

RESEARCH ARTICLE

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TSI modeling: A comparison of ground-based Ca II K-line data with space-based UV images from the SDO/AIA instrument

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Received 29 February 2024 / Accepted 26 September 2024

Abstract—The Total Solar Irradiance (TSI) is an important input for the Earth's climate. To describe the competing contributions of sunspots and faculae on irradiance variability, the San Fernando Observatory (SFO) irradiance model has two components: One component is an index derived from a continuum image that provides a sunspot signal. The other component is an index determined from a Ca II K-line image that provides a facular signal. These components are determined using two different methods, one based on feature identification and one based on photometric sum. Feature identification determines whether an active region feature is darker or brighter than the surrounding quiet Sun and by how much. Photometric sum simply adds up all the image pixels to determine a single value for that image. In this paper, we investigate the use of space-based UV images from the Solar Dynamics Observatory (SDO) as a substitute for ground-based Ca II K-line images from the San Fernando Observatory in modeling TSI variability. SDO indices are obtained by processing SDO/Atmospheric Imaging Assembly (AIA) 160 nm and 170 nm images with SFO algorithms, then SFO models are modified by substituting either a 160 nm or a 170 nm UV index from SDO in place of the Ca II K image. The different models are regressed against TSI measurements from the Total Irradiance Monitor (TIM) on the Solar Radiation and Climate Experiment (SORCE) spacecraft. The sunspot signal for all models used here is determined from SFO red continuum images at 672.3 nm. The facular signal is determined from either Ca II K-line images at 393.4 nm or space-based UV images from the SDO/AIA experiment. Images at both AIA wavelengths are processed with the standard San Fernando Observatory (SFO) algorithms. The SFO data is obtained from two photometric telescopes, which differ in spatial resolution by a factor of 2. The results of the linear regressions show good agreement between the fits that use SFO Ca II K-line data and the fits that use SDO UV data. However, facular indices obtained from SDO/AIA 170 nm images give significantly better fits than SDO/AIA 160 nm. We compare the goodness of the correlation using R^2 , that is, the multiple regression coefficient R , squared. The best two-component fit using ground-based Ca II K-line data was $R^2 = 0.873$; using AIA 170 nm produced $R^2 = 0.896$. Correlations using the AIA 160 nm data were consistently lower with values of R^2 as low as 0.793, where R^2 is the coefficient of multiple correlation.

Keywords: Total irradiance / Sun / Variability / Photometry / Solar indices

1 Introduction

Total Solar Irradiance (TSI) is the amount of radiant energy emitted by the Sun striking the top of the Earth's atmosphere at the mean distance of 1 astronomical unit, and is the most important input to the Earth's climate system, providing almost all the energy (99.96%) needed to drive the climate (Kren et al., 2017). TSI has been measured to a great degree of accuracy with space-based instruments beginning in 1978 (Hickey et al.,

1980; Willson & Hudson, 1988; Fröhlich, 2012) and continuing to the present (Kopp, 2021) and found to vary on timescales ranging from daily up to the 11-year solar cycle (Willson & Hudson, 1991; Zhao et al., 2019). In addition, some longer-than-solar-cycle variations have been studied through historical reconstructions of observations of sunspots and faculae by Montillet et al. (2022), Chatzistergos et al. (2023), Fröhlich (2006, 2016), and Kopp (2016). Numerous studies have shown that small changes in TSI over long time periods affect Earth's climate (Eddy, 1976; Ermolli et al., 2013; Solanki et al., 2013), making the understanding of TSI variability an important input to climate models.

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TSI variations appear to be due almost entirely to surface features associated with magnetic fields, especially sunspots, and faculae, except for variability on time scales of minutes which is largely due to oscillations and granulation (Marchenko et al., 2022; Yeo et al., 2017; Wenzler et al., 2005). Sunspots appear as dark features in visible wavelengths whereas faculae and plage appear as bright features on the disk (Title et al., 1992; Lawrence et al., 1993; Kobel et al., 2011; Yeo et al., 2017). Several successful models have been developed to reconstruct TSI in order to better understand this TSI variability, many of which use a two (or more)-component approach (Chatzistergos et al., 2023, Solanki et al., 2013). A two-component model, based on sunspot deficits (dark features) and facular excesses (bright features) extracted from full-disk images, and wavelength dependent, can reproduce TSI variations with high correlations. Sunspots can best be seen in continuum images while faculae are best seen in UV wavelengths because the facular contrast, away from the limb, becomes too small to be reliably detected in the visible continuum, especially towards the disk center (Lawrence et al., 1988; Title et al., 1992).

Long-term variations (solar-cycle length) in the TSI are associated with the presence of faculae and plage, more so than sunspots (Ermolli et al., 2003). The contribution of the near UV irradiance variation is approximately 19% of TSI variability (Lean, 1989), so it is important to develop proxies that are derived from images that capture the variations found in upper photosphere/low chromosphere features. One possible proxy can be made by measuring facular brightness on images derived from the ground using a filter placed in the Ca II K-line at 393.4 nm, making this wavelength important for TSI reconstructions (Chatzistergos et al., 2021, 2024). One type of proxy obtained in this way is one based on San Fernando Observatory (SFO) ground-based, full-disk photometric images of the Sun taken in the Ca II K-line (393.4 nm) to determine the bright facular excess signal.

TSI variations can also be calculated from physical models of features such as sunspots and faculae defined by their magnetic classification obtained from magnetograms as in the physics-based SATIRE model (Krivova et al., 2003, Wenzler et al., 2006, Ball et al., 2012, Yeo et al., 2014). A proxy for bright features can be obtained this way, but is not without its drawbacks. Most magnetograms are line-of-sight, causing the signal to decrease toward the limb. At lower resolutions, however, flux cancellation can occur, reducing the magnetograph signal. Ca II K brightness is not affected for such pixels. In addition, with magnetograms, a criterion needs to be established to distinguish faculae from sunspots (Yeo et al., 2017).

To help understand irradiance variability, we linearly regressed TSI (the independent variable) against two indices, a “dark” continuum index that responds primarily to sunspots and a “bright” line index that responds primarily to faculae as dependent variables (Chapman et al., 2012, 2013). Previous work produced models very highly correlated with spacecraft measurements of TSI. In Chapman et al. (2012), the multiple correlation coefficient, R , using Solar Radiation and Climate Experiment/Total Irradiance Monitor (SORCE/TIM) TSI data showed an R^2 as high as 0.9495. Results nearly as good were obtained using TSI data from UARS/Active Cavity Radiometer Irradiance Monitor (UARS/ACRIM) and SOHO/Variability of solar Irradiance and Gravity Oscillations (SOHO/VIRGO)

(Chapman et al., 2013). The SFO image set begins in 1986 for red and 1988 for Ca II K and continues to the present.

This work focuses on facular excesses and uses the SFO dataset, but it should be noted that SFO is not the only ground-based, full-disk, photometric image set available from which facular and sunspot information can be obtained. The two Precision Solar Photometric Telescopes (PSPT), one in Hawaii and one in Rome have Ca II K images as well as continuum images in the red and blue parts of the spectrum. Hawaii’s Ca II K (393.4 nm) image set runs from March 1998 through June 2015.¹ Rome’s Ca II K (393.4 nm) begins in 1996 and continues to the present.² In both cases, the method of image acquisition uses a two-dimensional CCD detector (Ermolli et al., 2022; Rast et al., 2008), whereas SFO uses a linear diode array (see Sect. 2 for further explanation). The Big Bear Solar Observatory (BBSO) in Southern California also has Ca II K images from 1988 to 2005.³ Unlike SFO, where the method of data acquisition has remained the same for the whole 38+ year dataset, the BBSO method, as well as the bandpass, was changed at one time during their data interval (Johannesson et al., 1998). Photometric images are also available from the National Solar Observatory’s (NSO) NISP/SOLIS program.⁴ Their Full Disk Patrol (FDP) images are taken in the 630.2 nm continuum and in the wing of the infrared Ca II line at 854.2 nm. Chatzistergos et al. (2021) have also developed an excellent method of reconstructing solar irradiance from several historical Ca II K image datasets, including photographic images that date back to 1892.

The work presented here examines the possibility of using space-based Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) (Pesnell et al., 2012, Lemen et al., 2012) UV images as a substitute for SFO ground-based Ca II K-line images for determining a facular component used in modeling variability. A question has arisen as to why use space-based images to develop a TSI model. Apart from the difference in image size that allows for greater identification of small bright features (SDO = 4096×4096 ; SFO CFDT1 = 512×512 , CFDT2 = 1024×1024), space-based images have greater temporal stability since atmospheric interference is not a problem. Determining this facular component is the first step, to be followed later by the development of a sunspot component from analysis of Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI) continuum images (Schou et al., 2012).

In the following, we develop two-component models from both SDO/AIA 160 nm and 170 nm images to determine which wavelength is a better proxy for a facular signal and compare the results to that of ground-based models that use SFO/CFDT Ca II K data. All images, whether space-based or ground-based, are processed using the same algorithms (Preminger et al., 2002; Walton et al., 1998) that were developed and applied at SFO for its photometry program.

2 Data description

This paper compares facular information obtained from both ground-based and space-based images to determine if

¹ https://lasp.colorado.edu/pspt_access/

² <https://www.oa-roma.inaf.it/pspt-project/>

³ <http://www.bbso.njit.edu>

⁴ <https://nso.edu/telescopes/nisp/solis>

space-based UV image data can be meaningfully integrated into and/or substituted for Ca II K data. The purpose of this is two-fold: (1) to produce a composite facular dataset that integrates ground-based and space-based facular excesses as a first step before examining the feasibility of obtaining and incorporating sunspot data from space-images images, and (2) to produce a shorter, strictly space-based, faculae dataset that can later be combined with space-based sunspot data. Establishing the ability to derive faculae data using the same algorithms that are used with ground-based data is the first step toward a set of space-based solar indices. The ultimate goal is to be able to use two-component models to help further understand irradiance variation. For this study, ground-based data was obtained from the San Fernando Observatory (SFO).⁵ A number of observatories have Ca II K images (Chatzistergos et al., 2022) that could be used (See Introduction) but SFO's is one of the longest, beginning in 1988 and continuing to the present; space-based data was obtained from Solar Dynamics Observatory (SDO)⁶ and TSI from the Solar Radiation & Climate Experiment/Total Irradiance Monitor (SORCE/TIM).⁷ SORCE operated from space for 17 years (2003–2020), taking both total and spectral solar irradiance measurements and was extremely successful in producing a number of data products used in solar irradiance variability, as well as in climate studies (Woods et al., 2021).

2.1 San Fernando observatory (SFO) data

The daily photometric program at SFO began observing in the Ca II K-line (393.4 nm) in mid-1988 with the Cartesian Full-disk Telescope #1 (CFDT1), producing 512×512 pixel images with 5 arcsecond/pixel resolution. Four years later, in mid-1992, CFDT2 came online with an image size of 1024×1024 pixels and 2.5 arcsecond/pixel resolution. Each telescope uses a linear diode array oriented in the north-south direction. (Chatzistergos et al. (2021, 2022) have claimed in several of their papers that the San Fernando Observatory uses CCDs in their observations; however, that is not the case.) Creating an image using a linear array requires a drift-scan method in order to build a 2D image containing the solar disk and some surrounding sky. Drift-scanning to create a solar image follows a suggestion by Gordon Hurford (Hudson, 1984). The telescope is pointed a little west of the Sun and a drift scan begins when the tracking motor is switched off, allowing the Earth to rotate so that the Sun passes across the diode array, producing 512 scans of a 512-diode array for CFDT1 and 1024 scans of a 1024-diode array for CFDT2. Such a drift scan takes roughly $2\frac{1}{2}$ –3 min to complete, depending on the solar declination.

Linear array imaging systems were widely available before CCDs were extensively used and offered the particular advantage of making image calibration relatively simple. Bright scans are produced by scanning the array lengthwise across the Sun and sky. Dark calibrations are made with the telescope objective covered. After a drift scan is taken, the raw image is calibrated, and stray light and instrumental artifacts are removed. Changing atmospheric transparency over the $2\frac{1}{2}$ min can be accounted for by taking an additional reading (513th pixel or 1025th pixel)

at the end of each scan. These procedures finally produce a fully calibrated full-disk photometric image (Walton et al., 1998). Modeling of variations in the TSI has been successfully carried out using this SFO ground-based data (Chapman et al., 1992, 1994, 2012, 2013). A detailed description of these two telescopes, as well as the method of obtaining images, can be found in Chapman et al. (1997, 2001).

SFO produces solar indices from both CFDT1 (512×512) and CFDT2 (1024×1024) instruments, resulting in two sets of sunspot signals and two sets of facular signals obtained through **feature identification**, as well as two sets each of Sigma-r and Sigma-K **photometric sums**. In addition, SFO produces a third set of facular signals that is a composite of CFDT1 and CFDT2 based on the need to compensate for a CFDT1 Ca II K-line filter change in 2002. The original filter was showing signs of degradation and was replaced with a Barr filter of the same wavelength and bandpass (393.4 nm, 1.0 nm). The creation of this composite K-line does not explicitly take into account the different pixel sizes and no correction (adjustment) is made for the different telescope resolutions. The indices from the two telescopes are highly correlated, as should be expected. This composite facular signal is used as the standard SFO facular excess index.

The work described herein includes data from both CFDT1 and CFDT2 Ca II K-line images. Both CFDT1 and CFDT2 K-line filters are centered on the Ca II K-line at 393.4 nm with a 1.0 nm bandpass (FWHM). This broad bandpass means the wavelength covers the upper photosphere with some contribution from the lower chromosphere (Björge et al., 2018).

Although SFO produces several facular indices based on Ca II K-line images, the relevant ones for this work are the facular excess, determined by feature identification, and Sigma-K (Σ_K), produced by photometric sum without the need to identify individual facular features. See Sections 2.1.1 and 2.1.2 for descriptions of these methods.

Both the feature identification and photometric sum methods require the creation of a photometric contrast image. This is an image that has been normalized by the quiet Sun limb-darkening, with 1 subtracted, resulting in an image where the quiet Sun intensity is equal to zero (see Sects. 2.1.1, 2.1.2, and Walton et al., 1998). Such an image can then be searched for bright or dark features.

Figure 1 shows three examples of calibrated images used in this work. Taken on 2013-05-02, scanning left to right, the images are of SDO/AIA 160 nm, SDO/AIA 170 nm, and SFO/CFDT1 Ca II K. The AIA images are calibrated by the SDO team already, while the CFDT1 images are calibrated using SFO techniques. Figure 2 shows these same three images after they have each been processed with SFO algorithms to produce contrast images.

2.1.1 Feature identification method

Surface features are identified from the processed, calibrated, and flattened contrast images (672.3 nm red continuum for sunspot information; 393.4 nm Ca II K-line for facular information) by looking at changes in contrast compared to the quiet Sun. To make a contrast image, the observed limb darkening is removed, resulting in an image where the quiet Sun is equal to zero. The contrast of features is in fractions of the mean quiet Sun. The algorithms are described in Walton et al. (1998).

⁵ <https://www.csun.edu/science-mathematics/physics-astronomy>

⁶ <https://sdo.gsfc.nasa.gov>

⁷ <https://lasp.colorado.edu/sorce/data/tsi-data/>

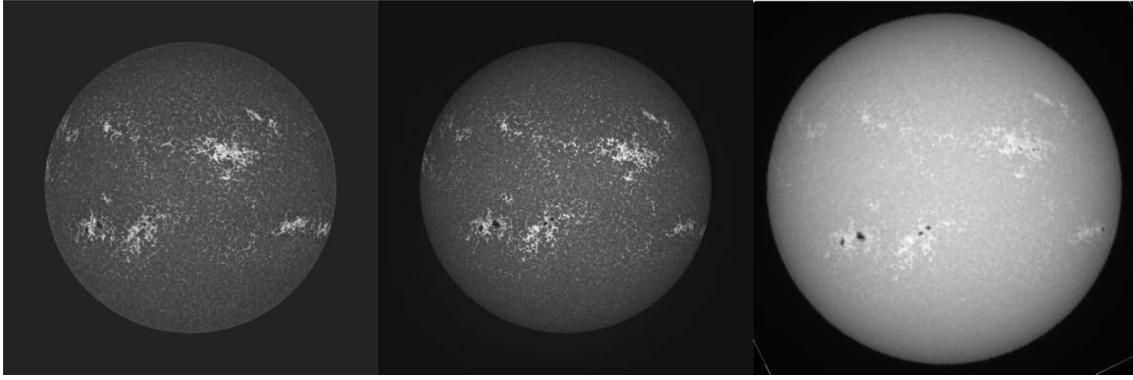


Figure 1. 2013-05-02. Left to right: AIA 160 nm, AIA 170 nm, SFO Ca II K-line.

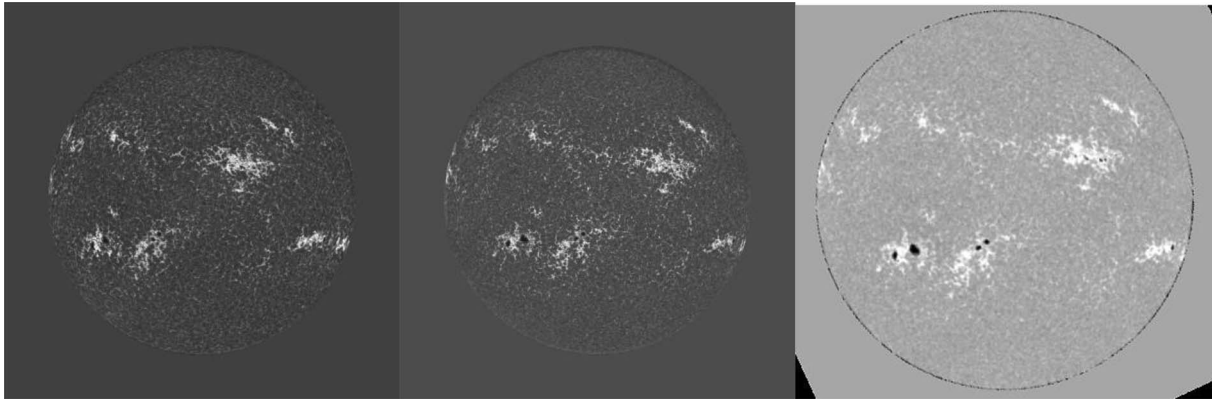


Figure 2. 2013-05-02 Contrast images: Left to right: AIA 160 nm, AIA 170 nm, SFO Ca II K.

Feature Identification identifies contiguous pixels on a photometric contrast image that are either darker or lighter than the surrounding quiet Sun, based on a pre-determined threshold contrast criterion. The outer 5% of the image radius is not used in the calculation of the model irradiance index. The default contrast criteria on SFO images are -8.5% for sunspot information from red images and $+4.8\%$ for facular information from Ca II K images (Walton et al., 1998). Identified features include sunspot area and deficit as well as facular area and excess. From this feature information, a database of solar indices is built, see Section 2.1.3.

2.1.2 Photometric sum (sigma) method

Calculating the photometric sum does not require feature identification and is simply the sum of all pixels on a contrast image. The photometric sum is defined by $\text{Sigma} = \sum[(\Delta I/I)_i * \Phi_i]$ summed over the entire solar disk. The quantity $(\Delta I/I)_i$ is the contrast of each pixel on a flattened contrast image and Φ is the observed limb darkening. The contrast image is obtained in the same way as for the feature identification technique.

Sigma, itself, is a measure of the relative change in spectral irradiance in the filter passband due to all pixels, whether or not they belong to identified features, and assumes that image noise is symmetric around zero. The resulting signal from bright and dark noise pixels cancels, leaving only contributions from real bright or dark pixels. The sum, Σ , is carried out for all pixels

on the solar disk. The contribution of each pixel to Sigma-K (Σ_K) or Sigma-r (Σ_r) is then weighted based on the limb darkening of the quiet Sun (see Preminger et al., 2002, for details). Photometric sum produces a single value for each image: a value that can be either positive or negative for red images (Sigma-r) and a positive value for Ca II K images (Sigma-K) that can be used in a two-component TSI model. Modeling the TSI using proxies for dark surface features and bright surface features has been described in Chapman et al. (2012, 2013).

2.1.3 SFO data availability

San Fernando Observatory solar indices, including sunspot deficit and area, and facular excess and area can be found by searching for “San Fernando Observatory.”⁸

2.2 Solar dynamics observatory data

The Atmospheric Imaging Assembly (AIA) instrument on the Solar Dynamics Observatory (SDO) satellite creates images in 10 spectral bands, ranging from 9.4 nm to 450 nm, most of which are used to observe chromospheric and coronal features. We selected 160 nm and 170 nm full-disk images, as these wavelengths are formed primarily in the upper photosphere (Cook et al., 1983; Lemen et al., 2012), and originate close to

⁸ <https://lasp.colorado.edu/lisird/>

those solar regions observed in SFO's Ca II K-line. It is also the case that SFO algorithms require images to have a clear and discernable limb in order to process and calibrate correctly and the AIA 160 nm and 170 nm images meet that requirement. Ca II K (393.4 nm) looks at the Sun's upper photosphere/lower chromosphere. SDO/AIA 160 nm originates in the upper photosphere and the transition region between the chromosphere and corona⁹ while SDO/AIA 170 nm is in the ultraviolet continuum, looking at the upper photosphere and low chromosphere.¹⁰

For accurate comparisons of facular data extracted from SDO/AIA 160 nm and 170 nm with SFO/Ca II K images, the same algorithms need to be used on the calibrated images from each source. There exist numerous algorithms for identifying and extracting faculae data (e.g., Fontenla et al., 1999), but in this case, the SFO algorithms have proven successful for many years and so these were applied to the SDO/AIA images. The primary goals of this project were, first, to determine if these wavelengths could be processed with SFO algorithms, thus producing flattened contrast images from which facular features could be identified and, second, to determine if meaningful facular areas and excesses could be extracted applying the same +4.8% contrast criterion as used for SFO's K-line images.

2.2.1 Determining a contrast criterion for SDO images

To be considered a facular pixel on an SFO photometric Ca II K image, the pixel contrast must be 4.8% greater than the quiet background Sun. A four-year subset of SDO 160 nm and 170 nm images were processed with the same contrast criterion, as well as smaller and larger criteria ranging from 2.8% to 8.8% in increments of 1.0%. Facular excesses at each contrast level were linearly regressed against the standard K-line facular indices. The variation in the SDO facular excess values did not change significantly for the different contrast criteria, therefore we adopted the 4.8% contrast criterion used for K-line images. The square of the multiple regression coefficient (R^2) results showed very little difference between contrast levels, ranging from 0.854 to 0.899 for 160 nm facular excess and 0.829–0.904. For 170 nm, the R^2 range for facular excess was 0.860–0.875. Since there was very little difference between the fits using a 4.8% contrast threshold versus fits using higher thresholds, we chose to use the 4.8% criterion for all wavelengths. No contrast test was necessary for the photometric sums (Σ_r and Σ_k) since their values do not depend on feature identification, hence, they do not change with the contrast criterion.

2.2.2 SDO data subset

After sample images were successfully processed, 8 years worth of 160 nm and 170 nm images were downloaded, covering a period from 2011-01-01 to 2018-12-31. (Although the SFO/CFDT1, the SDO/AIA, and the SORCE/TIM data sets continue until at least 2020, SFO/CFDT2 experienced an instrumental failure in late 2018 and did not come back online until after 2020. Because of this, we chose to end this preliminary work at the end of 2018). Data gaps occur in all datasets due to ground-based weather conditions and/or ground or space-based instrumental issues. Space-based SORCE TSI

(see Sect. 2.2.4) has instrumental gaps; SDO/AIA 160 nm and 170 nm sets are of different lengths due to missing days that does not always coincide.

Two separate datasets for each wavelength (AIA 160 nm and AIA 170 nm) were created, the first containing facular excesses derived from feature identification, the second containing the photometric sum value, either Σ_{160} or Σ_{170} .

The final length of each dataset depended on several factors. First, and most importantly, the reference dataset is composed of the number of common days between SFO/CFDT1 and SFO/CFDT2. The data days for these two telescopes do not always match for a couple of reasons. CFDT1 is always run first as it has the longest record but, sometimes, usually due to deteriorating sky conditions or time constraints, CFDT2 is not able to take images; and sometimes one of the telescopes produces a bad image for some reason, leaving only one image for that day.

The second step was to determine the number of common data days between the SFO/CFDT reference set and each SDO/AIA wavelength, separately, producing SFO/SDO datasets.

The third step was to determine the number of common data days between the SFO/SDO datasets and the SORCE/Total Solar Irradiance (TSI), resulting in final datasets for SDO/AIA 160 nm with 812 data points and SDO/170 nm with 782 data points. Because we wanted to maximize the SFO/CFDT image set, and because there was a 30-point difference between the AIA 160 nm and AIA 170 nm sets, we chose to keep the sets separate. Given the small difference in the number of data points, the effect on the results should be negligible.

2.2.3 SDO irradiance indices as determined by SFO algorithms from SDO data

SDO/AIA images processed with SFO algorithms are used to produce facular signal indices for SDO/AIA 160 nm¹¹ and SDO/AIA 170 nm¹² images.

2.2.4 Solar radiation and climate experiment (SORCE) total solar irradiance (TSI)

The space-based SORCE satellite operated from 2003 to 2020, taking measurements of TSI using the Total Irradiance Monitor (SORCE/TIM) as well as Spectral Solar Irradiance (SSI) with SORCE/SIM. The Level 3 data products include both daily and 6-h irradiance averages (Woods et al., 2021, 2022; <https://lasp.colorado.edu/sorce/data/tsi-data/>) and we chose to use a subset of TSI daily values, beginning 01 January 2011 and ending 31 December 2018, for all regressions of both SFO and SDO daily data. For more information on the SORCE instrument, please see Kopp & Lawrence (2005), Kopp et al. (2005), Kopp & Lean (2011), and Kopp (2021).

3 Analysis and results

To compare the data from these three datasets, each dataset was regressed separately against TSI in the standard

⁹ www.nasa.gov/content/goddard/sdo-aia-1600-angstrom

¹⁰ www.nasa.gov/content/goddard/sdo-aia-1700-angstrom

¹¹ <https://mysun.bos.com/s/8ogokzy1npnddo0cjc44y6r26mtwg5hq>

¹² <https://mysun.bos.com/s/789w9jnbxhyqvsmz10n91bq9c61pb8z>

Table 1. Results of linear regression fit of TSI versus dark sunspot and bright facular signals using **SFO/CFDT1** sunspot data and varying the facular signals.

CFDT1 comparisons of 2-component TSI models			
Feature identification method		Photometric sum method	
Regression components	R^2, A, B, C	Regression components	R^2, A, B, C
SDO 160 nm (812 data points)			
(sunspot deficit + cfdt1 K)	$R^2 = 0.8224$ A = 1360.715, B = 0.001983, C = 0.000237	(Σ_r + cfdt1 Σ_K)	$R^2 = 0.8779$ A = 1360.518, B = 0.00140, C = 0.000168
(sunspot deficit + composite K)	$R^2 = 0.8306$ A = 1360.695, B = 0.0019, C = 0.000244	(Σ_r + composite Σ_K)	$R^2 = 0.8782$ A = 1360.583, B = 0.001391, C = 0.00017
(sunspot deficit + cfdt2 K)	$R^2 = 0.8267$ A = 1360.717, B = 0.00197, C = 0.000256	(Σ_r + cfdt2 Σ_K)	$R^2 = 0.8700$ A = 1360.590, B = 0.00138, C = 0.00018
(sunspot deficit + SDO 160 nm)	$R^2 = 0.7241$ A = 1358.684, B = 0.00165, C = 0.000016	(Σ_r + SDO Σ_{160})	$R^2 = 0.7934$ A = 1359.504, B = 0.00143, C = 1.52E−5
SDO 170 nm (782 data points)			
(sunspot deficit + cfdt1 K)	$R^2 = 0.8262$ A = 1360.717, B = 0.00197, C = 0.000236	(Σ_r + cfdt1 Σ_K)	$R^2 = 0.8807$ A = 1360.521, B = 0.00139, C = 0.000167
(sunspot deficit + composite K)	$R^2 = 0.8343$ A = 1360.697, B = 0.00197, C = 0.000243	(Σ_r + composite Σ_K)	$R^2 = 0.8809$ A = 1360.587, B = 0.00138, C = 0.000173
(sunspot deficit + cfdt2 K)	$R^2 = 0.8303$ A = 1360.719, B = 0.00195, C = 0.000255	(Σ_r + cfdt2 Σ_K)	$R^2 = 0.8727$ A = 1360.594, B = 0.00137, C = 0.000180
(sunspot deficit + SDO 170)	$R^2 = 0.8514$ A = 1358.018, B = 0.00187, C = 2.6E−5	(Σ_r + SDO Σ_{170})	$R^2 = 0.8957$ A = 1359.274, B = 0.00155, C = 2.3E−5

two-component model used in studying solar irradiance variability. As previously stated, at SFO, one two-component model is determined by the feature identification method while a second two-component model is determined by the photometric sum method. For the **Feature Identification Method**, the first component represents a deficit irradiance signal, i.e., pixel areas that are darker and cooler than the surrounding quiet Sun (sunspots), taken from red continuum images (672.3 nm). The second component represents an excess irradiance signal from pixels that are brighter and hotter than the surrounding quiet Sun (faculae) and is determined from Ca II K-line (393.4 nm) images. For the **Photometric Sum Method**, Sigma-r (Σ_r) from continuum images supplies the irradiance deficit signal which can be positive, if there are few or no sunspots; Sigma-K (Σ_K) from Ca II K images supplies the irradiance excess signal. In both cases, the two components are used in a multi-linear regression against space-based TSI measurements (SORCE/TSI) in order to see how well the two components can explain irradiance variability.

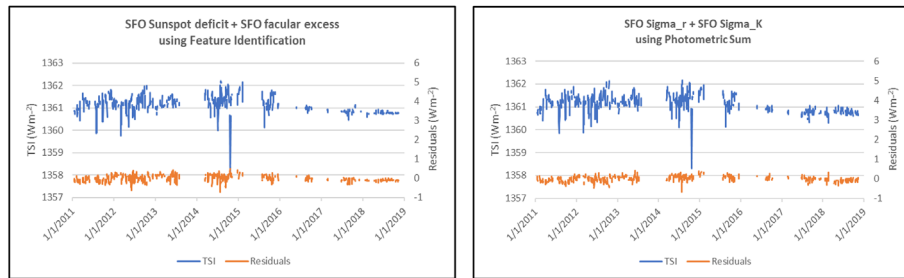
Although, as mentioned previously, SFO's standard facular excess index derived from Feature Identification and the standard Sigma_K derived from Photometric Sum are a composite of both CFDT1 and CFDT2 Ca II K images, it can also be instructive to look at facular data from each of the telescopes individually rather than combining them. In each of the regressions presented here, including those using SDO/AIA images, the sunspot signal and the Sigma-r signal obtained from SFO

red images supply the irradiance deficit index (the sunspot signal), either CFDT1 or CFDT2. The facular signal is cycled through the three Ca II K-line signals (CFDT1, CFDT2, and the composite), and either the SDO/AIA 160 nm or the SDO/AIA 170 nm signals. Tables 1 and 2 show the R^2 values as well as the regression coefficients. The regression equation is of the form $TSI = A + B * (\text{sunspot index}) + C * (\text{facular index})$ with R^2 being the multiple regression coefficient. The scale of the indices is in millionths.

The following Tables 1 and 2 give results of linear regressions from two-component models using a dark (sunspot) signal and a bright (facular) signal, obtained from either the Feature Identification Method or the Photometric Sum Method, against SORCE TSI. In each table, the sunspot deficit signal is held constant and comes from either SFO/CFDT1 or SFO/CFDT2 red continuum images (673.3 nm). Planned future work will replace the SFO/CFDT dark sunspot deficit signal with space-based SDO/Helioseismic and Magnetic Imager (HMI) sunspot signals obtained with the same methods used here, i.e., processing with SFO algorithms and using both Feature Identification and Photometric Sum methods, in order to construct a totally space-based set of solar indices with both sunspot and facular components. For now, each regression represented here couples the CFDT1 or CFDT2 deficit with each of the known facular signals, i.e., the three SFO K-line indices and either the SDO/AIA 160 nm or SDO/AIA 170 nm indices.

Table 2. Results of linear regression fit of TSI versus dark sunspot and bright facular signals using **SFO/CFDT2** sunspot data and varying the facular signals.

CFDT2 comparisons of 2-component TSI models			
Feature identification method		Photometric sum method	
Regression components	R^2, A, B, C	Regression components	R^2, A, B, C
SDO 160 nm (812 data points)			
(sunspot deficit + cfdt1 K)	$R^2 = 0.8267$ A = 1360.723, B = 0.0019, C = 0.000240	(Σ_r + cfdt1 Σ_K)	$R^2 = 0.8819$ A = 1360.612, B = 0.00137, C = 0.000153
(sunspot deficit + composite K)	$R^2 = 0.8364$ A = 1360.702, B = 0.00199, C = 0.000247	(Σ_r + composite Σ_K)	$R^2 = 0.8848$ A = 1360.669, B = 0.00137, C = 0.000158
(sunspot deficit + cfdt2 K)	$R^2 = 0.8337$ A = 1360.724, B = 0.00198, C = 0.000260	(Σ_r + cfdt2 Σ_K)	$R^2 = 0.8809$ A = 1360.673, B = 0.00136, C = 0.000165
(sunspot deficit + SDO 160)	$R^2 = 0.7237$ A = 1358.685, B = 0.00165, C = 1.66E−5	(Σ_r + SDO Σ_{160})	$R^2 = 0.8155$ A = 1359.689, B = 0.00144, C = 1.39E−5
SDO 170 nm (782 data points)			
(sunspot deficit + cfdt1 K)	$R^2 = 0.8278$ A = 1360.723, B = 0.00199, C = 0.000240	(Σ_r + cfdt1 Σ_K)	$R^2 = 0.8822$ A = 1360.612, B = 0.00137, C = 0.000153
(sunspot deficit + composite K)	$R^2 = 0.8374$ A = 1360.702, B = 0.00199, C = 0.000248	(Σ_r + composite Σ_K)	$R^2 = 0.8851$ A = 1360.670, B = 0.00137, C = 0.000165
(sunspot deficit + cfdt2 K)	$R^2 = 0.8347$ A = 1360.724, B = 0.00198, C = 0.000260	(Σ_r + cfdt2 Σ_K)	$R^2 = 0.8812$ A = 1360.675, B = 0.00137, C = 0.000165
(sunspot deficit + SDO 170)	$R^2 = 0.8536$ A = 1357.985, B = 0.0018, C = 2.69E−5	(Σ_r + SDO Σ_{170})	$R^2 = 0.8912$ A = 1359.500, B = 0.00150, C = 2.092E−5

**Figure 3.** TSI determined from SFO/CFDT1 red continuum and Ca II K-line images after linear regressions against SORCE/TSI. Left-hand graph uses sunspot deficit and facular excess; $R^2 = 0.8224$. Right-hand graph uses Σ_r and Σ_K photometric sums; $R^2 = 0.8779$.

Tables 1 and 2 show the results of linear regression fits of TSI versus dark sunspot and bright facular signals using SFO/CFDT sunspot data and varying the facular signals. Spot deficit refers to either SFO/CFDT1 (Table 1) or SFO/CFDT2 (Table 2) sunspot deficit from red images. Σ_r also refers to either SFO/CFDT1 (Table 1) or SFO/CFDT2 (Table 2) red images.

The R^2 results, displayed in Tables 1 and 2, show that the correlations in TSI variation using the Photometric Sum Method, with bright facular data derived from either the ground-based Ca II K-line or the space-based SDO UV images, are slightly better than those using the Feature Identification Method on the same images. The highest R^2 value, 0.8912, is

obtained using the 170 nm photometric sum index for the bright signal and the CFDT2 dark signal (last line of Table 2). The lowest R^2 value, 0.7237, is obtained using the 160 nm data and CFDT2. It is suggested that the lower correlations with the 160 nm data are due to the presence of chromospheric lines in the 160 nm pass band. (The lower values of the parameter C for the 160 nm and 170 nm regressions are due to the larger scale of the 160 nm and 170 nm indices.)

The following Figures 3–8 graphically illustrate several of the linear regressions presented in Tables 1 and 2 and are further explained in Section 4. In all figures, the residuals are downshifted by 3 Wm^{-2} (see right-hand scale where the zero level

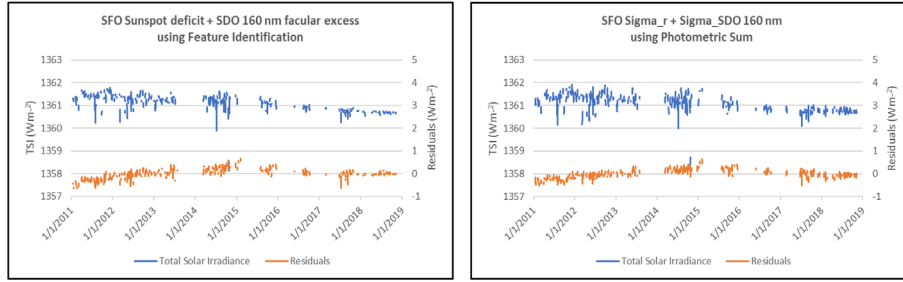


Figure 4. TSI determined from SFO/CFDT1 red continuum images and SDO/AIA 160 nm images after linear regressions against SORCE/TSI. Left-hand graph uses sunspot deficit and facular excess; $R^2 = 0.7241$. Right-hand graph uses Σ_r and Σ_{160} photometric sums; $R^2 = 0.7934$.

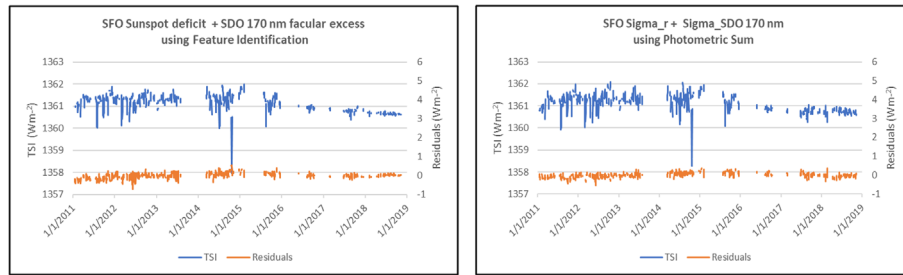


Figure 5. TSI determined from SFO/CFDT1 red continuum images and SDO/AIA 170 nm images after linear regressions against SORCE/TSI. Left-hand graph uses sunspot deficit and facular excess; $R^2 = 0.8514$. Right-hand graph uses Σ_r and Σ_{170} photometric sums; $R^2 = 0.8957$.

is downshifted by 3 Wm^{-2}). All left-most figures obtain data using the Feature Identification Method, while all right-most figures obtain data using the Photometric Sum Method. Vertical units are in Wm^{-2} for Figures 3–5 and in parts per million (ppm) of the mean quiet Sun irradiance for Figures 6 and 7. Figure 8 is simply a ratio for any given data point.

4 Discussion and conclusions

The purpose of this work was to determine whether or not facular excesses could be derived from space-based images at 160 nm and 170 nm as a first step toward building a space-based data set that could be used in a 2-component model to help understand TSI variability. One of the components is calculated from a continuum image that responds to sunspots as well as faculae near the limb. The second component is from an image that responds to the mid- to upper-photosphere (for example, the Ca II K-line, or an SDO UV image) and shows faculae across the entire solar disk. There is no one SFO TSI model but several, depending on whether the data are from CFDT1 or CFDT2 and whether feature identification or photometric sum method is used. An important requirement was that images had to be processed with the same algorithms used at SFO for ground-based Ca II K images with the future hope of developing a composite dataset of ground- and space-based information as well as a totally space-based dataset.

Table 1 displays the results from using CFDT1 data (512×512 images) for the ground-based component of the multiple regressions. The left half of both Tables 1 and 2 show results from indices determined from feature identification. The right half shows results from using the photometric sum, Sigma (see Sect. 2.1.2 for a definition of Sigma) to determine the indices.

Table 2 displays the results from using higher resolution CFDT2 data (1024×1024 images) for the ground-based component. The regression results are listed in both Table 1 and Table 2 for both SDO/AIA 160 nm and SDO/AIA 170 nm. Most of the indices give good regression results, explaining between 82 and 90 percent of the variance in TSI. The 160 nm indices gave lower results. As stated previously, this facular information is only one component of a two-component SDO TSI model and future work will examine the results from a substitution of SDO/HMI images for the SFO/CFDT red images used here.

Figure 3 (left) shows computed TSI and residuals from a standard 2-component model using only SFO/CFDT1 sunspot and facular excess indices from feature identification. A linear regression fit gives an $R^2 = 0.8224$. The residuals fit to a straight line give coefficients of $-3.087 \pm 6.6\text{E}-06$ for the slope and 1.293 ± 0.277 for the constant. Figure 3 (right) shows the 2-component fit for SFO/CFDT1 photometric sum (sigma) indices with $R^2 = 0.8779$. A linear fit to the residuals gives $-3.314\text{E}-06 \pm 5.674\text{E}-06$ for the slope term and 0.139 ± 0.238 for the constant. All coefficients are in Wm^{-2} .

Figure 4 shows the model TSI and residuals when SDO/AIA 160 nm facular data is substituted for SFO/CFDT1 Ca II K data. The left graph uses feature identification with a linear fit of $R^2 = 0.7241$ and a fit to the residuals gives a slope of $8.528\text{E}-05 \pm 7.866\text{E}-06$ and a constant of -3.575 ± 0.329 . The right graph is a result of photometric sum with an $R^2 = 0.7934$, with a fit to the residuals giving a slope of $6.9119\text{E}-05 \pm 6.869\text{E}-06$ and a constant of -2.8942 ± 0.288 .

Figure 5 (left) is the model TSI and residuals when SDO/AIA 170 nm facular data is substituted for SFO/CFDT1 Ca II K and feature identification is used in a 2-component model. The resulting linear fit gives $R^2 = 0.8514$. A fit to the residuals

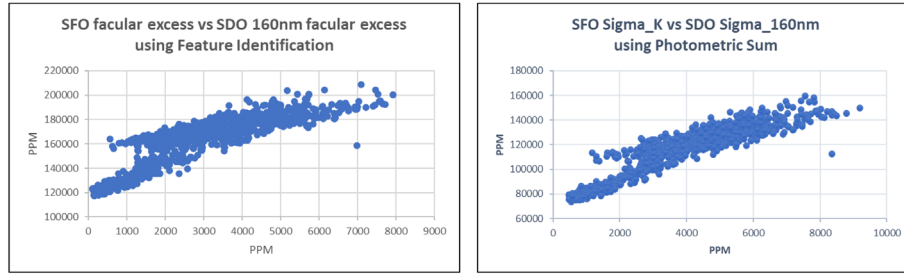


Figure 6. Scatter plots of SFO/CFDT1 Ca II K-line vs SDO/AIA 160 nm facular signals. Left-hand graph uses facular excess determined by feature identification. Right-hand graph uses photometric sums (Σ). Units are in parts per million of the mean quiet Sun irradiance.

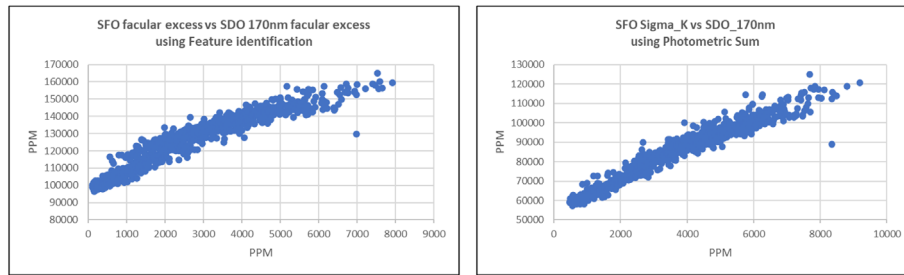


Figure 7. Scatter plots of SFO/CFDT1 Ca II K-line vs SDO/AIA 170 nm facular signals. Left-hand graph uses facular excess determined by feature identification. Right-hand graph uses photometric sums (Σ). Units are in parts per million of the mean quiet Sun irradiance.

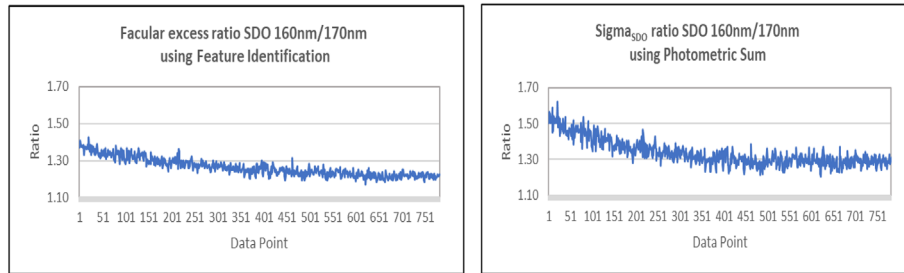


Figure 8. Ratio plots of SDO/AIA 160 nm to SDO/AIA 170 nm. Left-hand graph shows ratio of facular excesses determined from feature identification. Right-hand graph shows ratios determined from photometric sums Σ .

gives slope = $5.4843\text{E}-05 \pm 6.014\text{E}-06$ and constant = -2.2964 ± 0.252 . Figure 5 (right) uses photometric sum indices, giving $R^2 = 0.8957$ and a fit to the residuals results in the slope = $3.1584\text{E}-02 \pm 5.187\text{E}-06$ and constant = -1.3225 ± 0.217 .

One can see a trend in the residuals in Figure 4 (160 nm) but is apparent to a lesser degree in Figure 5 (170 nm). We believe that the decrease in the residuals at the endpoints, but mostly at the beginning, is time-dependent (see Fig. 3).

Scatter plots of SFO/CFDT1 Ca II K vs SDO/AIA are presented in Figures 6 and 7. Figure 6 (left) is a scatter plot of Ca II K vs 160 nm using facular excess values determined with feature identification while Figure 6 (right) is a scatter plot of the same 160 nm using photometric sum (Sigma) values. Figure 7 presents the same scatter plots but substitutes SDO/AIA 170 nm. It appears that there is more variation in the 160 nm than in the 170 nm. Also, at low activity levels, the 160 nm data appears to be double-valued. The apparent bifurcation of the

160 nm plots is most likely caused by the influence of the brightening of the chromospheric lines in this passband.

Figure 8 shows the ratio of SDO 160 nm/170 nm with feature identification of facular excess (left) and the same ratio with photometric sum Sigma (right). The smooth change in the ratios for both wavelengths shows that there are no sudden jumps in the ratios although there appears to be a slight difference over time. Further work is needed to determine the possible cause of the difference.

Since SDO/AIA 160 nm and 170 nm datasets are of slightly different lengths (812 data points for 160 nm and 782 data points for 170 nm), regressions using strictly SFO data had to be repeated for each SDO/AIA wavelength. We purposefully chose to keep the 160 nm and 170 nm datasets of different lengths in order to use as many SFO data points as possible.

Both the Feature Identification Method and the Photometric Sum Method were used in multilinear regressions against TSI and, in all cases, for all three wavelengths (393.4 nm,

160 nm, and 170 nm), the photometric sum using Σs gives a better fit to TSI than feature identification. This has been shown in previous work on ground-based images alone (Chapman et al., 2013).

Again, in all cases, fits using SDO 170 nm are only slightly better than SFO Ca II K fits but are significantly better than fits using SDO 160 nm. This is not unexpected since both the inner Ca II K-line wings and the 170 nm originate in the upper photosphere. Additionally, the 160 nm region contains a number of emission lines (Kurucz, 1991). Their contribution to the 160 nm passband may explain the bifurcation seen in the 160 nm contrasts shown in the Figure 6 scatter plots while no bifurcation occurs in the 170 nm Figure 7 plots.

Based on the results of these linear regressions, we have shown that SDO 170 nm images can be substituted for Ca II K-line images in order to provide a facular component for the 2-component model over short time scales. Future work will be needed to see whether these SDO UV images can be substituted for Ca II K-line data over longer time periods.

Future plans for this project include processing SDO/HMI continuum images to produce a space-based dataset of sunspot indices. As with the facular data, the resulting sunspot indices will be compared to SFO/CFDT sunspot indices derived from their full-disk red (672.3 nm) images. Then the sunspot data will be used in 2-component models based on feature identification and photometric sum against CFDT Ca II K, SDO/AIA 160 nm, and SDO/AIA 170 nm facular data. The results will be used in developing a space-based set of solar indices for the continuing study of solar irradiance variability.

Acknowledgements

This paper benefitted greatly from suggestions by the reviewers. We gratefully acknowledge the many students who participated in the San Fernando Observatory's solar photometric program for their help in obtaining much of these data over the past 38 years. This research was partially supported by grants from NSF and NASA over the years, and currently by NASA grant (80NSSC21K1863). The editor thanks Thomas Woods and an anonymous reviewer for their assistance in evaluating this paper.

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Cite this article as: Chapman GA, Cookson AM & Choudhary DP. 2024. TSI modeling: A comparison of ground-based Ca II K-line data with space-based UV images from the SDO/AIA instrument. *J. Space Weather Space Clim.* **14**, 34. <https://doi.org/10.1051/swsc/2024035>.