts were not able to discern the double peaks at solar maximum. This is one of the short comings of the prediction technique. Later forecasts (not shown) occurring at the time of solar maximum were also not able to discern the double peaks.

The forecast's uncertainty bounds of approximately ± 2 SD are also shown in Fig. 2. The uncertainty bounds for SSN and F10.7 are fairly large especially at the peak of the cycle. For mission planning applications the uncertainty bounds are important. The upper uncertainty bound is often used for orbital lifetime studies. The forecasts beginning later in the cycle (not shown) do reduce the forecast's uncertainty, but large uncertainties at the peak of the cycle remain due to the variability seen at solar maximum which often includes double peaks.

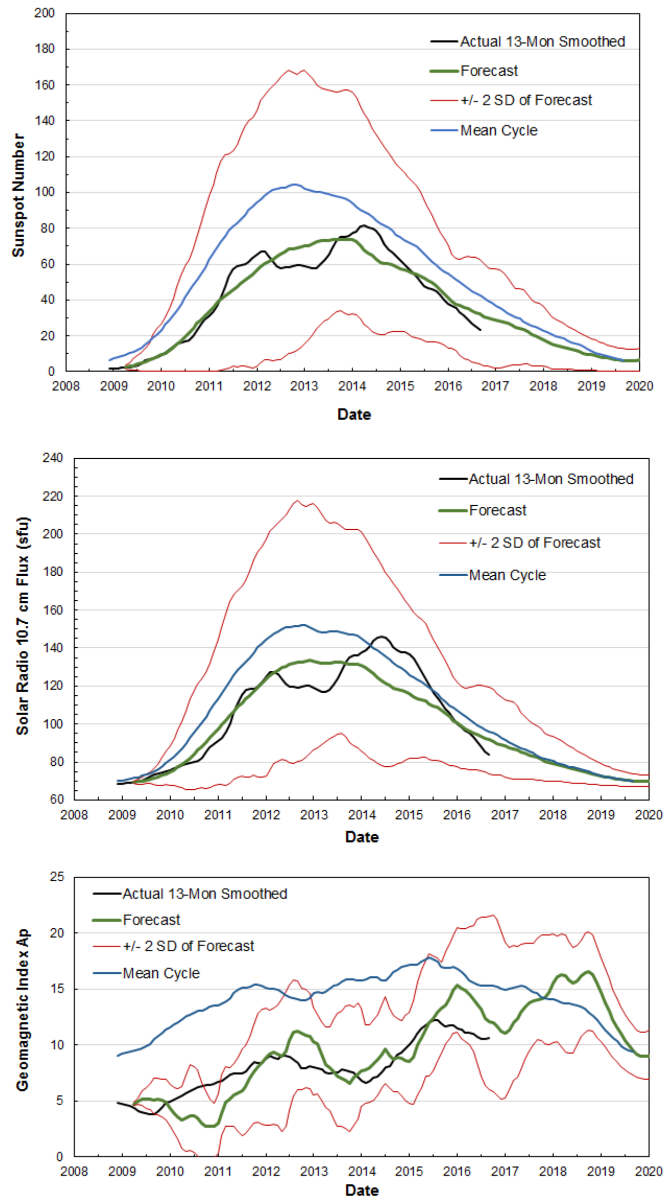

Figure 2. MSAFE forecasts of sunspot number (top), solar radio 10.7 cm flux (middle), and geomagnetic index *Ap* (bottom). The forecasts were made using the Mar. 2009 observed smoothed index. Also shown are the forecast uncertainty bounds of ± 2 standard deviations. The mean cycle for each index is also shown.

The 13-month smoothed *Ap* forecast given in Fig. 2 (bottom panel) successfully predicted a lower than average smoothed geomagnetic activity during solar cycle 24. Though the *Ap* shows significant variability during a cycle, the mean *Ap* of previous solar cycles does indicate a cyclical nature. The *Ap* forecast does fairly well in capturing the trend of the current cycle variation, but is unable to reproduce the variability present in the observed smoothed values. The uncertainty in the *Ap* forecast is also seen to vary significantly over the cycle.

III. SUMMARY

The MSAFE model provides forecasts for the solar indices SSN, F10.7, and *Ap*. These solar indices are used as inputs to many space environment models used in orbital spacecraft operations and space mission analysis. Forecasts from the MSAFE model are provided on the MSFC Natural Environments Branch's solar webpage and are updated as new monthly observations come available.

The MSAFE prediction routine employs a statistical technique that calculates deviations of past solar cycles from the mean cycle and performs a regression analysis to predict the deviation from the mean cycle of the solar index at the next future time interval. The prediction algorithm is applied recursively to produce monthly smoothed solar index values for the remaining of the cycle.

The forecasts are initiated for a given cycle after about 8 to 12 months of observations are collected. A forecast made at the beginning of cycle 24 using the MSAFE program captured the cycle fairly well with some difficulty in discerning the double peak that occurred at solar cycle maximum.

REFERENCES

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