Estimation of total solar irradiance from sunspot number

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Abstract

Annual levels of the Sun's irradiance are estimated since 1915 using parameterization of the sunspot number and Ca II K index. The regression estimation technique is applied to estimate the total irradiance. The goodness of fit statistics was used to choose the best fit among the different models (linear, quadratic and cubic). Therefore, from the statistical indictors, the quadratic model is considered as the best fit among the three models using TSI and sunspot number. The comparison with satellite data reveals a correlation coefficient of 0.97. We conclude that using sunspot numbers as proxy to estimate the contribution of active region for total solar irradiance estimation is useful to explain the phenomena of emitted energy at all wave lengths in temporal variations.

Keywords: Sunspot number, total solar irradiance, active region, quiet sun.

Resumen

Los niveles anuales de la radiación del Sol son estimados desde 1915 usando parametrización del número de manchas solares y el índice de Ca II K. La técnica de estimación de regresión es aplicada para calcular el total de irradiación. La bondad de las estadísticas de ajuste fue utilizada para seleccionar el mejor ajuste entre los diferentes modelos (lineal, cuadrático y cúbico). Por lo tanto, de los indicadores estadísticos, el modelo cuadrático es considerado como el mejor ajuste entre los tres modelos usando TSI y el número de las manchas solares. La comparación con los datos de satélite revelan un coeficiente de correlación de 0.97. Llegamos a la conclusión que usando los números de manchas solares como proxy para estimar la contribución de la región activa para la estimación total de la irradiación solar es útil para explicar los fenómenos de la energía emitida en todas las longitudes de onda en las variaciones temporales.

Palabras clave: Número de manchas solares, radiación solar total, región activa, quietud del sol.

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I. INTRODUCTION

Total solar irradiance describes the electromagnetic radiant energy emitted by the sun overall wavelengths that fall each second on one square meter outside the Earth's atmosphere. Total solar irradiance means that the solar flux has been integrated overall wavelengths to include the contribution from ultraviolet, visible and infrared radiation [7]. However, large proportion of the high–energy component corresponding to the ultraviolet (UV), extreme (EUV) and x-ray bands (XUV) is strongly absorbed in the atmosphere [6].

The number of sunspots correlates with the intensity of solar radiation over the period (Since, 1979), when satellite measurements of absolute radiation flux were available. Dark sunspots and bright faculae are the two primary sources of solar irradiance variations. Both are magnetic features that occur in varying number and size on the solar disk, altering the Sun's irradiative output affecting the Earth by respectively decreasing and enhancing the local emission [9].

Following 1978 solar irradiance measurement from Satellite researchers had shown the figure print of solar activity in our climate [14, 13, 5, 1, 10]. However, the exact physical mechanisms responsible for this influence are yet to be understood. Research findings attempted that one of the proposed responsible mechanisms are the change in total solar irradiance. In order to analyze the effect of solar activity in our climate, and global seismicity long term solar activity data is crucial. Since 1978 Satellite solar irradiance data climatologists and physicist develop different technique to predict total solar irradiance from solar activity. Studies conducted by Vaquero *et al*. [18] and Preminger and Walton [11] they reconstruct total solar irradiance from sunspot areas while Solanki and Fligge [17], they used daily sunspot numbers. Seme *et al.* (2009) in their study applied neural network for predicting daily

distribution of solar irradiance. Here we intended to obtain reconstruction of solar activity based on annual sunspot number and Ca II K index since 1915. The reason we chose this year is that the Ca II K index photometric data is since 1915. For this purpose we use the international sunspot number from NOAA and solar data from PMOD World Radiation Center Davos, Switzerland.

II. DATA ANALYSIS AND RESULTS

From satellite observations the solar total irradiance is known to vary. Sunspot blocking, facular emission, and network emission are three identified causes for the variations [8]. Variations in the Sun's total energy output (luminosity) are caused by changing dark (sunspot) and bright structures on the solar disk during the 11-year sunspot cycle [4].

Solar activity modulates TSI in a complex way. At solar maximum, when there are large numbers of active regions, TSI is high on average but TSI drops sharply every time a large sunspot group transits the solar disk. On Fig. 1 the top panel indicates daily sunspot number versus year from 1978-2011, where as the lower panel indicates the composite TSI record, compiled by the PMOD World Radiation Center (Fröhlich 2000, 2006). Sunspot cycles 21, 22, and 23 are clearly visible. The daily composite data has 1362 minimum and 1368W/m² maximum value while the sunspot number varies 0 and 288.8. As it is shown in both of the two figures, there is some trend when the sunspot number increases or decreases then this trend also can be seen in the total solar irradiance plot.

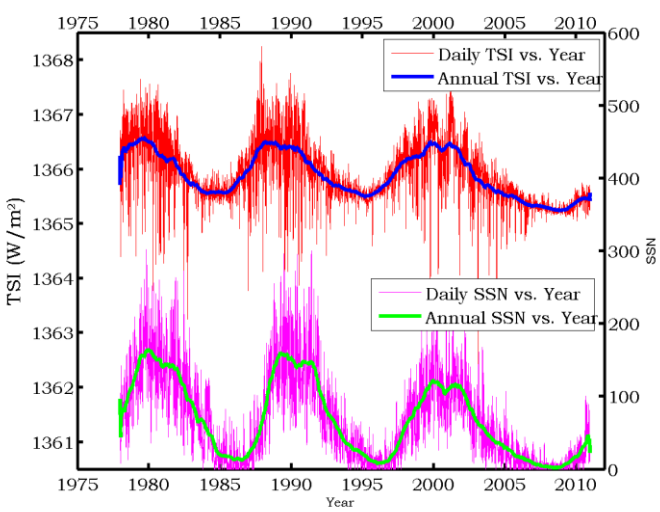

FIGURE 1. Solar irradiance and sunspot number since January 1978. The thin line indicates the daily total irradiance (TSI) red and sunspot number (SSN) magenta while the thick lines indicate the running of annual average for these two parameters.

A. Modeling the Active region and facular Contribution

The majority of the estimation of the total irradiance (S_{est}) is based on the following model:

$$S_{est} = S_o + \Delta \text{ Sact} + \Delta\, Sqs, \qquad (1)$$

where S_o is just a constant which is added in order to produce the correct absolute value of the observed irradiance [18]. The term ΔSact is the contribution of TSI of the solar active regions, while the term ΔS_{qs} corresponds to the contribution of the quite sun.

Research findings showed that in order to estimate the contribution of solar active regions one can use the relationship between the modern satellite measurements of solar irradiance and sunspots numbers. Vaquero *et al.* [18] used the relation between the satellite measurement of solar irradiance data and sunspot areas. While, the contribution of quiet sun irradiance variation ΔS_{qs} can be obtained from Ca II k line photometric data. Using the relationship between satellites measured solar irradiance value which is found in PMOD World Radiation Center and sunspot number since 1979-2010. Fig. 2 indicates from the top panel to the bottom, the fitted and the observed plot for total solar irradiance. By considering the goodness of fit statistics validity parameters the best fit for the model is quadratic one that is indicated in between the two plots. Table I shows the summary of those different fitting techniques to the model with their validity parameters. From the statistical indictors, the quadratic model is considered as the best fit among the three models using TSI and sunspot number. Therefore, all the estimation of our total irradiance from sunspot number since 1915 is done by using this quadratic fit.

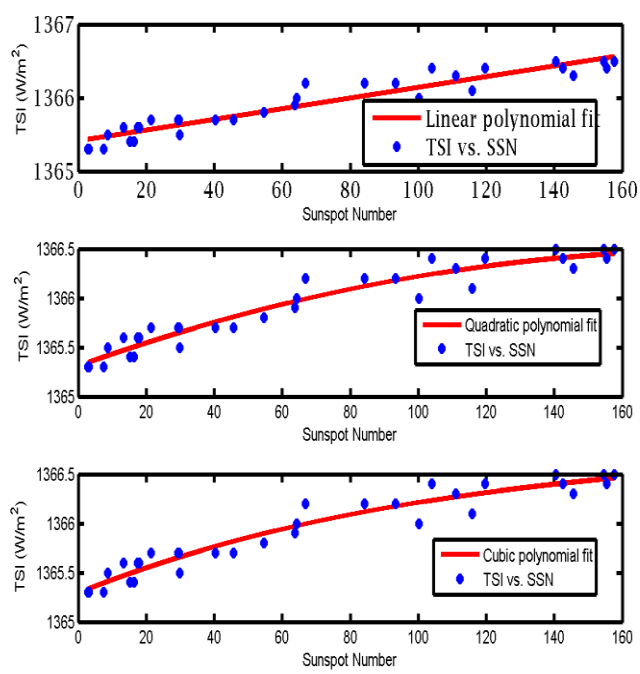

FIGURE 2. Annual total solar irradiance versus sunspot number. The top panel indicates the linear model while the middle and the bottom show polynomial degree two and three respectively.

TABLE I. The summary of validity for different fitting technique.

Model	SSE	R-square	RMSE	Coefficients
Linear	0.3913	0.9241	0.1142	2
Quadratic	0.2618	0.9492	0.09502	3
Cubic	0.2601	0.9496	0.09638	4

The mathematical equation of our model for active region contribution is:

$$S = 1365.32 \pm 0.038 + (-3.153 \pm 0.8) \times 10^{-5}\, SSN^2 + (0.01231 \pm 0.0013)\, SSN. \quad (2)$$

Where S is the Satellite measured solar data and SSN is the sunspot number.

Therefore the contribution of the active region to the TSI can be estimated:

$$\Delta Sact = (-3.153 \pm 0.8) \times 10^{-5} SSN^2 + (0{:}01231 \pm 0.0013)\, SSN \quad (3)$$

The estimated standard error of S_{est} and the measured value from satellite is $0.5744 W/m^2$. Hence this result shows that estimated solar irradiance and its measured value from satellite have good agreement. By using Eq. 3 we can estimate the contribution of active region for the total solar irradiate since 1915. Fig. 3 shows the estimated value of TSI versus the year from the contribution of active region. The maximum contribution reaches 1.2 W/m^2.

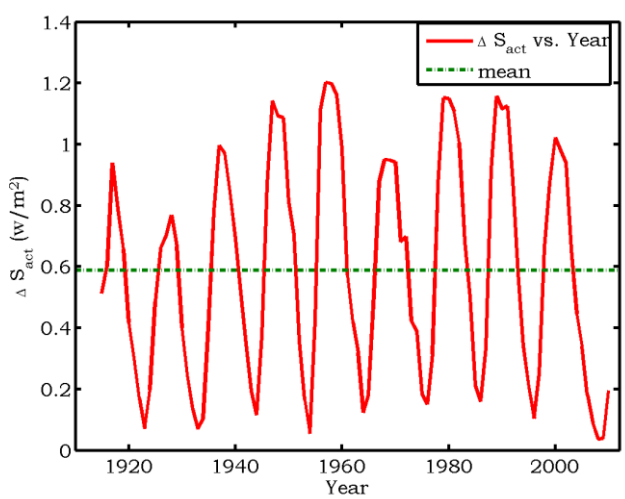

FIGURE 3. Estimated solar irradiance due to solar active region ΔS_{act} vs. Year. The irradiance is annual average value.

B. Modeling the Quiet Sun Contribution

It is well established that total solar and spectral irradiance are modulated by variable magnetic activity on the solar surface. However, there is still disagreement about the contribution of individual solar features for change in solar output, in particular over decadal time scales. Ionized Ca II K line spectroheliograms are one of the major resources for long term studies [2]. Precise measurement of the disk integrated solar Ca II K and H index lines play a crucial role in many investigations of solar activity and studies related to solar irradiance variability [12]. In line with this Ermolli *et al.* [3] discussed the potential of Ca II K data in providing far more detailed information on solar magnetism than just sunspot number and area records to which most of solar activity and irradiance changes are restricted.

The estimation technique of the contribution of quiet sun for the total irradiance from the proxy of Ca II K index is speculative and uncertain. In this paper we consider the assumption and equation stated by Shapiro *et al.* [16], but in our case we employed the yearly average of the Ca II K index as the proxy. The Ca II k index from 1915-2009 is taken from [2] and for year 2010, we calculated it is value by linear interpolation technique in order to have the same dimension data with the sunspot number. The contribution of the quiet sun using Ca II K is very small. The maximum contribution is to the order of 0.0079 and the minimum is $0.0022 W/m^2$. One can see Fig. 4 in the vertical axis the estimated value from this data.

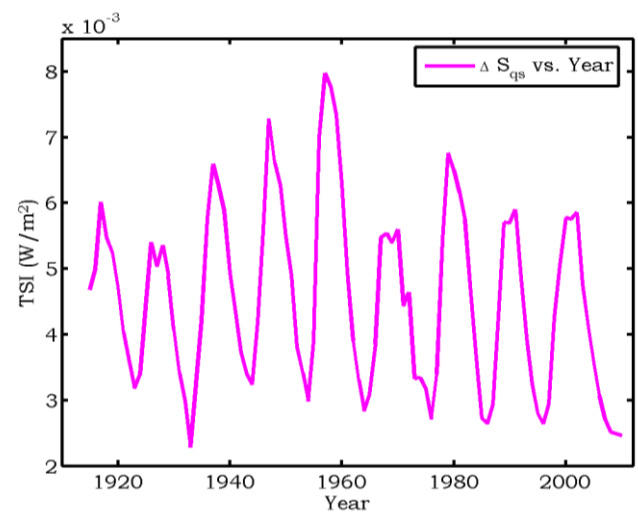

FIGURE 4. Estimated solar irradiance due to quiet sun ΔS_{qs} vs. Year. The irradiance is the annual average value.

The total solar irradiance was estimated using the contribution of sunspot number and Ca II K index since 1915 by adopting Eq. 1. Finally, the estimated and the measured data are plotted to indicate the agreement between them. Hence, Fig. 5 temporal variation plot indicates the fitting of satellite measured solar irradiance and the measured data against time.

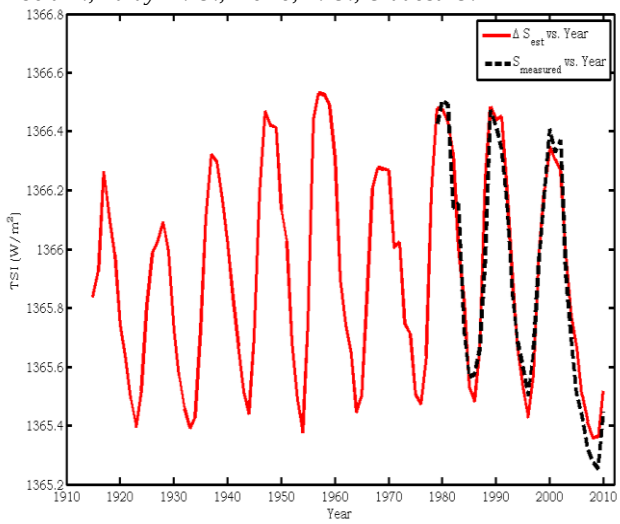

FIGURE 5. Estimated total solar irradiance since 1915 (red line) S_{est} including contribution to the irradiance variations due to active regions, S_{act}, and the quiet Sun, S_{qs} : S_{est}= ΔS_{act} + ΔS_{qs} + S_o and the measured total solar irradiance since 1979 (black dotted line).

The TSI estimation provides a good test of the TSI composites. We confirm the agreement of the real data and the estimated one by taking their correlation. Therefore, Fig. 6 shows a scatter plot of the annual TSI, as a function of the PMOD composite value for the interval 1979-2010 which has the correlation coefficient of 0.97 and the slope is 0.955.

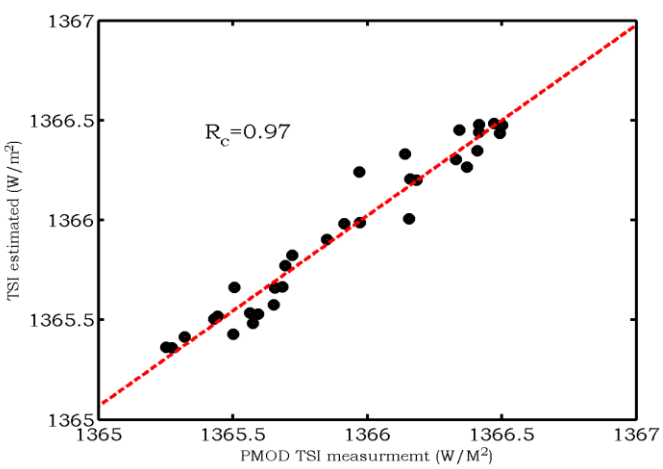

FIGURE 6. The scatter plot of TSI estimated as the function of PMOD measured TSI.

In order to validate our model we compare the model with the one reconstructed by Vaquero *et al*. [18] from the sunspot area and by Solanki and Fligge [17] from daily relative sunspot number. And Fig. 7 indicates the annual difference between the estimation of ΔS_{act}, the one obtained in this work and their reconstruction respectively. The maximum difference between the one we estimated and Solanki and Fligge [17] reaches 2.884 W/m^2, although the average value these difference is 0.84W/m^2 and the standard deviation is 0.7055W/m^2.

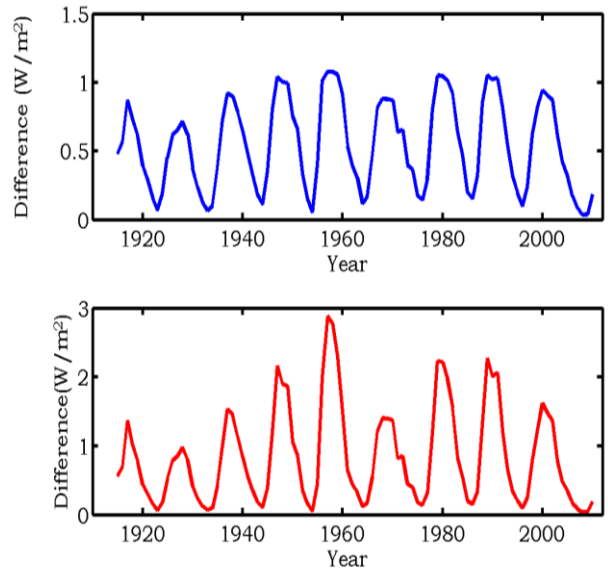

FIGURE 7. The top panel indicates: Difference between our model and the reconstructed by Vaquero *et al*. (2006) and also the lower one is between our model and the one reconstructed by Solanki and Fligge (1999).

III. CONCLUSION

We estimated total solar irradiance from onset of solar cycle 9 to 23. The data that we used for this study is to develop the total solar irradiance model by using sunspot number which is the annual average value from 1979-2010. During three decade solar irradiance satellite measurement, the solar minimum was commenced in 1986, 1996 and 2008.and the corresponding annual total solar irradiance also was 1365.575, 1365.502 and 1365.275W/m^2. At the solar minimum of 2008 the value of the total irradiance was more than 0.2W/m^2 lower than the minimum that observed in 1996.

Goodness of fit statistics validates the best fit of the model and based on this testing mechanism the best fit of the model is the quadratic one. This model successfully reproduces 97% of all TSI, variability over the time 1979-2010. The estimated TSI and the measured one have the correlation coefficient of about 0.97. This indicates our model and the TSI have a good agreement. However, the technique that we follow to estimate the contribution of quiet sun from Ca II K photometric data has limitation.

Finally, we conclude that using sunspot numbers as proxy to estimate the contribution of active region for total solar irradiance estimation is useful to explain the phenomena of emitted energy at all wave lengths in temporal variations.

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