

Understanding the secular variability of solar irradiance: the potential of Ca II K observations

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Received 30 August 2023 / Accepted 7 March 2024

Abstract – With the increasing concern about climate change, it is important to have accurate information on the individual contributions by the potential driving agents, solar variability being one of them. Long and reliable records of solar irradiance, which describe the solar radiative energy input into the climate system, are essential for assessing the role of the Sun. The short temporal extent (since the 1970s) of direct space-based irradiance measurements leaves reconstructions of the past variability with the help of models as the only avenue. Such models require information on the surface distribution and evolution of solar magnetic regions, dark sunspots and bright faculae, and network regions. However, such data become increasingly scarce and of diminishing quality further back in time. Prior to the period of direct irradiance measurements, reconstructions mainly rely on sunspot observations or other indirect data to describe facular and network regions. The resulting estimates of the long-term change between the Maunder minimum and the present diverge by about an order of magnitude. Having direct information on bright magnetic regions can help resolve these discrepancies. The by far most promising data for this purpose are the full-disc observations of the Sun in the Ca II K line. Despite the wealth of such data all the way back to 1892, their use up to now has been rather limited, owing to a number of intricacies of the data. Here we review the recent efforts to bring Ca II K datasets to their full potential. We briefly discuss the problems plaguing the data and processing methods that have been developed to account for them before switching to a summary of the products derived from them. Focus is given to reconstructions of total and spectral irradiance variations from Ca II K observations. We summarise the available such reconstructions and discuss various aspects requiring further attention in order to allow Ca II K observations to be used to their full potential and thus eventually more accurate irradiance reconstructions back to 1892.

Keywords: Solar variability / Solar activity / Spectral irradiance / Total irradiance

1 Introduction

The Sun provides most of Earth's energy (see e.g., Kren et al., 2017) and can thus affect Earth's atmosphere and climate. Several mechanisms have been proposed for solar influence on climate, among which variability of the Sun's radiative energy flux is the most prominent one (Haigh, 2007; Gray et al., 2010; Solanki et al., 2013; Krivova, 2018; IPCC, 2021). The solar radiative output received by Earth is typically quantified by the total and spectral solar irradiance (TSI and SSI), which are the wavelength-integrated and wavelength-resolved solar radiative energy flux, respectively, as measured at the top of Earth's atmosphere and normalised to the mean Sun-Earth distance (1 AU). Other proposed mechanisms of solar influence on climate include changes in the solar energetic particle flux

(e.g. Rozanov et al., 2005, 2012; Gray et al., 2010; Sinnhuber et al., 2012; Sinnhuber & Funke, 2020; Mironova et al., 2015) and the flux of the galactic cosmic rays (Gray et al., 2010; Matthes et al., 2017). The roots of all of these mechanisms lie in the incessantly evolving solar surface magnetic field, which in turn modulates the interplanetary magnetic field as well (for a review see Owens & Forsyth, 2013). Therefore, having long and reliable records of solar surface magnetism as well as of TSI and SSI is crucial for understanding the role of the Sun in climate change.

Early attempts to measure TSI from the ground could not detect any variations in this quantity, which is why it was also known as the “solar constant”. Direct space-based measurements of TSI started in 1978 (e.g. Hickey et al., 1980; Willson et al., 1981; Fröhlich et al., 1995; Dewitte et al., 2004; Kopp & Lawrence 2005; Pilewskie et al., 2018, for a review see Kopp, 2016). These measurements revealed variations on all

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measurable timescales (Kopp, 2016), the most prominent being the $\sim 0.1\%$ variability in-phase with the solar cycle. The measurements have been done by multiple satellite missions and show somewhat different absolute levels. Combining all of them together into a coherent record proved to be a non-trivial task. Several TSI composites have been produced, differing in the methodologies used to stitch the data together, the favoured instruments, as well as the corrections applied to the data (see Fröhlich, 2012; Chatzistergos et al., 2023b, for more details). The most commonly used TSI composites are the PMOD¹ (named after Physikalisch-Meteorologisches Observatorium Davos; Fröhlich, 2006), ROB² (named after Royal Observatory of Belgium, previously referred to as RMIB, Royal Meteorological Institute of Belgium, in French called IRMB; Dewitte et al., 2004; Dewitte & Nevens, 2016), and ACRIM³ (Active Cavity Radiometer Irradiance Monitor, which is the instrument taken as the reference by Willson, 1997; Willson & Mordvinov, 2003) ones, while more recently several new series have been presented such as those by Dudok de Wit et al. (2017)⁴, Schmutz (2021), and Montillet et al. (2022, Composite PMOD-Data Fusion, CPMDF, hereafter). All of the available composites suggest a decreasing TSI trend since the 1990s, while half of them (that is PMOD, Schmutz, 2021, Montillet et al., 2022 series) also favour a decreasing TSI trend of about $-(0.15 - 0.25) \text{ Wm}^{-2}$ over the entire period of direct measurements. The composites by Dudok de Wit et al. (2017) and ROB show essentially no trend, while only ACRIM shows an increasing trend when considering the entire period. However, we note that the last official update of ACRIM was in 2013, which does not include the last activity minimum, whereas between the 1996 and 2008 activity minima ACRIM also shows a decrease in TSI. The increasing trend of the ACRIM composite has been shown to be most likely an artefact of the ACRIM-gap (e.g. Lee III et al., 1995; Fröhlich & Lean, 1997; Fröhlich, 2000; Krivova et al., 2009; Amdur & Huybers, 2023; Chatzistergos, 2024). It is noteworthy that a recent extension of the ACRIM composite to 2022 by Scafetta (2023, we refer to this as ACRIM-rev) suggests that the initial uptick in TSI in the ACRIM series was almost completely balanced by the decrease in the following years, resulting in marginally increasing TSI between 1986 and 2019 by 0.06 Wm^{-2} .

Also, SSI measurements started in 1967 (e.g. Arvesen et al., 1969; Samain & Simon, 1976; Rottman et al., 1982; Meftah et al., 2016; Snow et al., 2022, for a review see Ermolli et al., 2013). The early measurements were limited to the UV part of the spectrum, and only later over a broader range. As a result, the spectral coverage of SSI measurements was rather limited before the 2000s. The SSI measurements also revealed variability which is strongly wavelength-dependent reaching up to 100% at Lyman- α .

The direct irradiance measurements proved to be extremely valuable for understanding the mechanisms of irradiance

variability and improving our insight into the role of the Sun in Earth's climate change. However, their limited availability over just above four decades necessitates reconstructions of past irradiance variations to the times not covered by direct measurements. Such reconstructions are only possible with appropriate models.

Variations in the brightness of the Sun on time scales of relevance to climate studies are due to the evolution of solar surface magnetic regions (Shapiro et al., 2017; Yeo et al., 2017b), most prominently sunspots and faculae. Sunspots are regions with strong magnetic field which suppresses the convective flows and renders sunspots cooler and thus darker than their surrounding (Solanki, 2003). In contrast, faculae are ensembles of smaller and brighter magnetic elements. On average, they cover greater areas on the solar surface than sunspots (Solanki et al., 2006). Faculae typically surround sunspots but facular elements also form bright regions away from sunspots as well as the so-called network regions. When observed in the chromosphere, e.g. in the Ca II K line as discussed below in more detail, faculae are called plage. Figure 1 shows the effect of sunspots and faculae on TSI variations over the course of one year, both individually and combined.

A number of models have been developed to compute irradiance variations from various data or proxies describing solar surface magnetism (see Chatzistergos et al., 2023b, for a recent review). There are currently three types of models – empirical, semi-empirical, and physical – depending on the amount of physics they involve. However, irrespectively of the model architecture, they all require data on the temporal and ideally also the spatial distribution of solar magnetic regions.

Full-disc measurements of the solar surface magnetic field (magnetograms) are unfortunately available for roughly the same period as direct measurements of solar irradiance (e.g. Livingston et al., 1976; Scherrer et al., 2012). Thus other measures of solar activity and magnetism have to be employed for the past irradiance reconstructions. The amount and the quality of the data suitable for irradiance reconstructions are unfortunately progressively slumping when going back in time. The longest available record is that of sunspot observations (Vaquero & Vázquez, 2009; Vaquero et al., 2016; Arlt & Vaquero, 2020). Full-disc photographs provide accurate information on sunspots over the last century, with modern high-quality CCD-based observations such as those from the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012; Schou et al., 2012) aboard the Solar Dynamics Observatory (SDO; Pesnell et al., 2012, since 2010), or Rome observatory (performed with the Precision Solar Photometric Telescope, hereafter referred to as Rome/PSPT; Ermolli et al., 2022, since 1996)⁵, while photographic observations exist since 1874 from the Royal Greenwich observatory (Willis et al., 2016) as well as other sites such as Kodaikanal (Jha et al., 2022)⁶ or the Einstein tower in Potsdam (Pal et al., 2020). Such photographs have been used to extract sunspot areas back to 1874 (Mandal et al., 2020). Finally, over yet earlier periods, information on sunspot regions comes from drawings of the solar disc (e.g. Arlt & Vaquero, 2020; Ermolli et al., 2023) or tabulations and annotations of counts of sunspots and/or sunspot groups made

¹ Available at <https://www.pmodwrc.ch> and ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite_old/DataPlots.

² Available at <https://www.sidc.be/observations/space-based-time-lines/tsi>.

³ Available at <https://web.archive.org/web/20170611210135/http://acrim.com/>.

⁴ More recent versions are available at <https://spot.colorado.edu/~kopp/TSI/>.

⁵ The archive can be found at <https://www.oa-roma.inaf.it/fisica-solare/>.

⁶ The archive can be found at <https://kso.iap.res.in/data>.

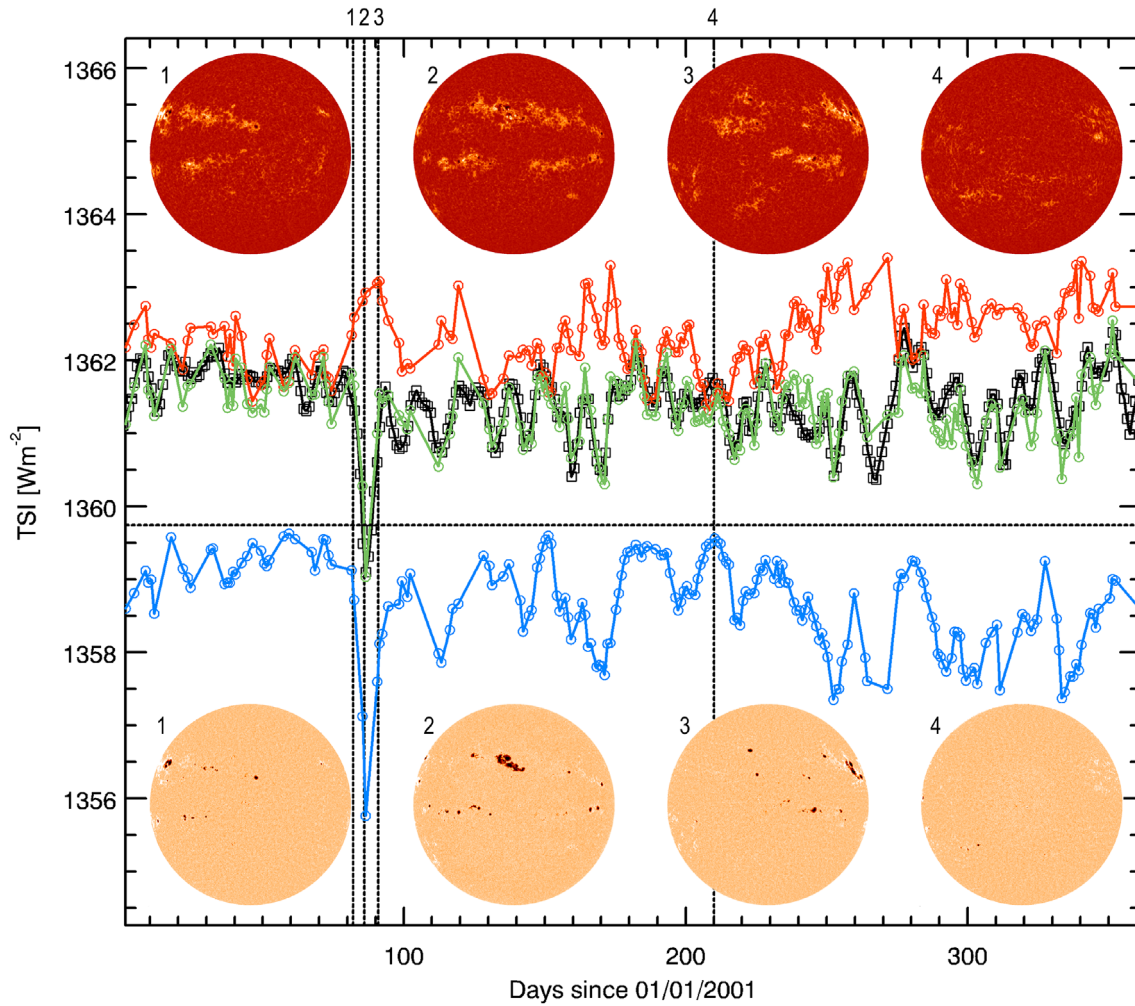


Figure 1. Daily TSI values over 2001 (around the maximum of solar cycle 23) from the PMOD TSI composite (black squares) and the reconstruction with the SATIRE-Ca model using Rome/PSPT Ca II K observations (Chatzistergos et al., 2021a, green circles). Also shown are the individual contributions of faculae (red) and sunspots (blue), as deviations from the mean level of TSI at 1359.7 Wm^{-2} (horizontal dotted black line). Exemplary Ca II K (where plage is well visible) and red-continuum (with visible sunspots and faculae, the latter more easily seen near the disc edge) same-day observations are shown in the upper and lower parts of the figure, respectively. The dates, on which these images were taken, are marked with vertical dotted lines which are numbered to link them to the corresponding images. The images have been compensated for limb darkening with the method by Chatzistergos et al. (2018b) and oriented to show the solar north pole at the top, while they are all shown in the same contrast range $[-1, 1]$ and $[-0.2, 0.2]$ for the Ca II K and red-continuum ones, respectively; see Sect. 2 for the definition of contrast values).

by the observers (Clette et al., 2021, 2023; Bhattacharya et al., 2023). Unfortunately, these data have varying quality and completeness over the years, partially even sporadic (e.g. Arlt & Vaquero, 2020; Ermolli et al., 2023). Thus, the main information about sunspots that can be used for long-term (>400 years) irradiance reconstructions is the disc-integrated number of sunspot groups (e.g. Hoyt & Schatten, 1998; Svalgaard & Schatten, 2016; Usoskin et al., 2016a; Chatzistergos et al., 2017).

Unfortunately, the available facular data are even sparser than those for sunspots (Ermolli et al., 2014). This is because individual facular regions are not only smaller than sunspots but also mainly because they have rather low contrast in white light. Notwithstanding, facular data extend back to at least the mid-1800s, such as through rough drawings of white-light facular ensembles (e.g. Ermolli et al., 2023) or tabulations of

their location and area made by the observers (e.g. Carrasco et al., 2021; Illarionov & Arlt, 2022). These data were followed by more regular observations in the singly ionised calcium line ($3933.67 \text{ \AA}$, Ca II K; Chatzistergos et al., 2022b) since the late 19th century, which however have not been brought to their full potential for irradiance reconstructions, as discussed below. In the absence of a suitable facular index, TSI reconstructions extending before the period covered by direct TSI measurements have mainly relied on indirect data to derive the facular information. Foremost, sunspots and cosmogenic radioisotope data (e.g. Beer et al., 2012; Usoskin et al., 2016a; Muscheler et al., 2016; Wu et al., 2018b; Brehm et al., 2021; Kaiser Kudsk et al., 2022) have been used. This, however, requires some assumptions on the relation between faculae and sunspots or cosmogenic radioisotope data, thus potentially introducing

considerable uncertainties. A number of studies have addressed the relation between faculae and sunspots (e.g. Foukal, 1993, 1996; Solanki & Unruh, 2013; Shapiro et al., 2014; Bertello et al., 2016; Criscuoli, 2016; Yeo et al., 2020a; Chatzistergos et al., 2022a; Nèmec et al., 2022) and found evidence for its non-linearity with hints to variations with the activity level (see also Krivova et al., 2021). Furthermore, it was also shown that the relation depends on the observational characteristics of the data (Chatzistergos et al., 2022a, see also Sect. 2). More importantly, in most models absence of emerging sunspots automatically leads to no faculae and network either, which contradicts observations (for a discussion, see, e.g., Krivova et al., 2021). As a result, existing reconstructions show considerable scatter in their estimates of the change between the Maunder minimum and now, see Figure 2, ranging between -0.09 and $+5.5 \text{ Wm}^{-2}$ (see Chatzistergos et al., 2023b for a recent review of long-term irradiance reconstructions and the discussion of their uncertainties). We note, however, that over the last decade, our improved understanding of the physical processes has led to a general consensus towards a lower secular trend in TSI than estimated in previous decades (Yeo et al., 2020b; Lockwood & Ball, 2020; Marchenko et al., 2022; Chatzistergos et al., 2023b). Thus, we caution against using old and outdated versions of the TSI models.

At the same time, as mentioned above, observations of the Sun carrying information on plage regions started as early as in the late 19th century, namely the full-disc solar photographs in the Ca II K line. Such observations have been performed since 1892, at the beginning rather irregularly but then progressively in a more and more systematic manner, and they continue to this day, at various sites around the globe (a review of the available data, their challenges and efforts to account for them can be found in Chatzistergos et al., 2022b). Over the last couple of decades, there has been a concerted effort to digitise the available data. This process is still ongoing, but by now the most prominent Ca II K archives have been digitised. Modern processing techniques have also been developed which can to a large degree overcome most issues that were previously hindering the use of Ca II K data for irradiance reconstructions. Thus we are now approaching the state when Ca II K observations could be used to produce more accurate irradiance reconstructions back to 1892 than it was possible before. This period is marked in green and blue in Figure 2. This would allow resolving the discrepancies between the existing TSI reconstructions, constraining the secular variability and thus considerably improving our knowledge of past TSI variations.

Moreover, due to the intimate connection between Ca II K emission and solar surface magnetic field (Babcock & Babcock, 1955; Skumanich et al., 1975; Schrijver & Harvey, 1989; Loukitcheva et al., 2009; Kahil et al., 2017; Chatzistergos et al., 2019d), Ca II K data are also important for understanding solar magnetism more generally, with numerous applications in solar physics. In particular, using the empirical relationship between the Ca II K brightness and the magnetic field strength, it is in principle possible to reconstruct (at least unsigned) solar magnetograms from Ca II K images (e.g. Chatzistergos et al., 2019d; Mordvinov et al., 2020). Thus, Ca II K data are a real treasure trove for reconstructions of past solar activity and understanding solar influence on climate, whichever of the above-mentioned mechanisms or their combination are in play.

Here we give an overview of the recent advances in irradiance reconstructions using Ca II K observations. For more general reviews on irradiance modelling and reconstructions, we refer the reader to Domingo et al. (2009), Solanki et al. (2013), Ermolli et al. (2013), Yeo et al. (2015b), Chatzistergos et al. (2023b). In Section 2, we give an overview of Ca II K data, focusing on data characteristics, processing and results which are of relevance to irradiance reconstructions. In Section 3, we briefly describe different models that have used Ca II K data to reconstruct irradiance. In Section 4, we compare the various irradiance reconstructions from Ca II K data, while we discuss results in the context of the long-term trends in TSI in Section 5. Finally, in Section 6 we draw our conclusions.

2 Ca II K data

A comprehensive overview of Ca II K archives, various processing techniques and results derived from them was recently given by Chatzistergos et al. (2022b). Here we briefly introduce only those aspects of Ca II K data that are relevant to irradiance reconstructions, focusing on Ca II K archives that have been used to reconstruct irradiance variations.

2.1 Overview of the data

Observations of the Sun in Ca II K line have been done both as full-disc images and as disc-integrated time-series. Ca II K line was in fact the first to be observed with a spectroheliograph (Hale, 1892), and full-disc photographs of the Sun have been taken since 1892. Since then, over 40 sites around the globe have carried out regular Ca II K full-disc observations over different periods of time (see Chatzistergos et al., 2022b, for the full list of archives currently known to us and for further details). Some of the most prominent archives are those from Meudon (since 1893; Malherbe, 2023)⁷, Kodaikanal (1904–2007; Chatzistergos et al., 2019c), Mt Wilson (1915–1985; Lefèbvre et al., 2005)⁸, Coimbra (since 1925; Lourenço et al., 2019)⁹, Mitaka (1917–1974 and since 2015; Hanaoka, 2013)¹⁰, and Arcetri (1931–1974; Ermolli et al., 2009a)¹¹.

Disc-integrated, also referred to as “sun-as-a-star”, measurements in the Ca II K line started much later – in the 1960s, and thus the period they cover is not significantly longer than that covered by direct TSI measurements. There are also considerably fewer such archives compared to the full-disc images. For disc-integrated observations, the solar spectrum is scanned across wavelengths around the Ca II K line allowing the derivation of a number of various parameters. The most commonly used ones are the core (K3) intensity and the 1 Å emission index, which is defined as the equivalent width of a 1 Å band

⁷ The archive is at <https://bass2000.obspm.fr/piwigo/index.php?category/157>.

⁸ The archive is available at https://www.astro.ucla.edu/ulrich/MW_SPADP/index.html.

⁹ The archive is available at <ftp://ftp.bass2000.obspm.fr/pub/coimbra/K3/>.

¹⁰ The archive is available at https://solarwww.mtk.nao.ac.jp/en/db_ca.html.

¹¹ The archive is available at <https://www.oa-roma.inaf.it/fisica-solare/>

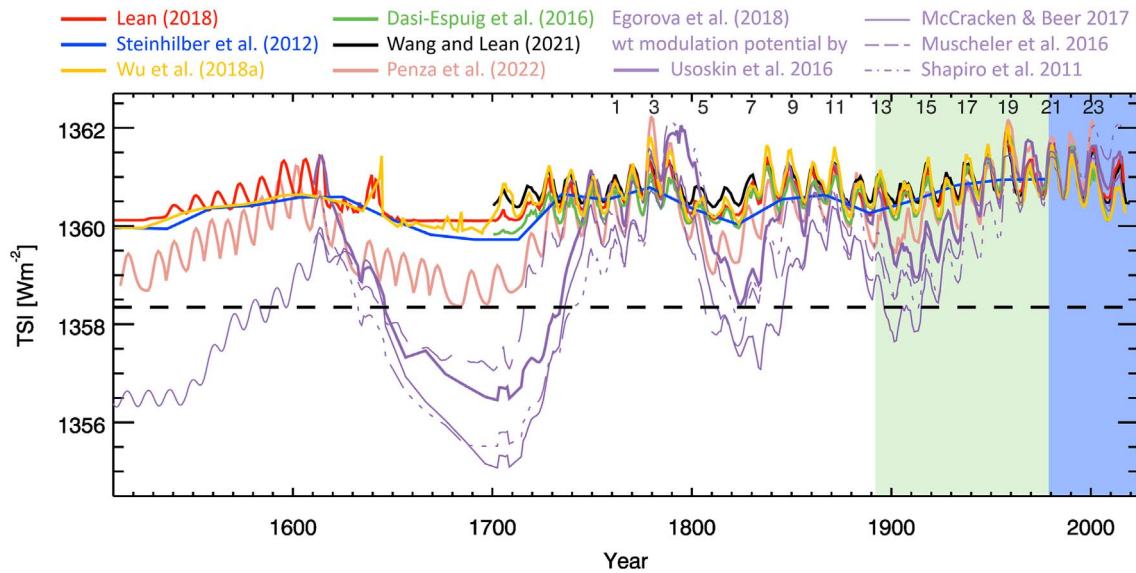


Figure 2. Selected TSI reconstructions, published over roughly the last decade, extending back to 1510. Shown are the ones by Steinhilber et al. (2012), blue), Wu et al. (2018a, yellow), Dasi-Espuig et al. (2016), green), Egorova et al. (2018, purple, shown are four different versions of this model based on the modulation potential used; thick solid line for Usoskin et al., 2016a, thin solid line for McCracken and Beer, 2017, sparse dashed line for Muscheler et al., 2016, and dashed line for the composite series as used by Shapiro et al., 2011), Lean (2018, red), Wang and Lean (2021, black), and Penza et al. (2022, pink). The horizontal black line marks the constraint derived by Yeo et al. (2020b) on the lowest possible level of TSI under the hypothetical assumption of full stoppage of the global dynamo. All series are offset to match the value of Montillet et al. (2022) composite over 1986. There is one exception for the series by Steinhilber et al. (2012), which does not extend to 1986, and for which we used its overlap with the series by Wu et al. (2018a) over 1900–1980, after offsetting the latter to Montillet et al. (2022) composite over 1986. Shown are annual median values, while the numbers in the upper part of the panel denote the conventional solar cycle numbering. The blue shading marks the period of direct TSI measurements, while Ca II K observations exist over the period shaded both in green and blue.

centred at the core of the line (see Fig. 3), as well as the S-index (Egeland et al., 2017; Sowmya et al., 2021), which requires information on the blue wing of the Ca II K line as well as the core and the red wing of Ca II H line. This latter index is often used for solar-stellar comparisons. Some of the most prominent disc-integrated Ca II K series are those from Sacramento Peak (1976–2015; Keil and Worden, 1984), Synoptic Optical Long-term Investigations of the Sun Integrated Sunlight Spectrometer (SOLIS/ISS; Keller et al., 2003, which operated at Kitt Peak between 2006 and 2014, then in Tucson until 2018, and at Big Bear Solar Observatory in California since then), Utrecht (1979–1982; Oranje, 1982, 1983), and Kodaikanal (since 1969 Sindhuja & Singh, 2015).

Despite the huge amount of full-disc Ca II K data, up to now only a few, mainly modern, of these archives have been used for irradiance studies. The major hindering factors for using full-disc Ca II K observations for irradiance studies have been the difficulty in accounting for the non-linear response of detectors to irradiation, for image artefacts, as well as for archive inconsistencies (mainly variations and differences in passbands). The disc-integrated series are only impinged by the last factor, but their use is limited by their short temporal coverage, adding rather little to the direct TSI measurements.

The main hindrance to the use of full-disc Ca II K data arises from the fact that photographic plates are not linear detectors and require photometric calibration. This issue affects all Ca II K data prior to the 1980s as well as data up to 2007, which were stored on photographic plates (we will refer to them as plates

irrespectively of the material used, whether glass or celluloid), but does not affect the data taken with a CCD camera (Chatzistergos, 2017; Chatzistergos et al., 2022b). Unfortunately, most available photographic data were not accompanied by controlled exposures (called calibration wedges), which would allow for recovering the response of the plates to incident radiation (Ermolli et al., 2009b). To overcome this problem, Chatzistergos et al. (2018b) developed a novel approach which allowed a photometric calibration of the historical data. The method is based on the assumption that the centre-to-limb variation (CLV) of the quiet-Sun regions does not change on time-scales of interest (supported by White & Livingston, 1978, 1981; Livingston & Wallace, 2003; Livingston et al., 2007; Bühler et al., 2013; Lites et al., 2014). Employing the centre-to-limb variation observed in modern CCD-based data enabled historical data from different sources to be photometrically calibrated (Chatzistergos et al., 2019b, 2020c). We stress, however, that most other published studies using historical Ca II K data have been performed on photometrically uncalibrated data.

Many factors contribute to the data from different sources, but also data from the same source over different periods, exhibiting marked inconsistencies (e.g. Ermolli et al., 2018; Chatzistergos et al., 2019c; Mishra et al., 2024). A major contributor to that is that there has not been just one single organised approach of Ca II K observations, rather each observatory used different setups and observing strategies. This has resulted in Ca II K archives being a collection of quite diverse observations. The archive inhomogeneities that are relevant to

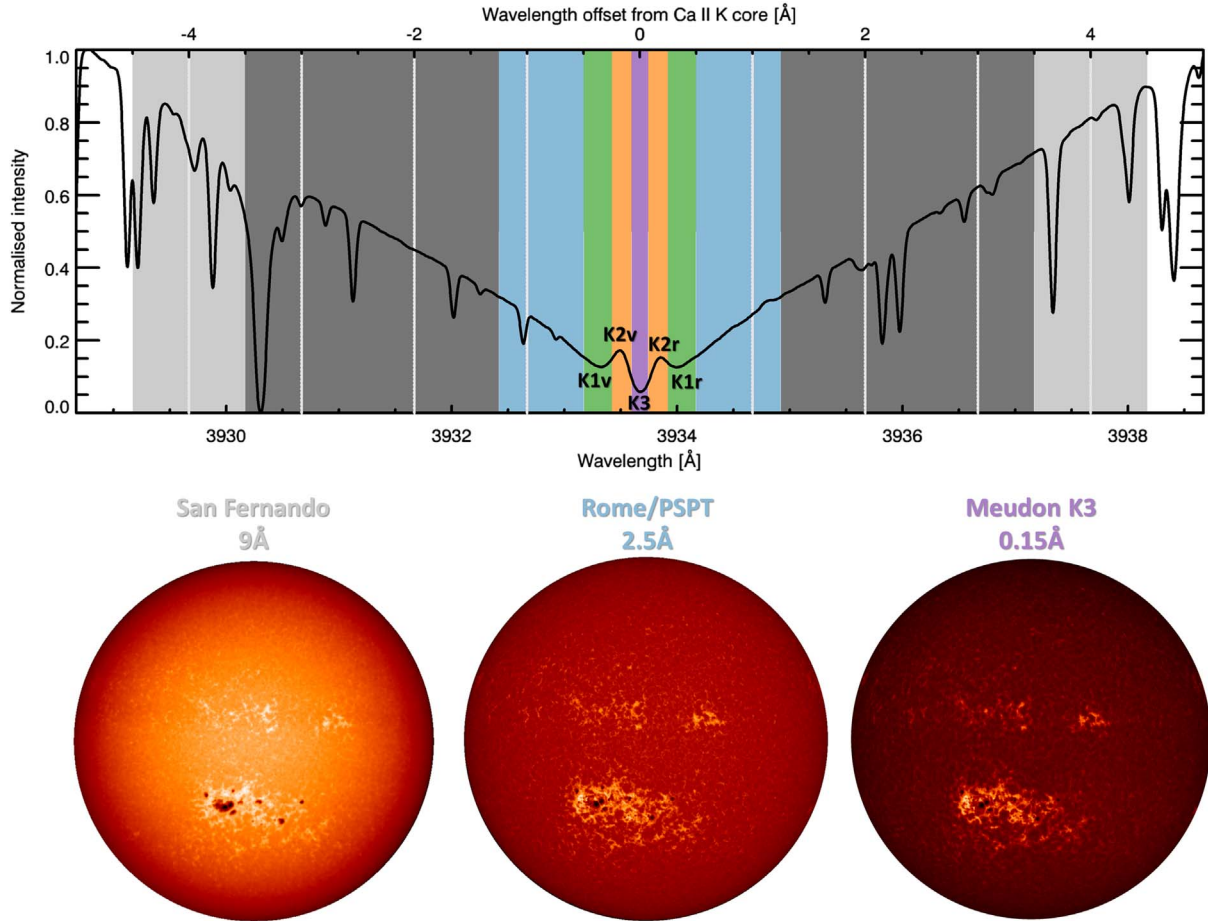


Figure 3. The normalised high-resolution disc-integrated quiet-Sun spectrum over a 10 Å interval centred at the core of the Ca II K line from the atlas of the Hamburg Observatory. Also shown (various coloured bands) are the nominal bandwidths of typical Ca II K archives (shown are 9, 7, 2.5, 1, 0.5, and 0.15 Å), including the two extreme cases from San Fernando (broadest, light grey) and Meudon (narrowest, lavender). The vertical light grey lines mark wavelength intervals of 1 Å from the core of the Ca II K line. The bottom part of the figure presents three exemplary observations taken with CCD cameras on the same day (11 July 2012) at the San Fernando, Rome/PSPT, and Meudon sites. The images have been compensated for ephemeris to show the North Pole at the top, but no other processing has been applied. The images are shown over their entire respective ranges of values.

our discussion here have to do with the passband of the observations.

The most prominent inhomogeneity among the various Ca II K archives is their use of a different nominal bandwidth. Figure 3 shows the quiet-Sun disc-integrated Ca II K line profile from the high-resolution atlas from the Hamburg Observatory (Neckel, 1999; Doerr et al., 2016) overplotted with some of the most typical bandwidths used for Ca II K observations. Also shown are same-day observations employing two extreme and one intermediate case of bandwidths, highlighting the differences in the resulting data. In particular, the narrower the bandwidth used, the higher the altitude in the solar atmosphere which is sampled, resulting in higher contrast of plage and network regions compared to those taken with broader bands (Chatzistergos et al., 2022b; Murabito et al., 2023). Furthermore, Ermolli et al. (2010) found a hint at the impact of the bandwidth on the centre-to-limb variation of the solar features. Most of the available Ca II K archives have a different nominal bandwidth, which leads to systematic changes in typical bandwidths of observations over the years. As reported by

Chatzistergos et al. (2020c) data prior to 1987 had an average nominal bandwidth of ~ 0.3 Å, while those after 1987 used an average bandwidth of ~ 2.5 Å with markedly greater dispersion of values. Another complication is that the nominal passband does not necessarily represent the actual one. Instrumental degradations and adjustments can affect the actual passband of the observations. We note that the observational setup of the photographic data was often based on manual and visual tuning of the instrument. Furthermore, at some sites observations were performed with various setups. For instance, Meudon performed daily observations in the core of the Ca II K line, and also at the blue wing of the line at 3932.3 Å. At Meudon, they were preserved as separate archives. However, at some sites, such data were sometimes mixed up.

On top of the already listed inhomogeneities, which have to do with the observational setups, there are also others related to the applied processing of the data that can affect irradiance reconstructions based on Ca II K data. Accurate compensation for the limb-darkening and a variety of artefacts plaguing the images is needed before using Ca II K observations for quantita-

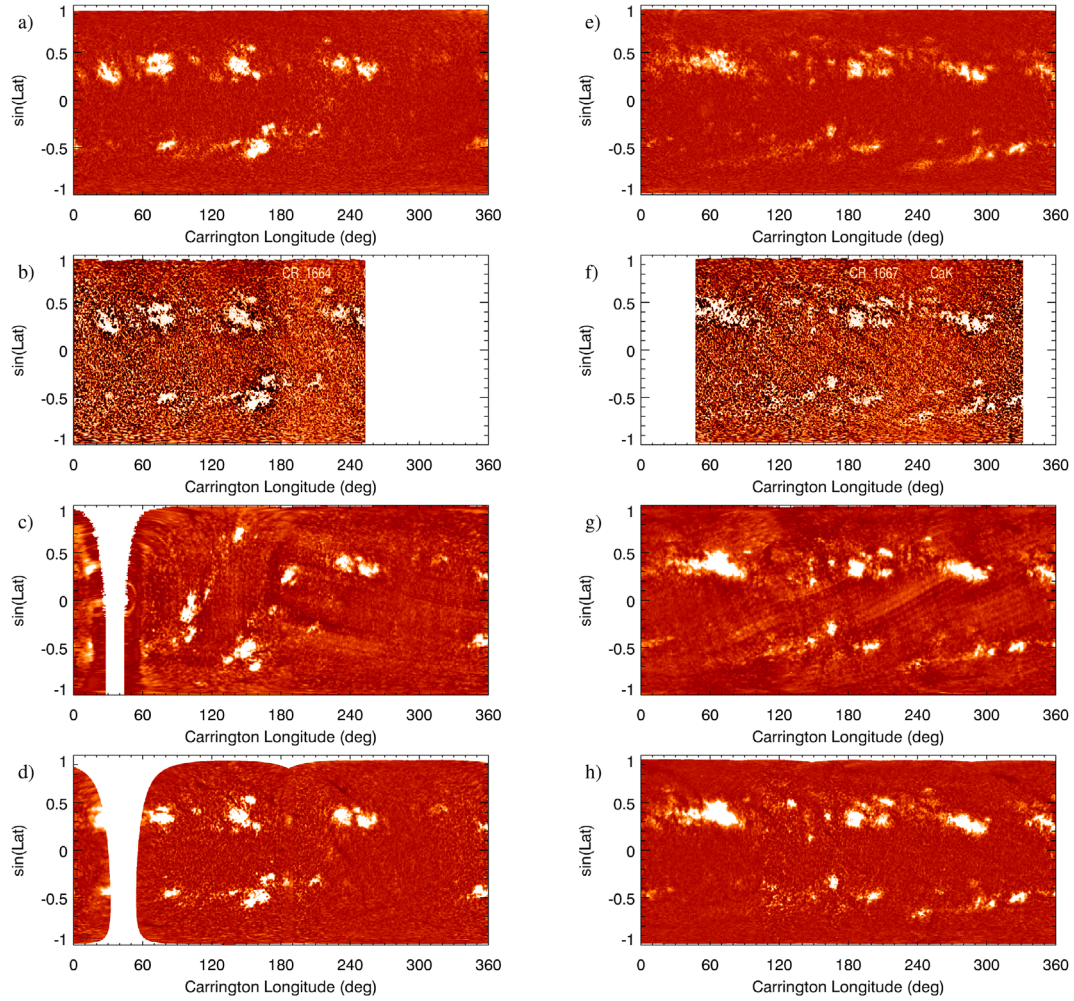


Figure 4. Examples of Carrington maps constructed from Ca II K data over rotations 1664 (17 January–12 February 1978, left) and 1667 (9 April–5 May 1978, right). Shown are Kodaikanal data processed by Chatzistergos et al. (2020c, 1st row) and by Chatterjee et al. (2016, 2nd row) as well as Mt Wilson data processed by Bertello et al. (2020, 3rd row) and Chatzistergos et al. (2020c, 4th row). Due to differences in the image processing the images are saturated at different levels in order to show plage at roughly similar levels. In particular, the contrast ranges are $[-0.5, 0.5]$ for the images processed by Chatzistergos et al. (2020c, 1st and 4th rows) and $[-1, 1]$ for the images processed by Bertello et al. (2020, 3rd row), while the ones processed by Chatterjee et al. (2016, 2nd row) are shown to their entire range since they are provided in PNG file format and the exact contrast values are not known to us. White areas are caused by gaps in the data.

tive analyses. Inconsistent application of the processing to different archives or inaccurate processing can introduce artefacts in the results. Typically the process of compensating the images for the limb darkening returns contrast images defined as either $C_{ij} = (I_{ij} - I_{ij}^{QS})/I_{ij}^{QS}$ or sometimes also as $C_{ij}^* = I_{ij}/I_{ij}^{QS} = C_{ij} + 1$, with I_{ij} being the intensity value of pixel i, j and I_{ij}^{QS} the intensity of the quiet Sun (QS) regions. The artefacts are, unfortunately, quite diverse and difficult to account for, as they have been accumulated over different stages of life of the plates, including observation, development, storage, and digitisation. Various processing techniques have been presented in the literature (reviewed by Chatzistergos et al., 2022b) with different performance levels. Only the method by Chatzistergos et al. (2020b,c) evaluated the accuracy of their performance with synthetic data, allowing also to demonstrate the superior performance compared to the other methods from the

literature. To illustrate the performance of different processing techniques from the literature, Figure 4 shows Carrington maps produced from full-disc Ca II K observations processed with different methods, namely those by Chatterjee et al. (2016), Chatzistergos et al. (2018b), and Bertello et al. (2020). Most homogeneous and least affected by artefact images are returned by the method by Chatzistergos et al. (2018b), while the others still clearly suffer from residual artefacts. If unaccounted for, they can affect studies using such data to reconstruct past solar activity and irradiance variations (see more examples in Chatzistergos et al., 2016, 2018a,b, 2019a,b, 2023a). Rather common are processing artefacts that reduce the contrast of plage regions. This is typical because inaccurate processing often overestimates the quiet Sun background in the immediate surroundings of plage regions. As a result, when such a quiet-Sun background is used to compensate for the limb darkening, it renders plage regions darker than they actually are. This is

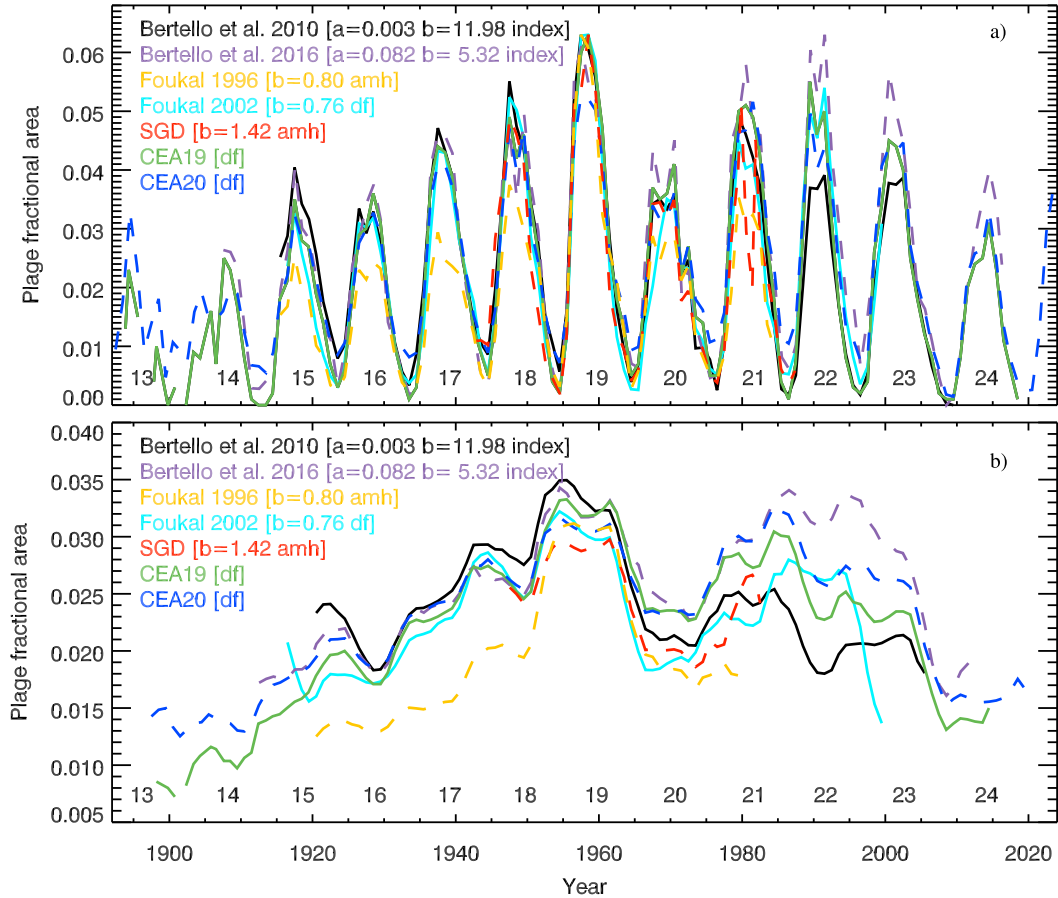


Figure 5. Selected timeseries of plage areas and 1 Å emission indices derived from full-disc Ca II K observations that have been used for irradiance reconstructions. Shown are the plage area series by [Foukal \(1996\)](#), from Mt Wilson data; dashed yellow), [Foukal \(2002\)](#), from Mt Wilson and Sacramento Peak data; solid cyan), Solar Geophysical data (SGD, from McMath-Hulbert, Mt Wilson, and Big Bear data; dashed red), [Chatzistergos et al. \(2019b\)](#), CEA19; composite of 9 Ca II K archives; solid green), and updated [Chatzistergos et al. \(2020c\)](#), CEA20; composite of 38 Ca II K archives; dashed blue) (see Sect. 2.2) as well as the 1 Å emission indices by [Bertello et al. \(2010\)](#), using Mt Wilson data; solid black) and [Bertello et al. \(2016\)](#), using Kodaikanal data; dashed purple). The series have been linearly scaled to match CEA19, with the slope (b) and the intercept (a) given in the legend for each series (when missing it means $a = 0$ and $b = 1$). The legend also specifies if a series gives projected plage areas as a fraction of the visible solar disc (df for disc fraction), or areas corrected for foreshortening and expressed as fractions of the solar hemisphere (amh, for areas in millionths of solar hemisphere), or as an emission index. The top panel includes annual median values, while the bottom panel shows 11-year running means. The numbers at the lower part of the panels denote the conventional solar cycle numbering.

particularly important for empirical irradiance reconstructions from Ca II K data. We refer the reader to [Chatzistergos et al. \(2020c, 2022b\)](#) for more comprehensive reviews of the available Ca II K archives and processing techniques.

2.2 Disc-integrated Ca II K indices

Full-disc Ca II K images have also been used to produce disc-integrated indices of plage evolution. By far the most used one for irradiance reconstructions is the plage areas, but also the disc-integrated intensity has been used.

To compile the plage area series, the following steps are usually taken. First, the images are compensated for the limb-darkening and various artefacts of non-solar origin. Then segmentation techniques are applied to isolate the regions and produce a time-series of their fractional areas. The segmentation has typically been done in an automatic way by applying a contrast threshold (sometimes also threshold in the identified

region size), although some studies derived plage areas manually (e.g. Solar Geophysical data, SGD, and [Foukal, 1996](#)). Manual identification of plage regions introduces biases and increases uncertainty in the derived areas. But also the realisation of the thresholding approach varies among studies, sometimes using a fixed threshold for all analysed images, while allowing it to vary with the standard deviation over either the entire image (e.g. [Chatterjee et al., 2016](#)) or the quiet Sun regions only (e.g. [Chatzistergos et al., 2019b](#)) in other studies. We note that some studies even used raw observations (physical photographs or digital images including limb darkening) to identify the plage regions and produce time-series of plage areas (e.g. SGD and [Barata et al., 2018](#)). More details on the various processing and segmentation techniques can be found in [Chatzistergos \(2017\)](#) and [Chatzistergos et al. \(2022b\)](#). Here we would like to stress that differences in the processing of the images affect the resulting plage areas, which is further aggravated by the arbitrariness of the various steps of the

segmentation approach. As a result, the various studies differ not only in which plage regions they select but also in the shape of identified plage regions.

Figure 5 shows most of the available plage area series that have been used to reconstruct irradiance variations. All shown records, except the ones by Chatzistergos et al. (2019b, CEA19) and Chatzistergos et al. (2020c, CEA20) used photometrically uncalibrated historical data. All of these series used Ca II K data from Mt Wilson observatory. However, Foukal (2002, 2012) extended Mt Wilson data with full-disc Ca II K data from Sacramento Peak, SGD additionally considered full-disc Ca II K data from McMath-Hulbert and Big Bear Solar Observatory (BBSO), while CEA19 and CEA20 are composites derived from nine and 38 Ca II K archives, respectively. For this study, we have updated the CEA20 plage area composite by including more recent data until 31 December 2023 from the Baikal, Brussels, Calern, Kanzelhöhe, Meudon, Pic du Midi, and Rome/PSPT observatories¹². This update covers the ascending phase of solar cycle 25 and allows for investigating the accuracy of various irradiance reconstructions over longer time intervals.

On annual timescales, the differences between the various plage areas shown here are rather small, with the exception of the series by Foukal (1996) which exhibits the largest increase over solar cycle 19 (most likely an artefact due to inconsistencies in the Mt Wilson data over that period unaccounted for in the analysis by Foukal 1996; see, e.g., Ermolli et al., 2009b; Tlatov et al., 2009; Chatzistergos et al., 2019b). The differences between the series become clearer when comparing their 11-year running means, where they show clearly deviating from long-term trends (see also Chatzistergos et al., 2019b, 2022a,b; Ermolli et al., 2018, for discussions on differences among the existing plage area series from Ca II K data).

Plage areas have also been regressed to convert them to other disc-integrated solar indices. For instance, Bertello et al. (2016) used plage areas by Tlatov et al. (2009) from Kodaikanal data to extend the 1 Å emission index from Sacramento Peak and SOLIS/ISS. Similarly, Bertello et al. (2010) produced a different Ca II K disc-integrated index after processing the Mt Wilson Ca II K data covering 1915–1985 to extend the Mt Wilson magnetic plage strength index (MPSI; Chapman & Boyden, 1986). MPSI is produced by integrating over the entire solar disc the absolute magnetic field strengths of regions in the range of 10–100 G. These two Ca II K emission indices are also shown in Figure 5. The long-term trend of these two indices differs, significantly diverging after solar cycle 19. Such differences can have significant effects on reconstructions of solar irradiance variations from these indices. We note that the index by Bertello et al. (2016) shows a similar decrease between the minima in 1996 and in 2008 as in the CEA20 plage area composite series.

Another quantity derived from Ca II K observations is the disc-integrated intensity. This is usually computed either as the excess brightness or as what is termed photometric sums (Chapman et al., 2012, 2013). The excess brightness is computed by first isolating plage regions (e.g., with a contrast threshold) and then integrating their contrast values (e.g. Dineva et al., 2022). A variation was used by Johannesson et al. (1995) who integrated the square root of the contrast values. However,

a more common index that has been used for irradiance reconstructions is the photometric sums. These are produced by reintroducing a standardised CLV pattern to the contrast images before integrating their values. Thus the photometric sums, Σ , are defined as:

$$\Sigma = \sum_i \sum_j (C_{ij} I_{ij}^{\text{CLV}}), \quad (1)$$

where I_{ij}^{CLV} is the standardised QS centre-to-limb variation (CLV). The latter is typically taken as an average CLV pattern derived from the actual Ca II K (or any other chosen wavelength interval) observations or as an estimated CLV as was done by Warren et al. (1996) to produce the photometric sums for the CIV line (1548.1 Å) from Ca II K data.

Figure 6 shows the photometric sums produced by Chatzistergos et al. (2020a) from Rome/PSPT and San Fernando data, as well as those produced by Chapman et al. (2013) from San Fernando data. The difference between the absolute level of the series for San Fernando data produced by Chatzistergos et al. (2020a) and Chapman et al. (2013) highlights the sensitivity of the photometric sums to the processing method for the same data. All series diverge before 1998, suggesting a slightly different trend between activity minima. This is partly owing to potential inconsistencies in the early Rome/PSPT (Ermolli et al., 2022) or San Fernando data, but also most likely due to the differences in the processing since the divergence is also seen between San Fernando data using different processing techniques. The mean relative, mean absolute relative, and RMS differences, along with the linear correlation coefficients, R , between some photometric sum series from Ca II K data are given in Table 1. The relative differences are given with respect to the photometric sum series by Chatzistergos et al. (2020a). When comparing the SFO and Rome/PSPT photometric sums the relative differences are with respect to the Rome/PSPT ones. The correlation between the various series remains quite high at 0.97–0.98, while the mean (mean absolute) relative differences after 1998 are between 1% and 2% (10 and 12%). However, between daily values, the differences sometimes exceed 100%.

In summary, accurate and consistent processing of the Ca II K images is crucial to mitigate various issues with the data and to avoid introducing artefacts that can eventually lead to spurious trends in irradiance reconstructions.

3 TSI reconstructions from Ca II K data

TSI and SSI have been reconstructed from Ca II K data both with empirical and semi-empirical models. Figure 7 gives an overview of the most available TSI reconstructions from Ca II K data. The reconstructions are shown in three panels covering different time intervals. Specifically, we show reconstructions over the year 1980, over the more recent period since 1988 using only CCD-based data, as well as long-term reconstructions since 1892. The models used for these reconstructions are described in more detail below.

3.1 Empirical models

Empirical models recover irradiance variations by regressing solar magnetic activity indices to actual irradiance

¹² The updated composite is available at <http://www2.mps.mpg.de/projects/sun-climate/data.html>

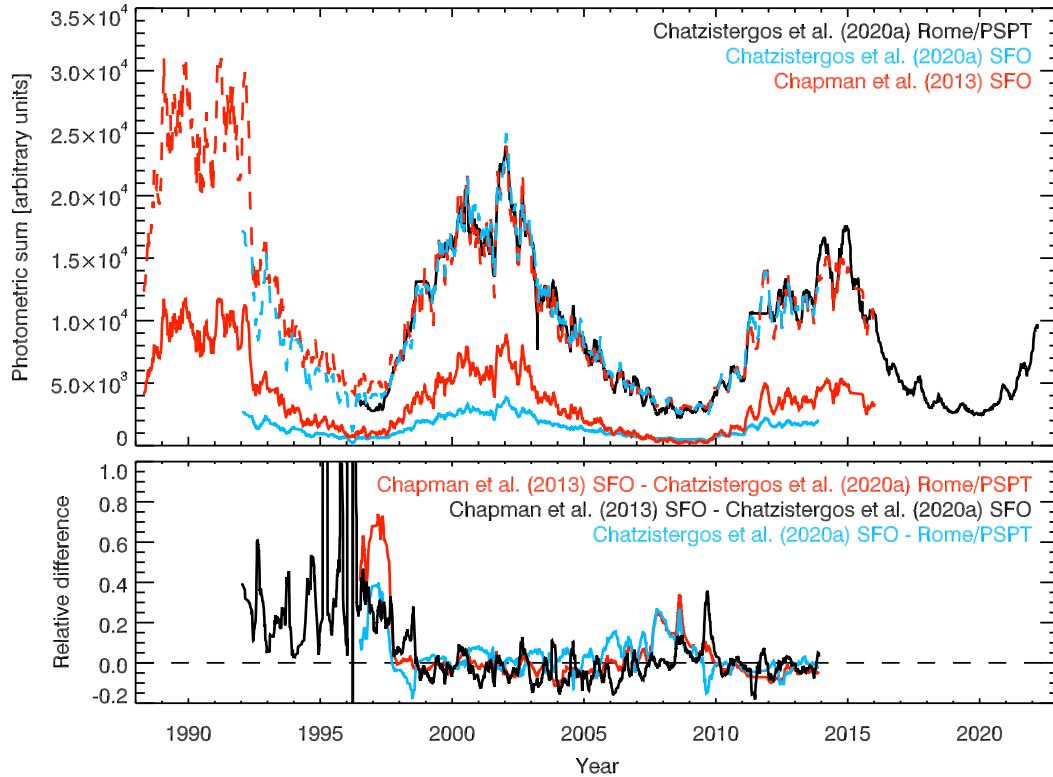


Figure 6. *Top:* Disc-integrated Ca II K intensities (photometric sum series, see Sect. 2.2). For San Fernando data the solid lines show the original series, while dashed ones are after linear scaling to match the photometric sum series from Rome/PSPT. Shown are 27-day running means, whereby the means are computed for all series within the same time intervals, even though these intervals might not include the same number of data points in all series due to their different availability. *Bottom:* Relative differences between the scaled photometric sum series as denoted in the legend. The dashed horizontal black line denotes the zero relative difference.

Table 1. Comparison between selected photometric sum series in Ca II K.

Series	Mean relative	Mean absolute relative	RMS	R	R^2
Chatzistergos et al. (2020a) SFO – Chatzistergos et al. (2020a) Rome/PSPT	0.016	0.11	1312	0.98	0.95
Chapman et al. (2013) SFO – Chatzistergos et al. (2020a) SFO	0.010	0.10	1331	0.97	0.95
Chapman et al. (2013) SFO – Chatzistergos et al. (2020a) SFO	0.021	0.12	1176	0.98	0.96

Note. Shown are mean relative, mean absolute relative, and RMS differences [Wm^{-2}] as well as the linear correlation coefficient, R , and R^2 . The differences are computed after linearly scaling the photometric sum series to match those from Rome/PSPT (shown as dashed lines in Fig. 6).

measurements or by using measured spectra of active regions weighted by their observed surface coverage. Such models typically use two activity indices to account for the competing contributions of facular and sunspot regions to irradiance variations. However, some models simply scale plage and/or sunspot indices to reconstruct irradiance (e.g. Ambelu et al., 2011; Xu et al., 2021). Ca II K timeseries that have been used for empirical irradiance reconstructions to account for the facular contribution include Ca II K plage areas and disc-integrated intensities (sometimes called photometric sums) or the Ca II K $1 \text{ \AA}$ emission index (see Sect. 2).

The majority of empirical irradiance reconstructions with Ca II K data relied on plage areas to describe the facular contribution (Oster et al., 1982; Sofia et al., 1982; Schatten et al., 1985; Foukal & Lean, 1986, 1988; Willson & Hudson, 1988; Pap et al.,

1991; Chapman et al., 1989, 1992; Steinegger et al., 1996; Solanki & Fligge, 1998; Lean et al., 1998; Foukal, 2002, 2012; Ambelu et al., 2011; Xu et al., 2021; Penza et al., 2022). To our knowledge, Oster et al. (1982) were the first to reconstruct TSI from Ca II K plage areas. The plage areas were derived by SGD from MW data (red curve in Fig. 5) and the model covered six months over 1980. Their reconstructed TSI is shown in Fig. 7a) along with the PMOD TSI composite and other more recent TSI reconstructions covering 1980. Most of the empirical reconstructions employed Ca II K data over a rather short period, between a few days and a few years, with the exception of the studies by Solanki & Fligge (1998), Lean (2000), Foukal (2002, 2012), Ambelu et al. (2011), Xu et al. (2021), Penza et al. (2022) who used Ca II K plage areas over most of the 20th century.

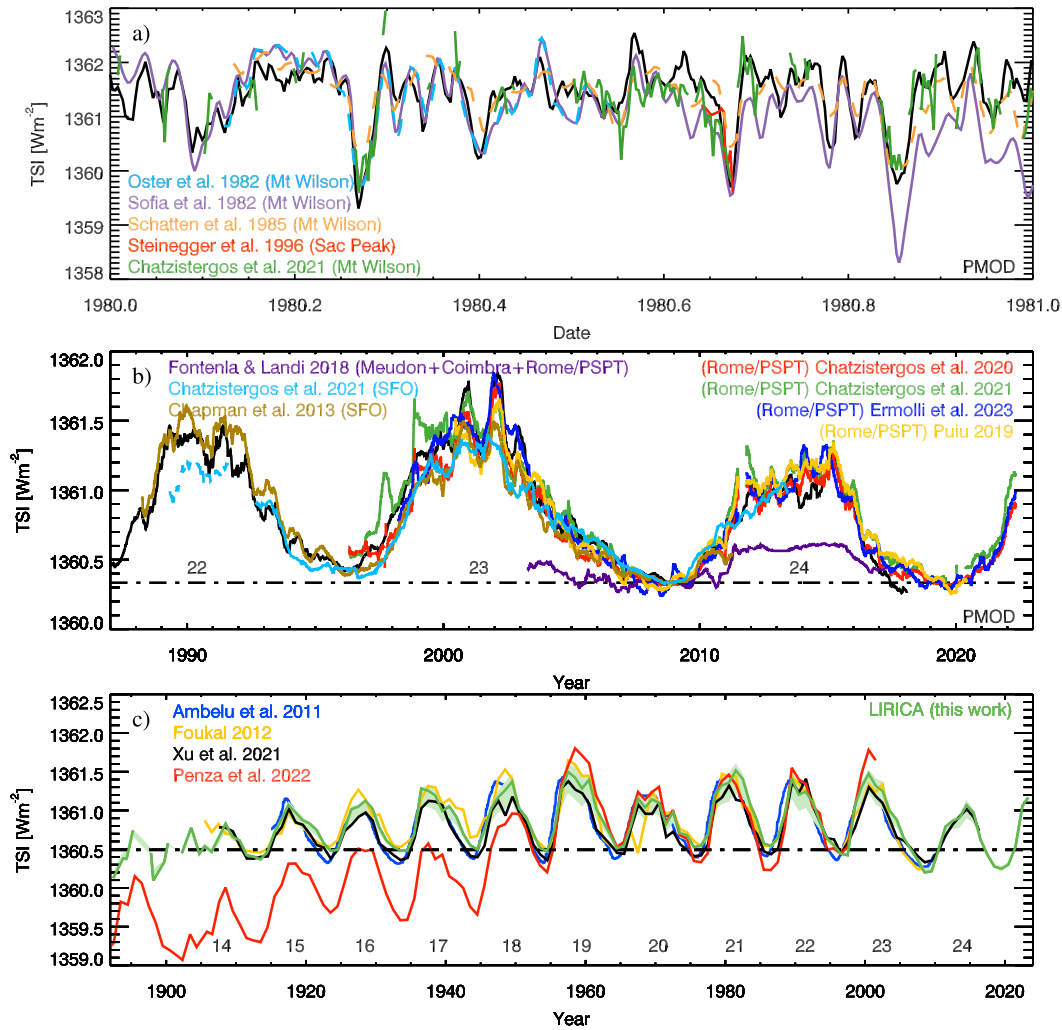


Figure 7. Overview of the most prominent existing TSI reconstructions using Ca II K data; see the legends in each panel for the details and references as well as Section 2 for the summary of archives used in the lower panel. *Panel a)*: Daily values of TSI reconstructions over the year 1980 along with the PMOD TSI composite (black). The series by Oster et al. (1982) and Steinegger et al. (1996) are offset so that their mean values match that of the PMOD TSI composite over their overlapping periods, the series by Sofia et al. (1982) was an extension of Oster et al. (1982) and is thus offset to match the one by Oster et al. (1982), while the reconstruction by Chatzistergos et al. (2021a) is shown unadjusted. *Panel b)*: TSI reconstructions with CCD-based Ca II K data. The series are offset to match their values over the 2008 minimum to that of the PMOD composite (marked by the black dot-dashed line). Shown are 180-day running means. *Panel c)*: Long-term TSI reconstructions using Ca II K data (see Sect. 3.1 for a description of most models and Sect. 4.2 for LIRICA). The series is offset to match the value of PMOD TSI composite over 1996 (marked by the dot-dashed black line). Shown are annual median values. The numbers in the lower part of the figure denote the conventional cycle numbering.

All empirical TSI reconstructions employing plage areas or emission indices used series produced from photometrically uncalibrated Ca II K data, with the exception of the study by Penza et al. (2022). A critical weak point of such models is the arbitrariness in the identification of facular regions (see Sect. 2).

In principle, regression models can be applied to compute variations of both TSI and SSI. However, for SSI the analysis has to be performed for each desired wavelength or wavelength interval separately and requires appropriate reliable SSI measurements, which is tricky below about 2500 Å (Yeo et al., 2015a). In particular, there have been several reconstructions of Lyman- α irradiance (Lean & Skumanich, 1983; Pap et al.,

1991), some of which are shown in Figure 8. Lean & Repoff (1987) and Lean et al. (1998) have also reconstructed the irradiance at 2050 Å and 2000 Å, respectively. The reconstructions by Morrill et al. (2011a, with spectral sampling of 10 Å) and Foukal (2012, as the wavelength integral) cover broader spectral intervals, 1500–4100 Å and 1300–2400 Å, respectively. We are not aware of empirical reconstructions with Ca II K data covering yet broader intervals.

Another group of empirical models are those using the disc-integrated intensity, or photometric sums, to reconstruct solar irradiance variations (Chapman et al., 1996, 2012, 2013; Preminger et al., 2002; Walton et al., 2003; Vogler et al., 2005; Pui, 2019; Chatzistergos et al., 2020a). These models

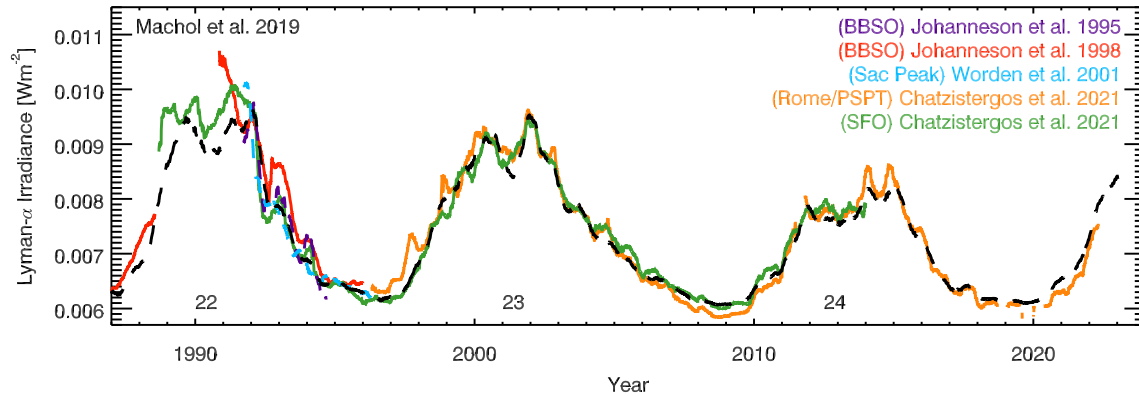


Figure 8. Reconstructions of Lyman- α irradiance variations from Ca II K observations compared to the composite of Lyman- α observations by Machol et al. (2019). In particular, we show the semi-empirical SATIRE-Ca (see Sect. 3.2) reconstruction from Rome/PSPT (orange) and San Fernando (SFO; green) data by Chatzistergos et al. (2021a), as well as the empirical reconstructions (see Sect. 3.1) by Johanneson et al. (1995, purple) and Johanneson et al. (1998, red) from Big Bear solar observatory (BBSO) data, as well as by Worden et al. (2001, blue) from Sac Peak data. All series are shown as 180-day running means. The numbers in the lower part of the figure denote the conventional solar cycle numbering.

reconstruct TSI by linearly regressing indices of disc-integrated intensities in Ca II K (Σ_k) and in a continuum wavelength interval observations to the measured TSI. Ca II K data are used to describe the facular contribution, while continuum data in the red (around 6071 Å) or blue (around 4092 Å) part of the spectrum have been used to describe the sunspot contribution. The photometric sums essentially represent the irradiance variations in arbitrary units over the specific wavelength intervals sampled by the employed Ca II K and continuum data. Some studies also used Σ_k to calculate Lyman- α (Johanneson et al., 1995, 1998) and CIV line (1548.1 Å; Warren et al., 1996) irradiance as well as MgII index (Johanneson et al., 1998).

Reconstructions employing the photometric sums are essentially limited to CCD-based data. The reason for that is that this approach is very sensitive to artefacts in the images and would have poor performance on historical observations if not properly processed. Furthermore, Chatzistergos et al. (2020a) demonstrated the sensitivity of photometric sums to the processing of the continuum data and showed that the results can be significantly affected by potential residual biases in the determination of the quiet Sun level. Uncertainty in the assessment of the quiet Sun level is expected to be significantly higher for the historical white-light data compared to the modern CCD-based continuum.

The only such irradiance reconstruction known to us that extends beyond the period covered by CCD-based data, that by Kakuwa & Ueno (2022), used the sunspot number series to describe the sunspot contribution instead of the photometric sum from white-light data. In particular, they used a linear regression model employing the Kodaikanal Ca II K integrated intensity produced by Kakuwa & Ueno (2021) along with the international sunspot number and the F10.7 series to reconstruct the UV irradiance integrated over three wavelength intervals, 5–1335, 1345–1995, and 2005–2995 Å, covering 1904–1978.

Finally, a few studies (Cook et al., 1980; Morrill, 2005; Morrill et al., 2011b; Worden et al., 2001) used measured spectra and Ca II K plage areas to reconstruct irradiance variations. This approach allows recovering the irradiance variations essentially only over the wavelength interval covered by the measured spectra. Cook et al. (1980) reconstructed irradiance

over 1175–2100 Å with SGD data. Morrill (2005) and Morrill et al. (2011b) used BBSO Ca II K data and spectra from the HRTS-9 (High-Resolution Telescope and Spectrograph; Brueckner & Bartoe, 1983) rocket flight on 18 April 1995 covering the wavelength range of 2760–2780 Å (with a spectral resolution of 0.15 Å). Worden et al. (2001) reconstructed irradiance over 1200–1700 Å from 800 Sac Peak Ca II K images covering 1991–1996 (their result for Lyman- α irradiance is shown in Fig. 8). The intensities and centre-to-limb variation of faculae at each wavelength were estimated with an iterative process of directly comparing the irradiance reconstruction to measurements by the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE; Woods et al., 1993).

3.2 Semi-empirical models

Semi-empirical models use brightness spectra for different surface features (e.g., sunspots, faculae, network, quiet Sun) computed with radiative transfer codes from the corresponding model atmospheres to reconstruct solar irradiance variations. These spectra are then weighted by the surface coverage by the respective features extracted from appropriate data. Only two semi-empirical models that used Ca II K observations have been reported in the literature, namely the Spectral And Total Irradiance Reconstruction (SATIRE; Krivova et al., 2003, as adapted by Chatzistergos et al. 2021a) and Solar Radiation Physical Modeling (SRPM; Fontenla et al., 1999, as used by Fontenla & Landi 2018, Ermolli et al., 2003, 2011; Ermolli & Chatzistergos 2023; Penza et al. 2003, Criscuoli et al. (2018); Criscuoli (2019); Berrilli et al. (2020); Criscuoli et al. (2023) and Harder et al. 2019).

Both models use full-disc Ca II K images to identify the locations of facular regions, while white-light or continuum observations are used to derive information on the spatial distribution of sunspots. SATIRE considers four types of regions in total (umbra, penumbra, faculae, and quiet Sun), while SRPM uses at least seven (umbra, penumbra, network, active network, plage, bright plage, and quiet Sun). For facular regions, SATIRE has only one component and scales its brightness with

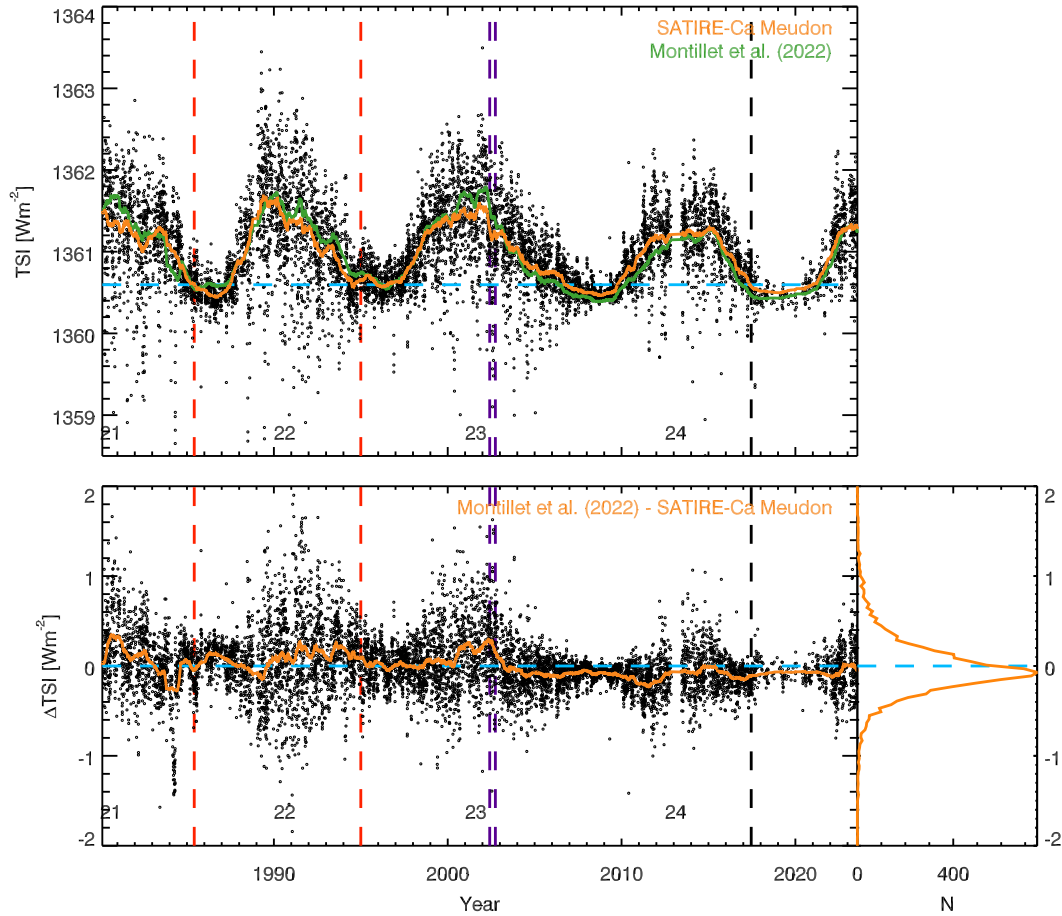


Figure 9. *Top:* TSI reconstruction with the SATIRE-Ca model using Meudon Ca II K data (black dots for daily and orange line for 180-day running means) along with the Montillet et al. (2022) TSI composite (green line). The running means are computed only over the common days in the two series. *Bottom:* Difference between the TSI reconstructed with SATIRE-Ca using Meudon Ca II K data and the PMOD TSI composite. Daily values are shown as black dots and 180-day running means as orange lines. The right panel shows the histogram of the residuals in bins of 0.04 Wm^{-2} . Vertical dashed lines mark periods of discontinuities in the Meudon Ca II K data. In particular, the black line marks the improvement of the system over 2017 along with reduction in bandwidth of observations, the purple lines mark the period when the switch between photographic plates and CCD camera occurred in 2002 (there was an overlap of CCD and photographic data, thus the lines mark the first application of the CCD camera and the last day that photographic plates were used), while the photographic data outside of the two red lines were derived from a different digitisation than the other data. The dashed horizontal blue line marks the level of Montillet et al. (2022) TSI composite during the 1996 minimum in the top panel and residuals of 0 Wm^{-2} in the lower panel. The numbers in the lower part of the figure denote the conventional cycle numbering.

the magnetic field strength in them. The scaling factor is a free parameter. SRPM subdivides faculae into at least four components (network, active network, plage, bright plage) using various intensity thresholds to identify them in the images, which are then all free parameters as well. The free parameters in both models are set by comparing the reconstructions to observations.

The original SATIRE-S model (Fligge et al., 2000; Krivova et al., 2003; Yeo et al., 2014) uses magnetograms and continuum images to extract information on the surface coverage by the various components. The spectra of the various features are then weighted by their fractional disc coverage. For the Ca II K-based reconstruction, first unsigned magnetograms were recovered from 13 Ca II K archives following Chatzistergos et al. (2019d), which were then fed into the adapted model. The SATIRE-Ca reconstruction by Chatzistergos et al. (2021a) is

the only one to date that employed photometrically calibrated historical Ca II K observations with a semi-empirical model. TSI reconstructions with SATIRE-Ca using Ca II K data are shown in Figures 1 and 7b for CCD-based data, Figures 7a and 9 for photographic data, while Figure 8 shows reconstruction of Lyman- α irradiance from Ca II K data.

Four major incarnations of SRPM have been presented in the literature, Fontenla & Landi (2018), Harder et al. (2019), Criscuoli et al. (2023), and Ermolli & Chatzistergos (2023), which we will refer to as Rome Irradiance Modelling, RIM, in the following). Fontenla & Landi (2018) used Meudon, Coimbra, and Rome/PSPT Ca II K data covering 2002–2017. They limited their analysis to CCD-based Meudon and Coimbra data to avoid issues with the photometric calibration of the photographic data (see Sect. 2). They combined data from all three datasets together by adjusting the segmentation parameters for

Table 2. Comparison of the various TSI series reconstructed from Ca II K data to TSI composites.

TSI reconstruction	Period	Model type	PMOD	ACRIM	ROB	Montillet et al. (2022)
			1978–2018	1978–2013	1992–2023	1980–2023
Annual						
Ambelu et al. (2011)	1915–2009	Empirical	0.13 (0.96)	0.33 (0.82)	0.11 (0.97)	0.11 (0.98)
Foukal (2012)	1915–1999	Empirical	0.14 (0.94)	0.34 (0.80)	0.14 (0.94)	0.09 (0.98)
Xu et al. (2021)	1907–2016	Empirical	0.14 (0.95)	0.33 (0.84)	0.13 (0.96)	0.13 (0.97)
Penza et al. (2022)	1893–2001	Empirical	0.14 (0.95)	0.31 (0.85)	0.10 (0.98)*	0.15 (0.95)
LIRICA	1892–2023	Empirical	0.11 (0.96)	0.33 (0.80)	0.24 (0.79)	0.11 (0.97)
LIRICI	1996–2022	Empirical	0.14 (0.95)	0.19 (0.90)	0.12 (0.96)	0.11 (0.96)
Chapman et al. (2013)	1988–2011	Empirical	0.15 (0.94)	0.25 (0.84)	0.09 (0.98)	0.12 (0.96)
Puiu (2019)	2000–2020	Empirical	0.14 (0.96)	0.23 (0.88)	0.09 (0.97)	0.11 (0.97)
PHSUM	1996–2022	Empirical	0.10 (0.98)	0.24 (0.86)	0.08 (0.98)	0.08 (0.98)
SATIRE-Ca Rome/PSPT	1996–2022	Semi-empirical	0.11 (0.96)	0.20 (0.91)	0.11 (0.96)	0.09 (0.97)
SATIRE-Ca Meudon	1978–2023	Semi-empirical	0.20 (0.89)	0.30 (0.85)	0.09 (0.97)	0.11 (0.97)
RIM	1998–2022	Semi-empirical	0.12 (0.96)	0.24 (0.89)	0.10 (0.97)	0.12 (0.97)
Fontenla and Landi (2018)	2002–2017	Semi-empirical	0.24 (0.85)	0.31 (0.69)*	0.22 (0.89)	0.25 (0.89)
Monthly						
Xu et al. (2021)	1907–2016	Empirical	0.24 (0.82)	0.38 (0.76)	0.20 (0.87)	0.26 (0.81)
Penza et al. (2022)	1893–2001	Empirical	0.26 (0.85)	0.37 (0.80)	0.17 (0.93)*	0.32 (0.79)
LIRICA	1892–2023	Empirical	0.19 (0.90)	0.37 (0.76)	0.15 (0.93)	0.20 (0.90)
LIRICI	1996–2022	Empirical	0.34 (0.74)	0.34 (0.77)	0.29 (0.78)	0.24 (0.86)
Puiu (2019)	2000–2020	Empirical	0.13 (0.96)	0.23 (0.89)	0.10 (0.97)	0.13 (0.96)
PHSUM	1996–2022	Empirical	0.12 (0.96)	0.26 (0.86)	0.10 (0.97)	0.12 (0.96)
SATIRE-Ca Rome/PSPT	1996–2022	Semi-empirical	0.16 (0.93)	0.26 (0.86)	0.15 (0.94)	0.15 (0.94)
SATIRE-Ca Meudon	1978–2023	Semi-empirical	0.18 (0.92)	0.34 (0.82)	0.13 (0.95)	0.19 (0.91)
RIM	1998–2022	Semi-empirical	0.22 (0.88)	0.31 (0.82)	0.18 (0.90)	0.20 (0.90)
Daily						
Puiu (2019)	2000–2020	Empirical	0.20 (0.92)	0.32 (0.82)	0.18 (0.93)	0.21 (0.90)
PHSUM	1996–2022	Empirical	0.16 (0.95)	0.31 (0.84)	0.14 (0.96)	0.21 (0.91)
SATIRE-Ca Rome/PSPT	1996–2022	Semi-empirical	0.21 (0.92)	0.34 (0.80)	0.18 (0.93)	0.25 (0.87)
SATIRE-Ca Meudon	1978–2023	Semi-empirical	0.27 (0.88)	0.46 (0.71)	0.21 (0.91)	0.33 (0.80)
RIM	1998–2022	Semi-empirical	0.40 (0.70)	0.44 (0.68)	0.36 (0.72)	0.33 (0.77)

Note. Shown are RMS differences [Wm^{-2}] and the linear correlation coefficient, R , in parentheses. In order to compute the RMS differences unaffected by potential differences in the absolute levels of the various series, they were all offset to match their mean value to that of the respective TSI composite over their overlapping period. The comparisons are made for annual values (top group), monthly means (middle group), and daily values (lower group). The values marked with an asterisk are derived with an overlap of less than 10 years and are thus less reliable. Under the names of the TSI composites, we also list the period covered by them, to remind that the comparisons were done over different periods. See Section 4.2 for the description of the LIRICA and LIRICI reconstructions, which are produced in this study.

each archive separately so to retrieve similar segmentation masks from the three archives. However, this approach does not account for the intrinsic differences of the archives, which employ significantly different passbands (Chatzistergos et al., 2022b).

A different version of the SRPM model has been applied by Ermolli et al. (2003, 2011), Penza et al. (2003), Ermolli & Chatzistergos (2023) who used only CCD-based Rome/PSPT Ca II K observations, Criscuoli et al. (2018); Criscuoli (2019); Berrilli et al. (2020) and Criscuoli et al. (2023) who used only CCD-based Mauna Loa Solar Observatory (MLSO/PSPT) Ca II K observations as well as by Harder et al. (2019) who used Rome/PSPT and MLSO/PSPT data. Harder et al. (2019) reconstructed SSI variations over 2080–24120 Å (with spectral resolution of 0.2 Å, 2 Å, and 1 Å for UV, visible, and infrared parts of the spectrum) with Ca II K observations and used them to fill gaps in the direct measurements by Solar Radiation and Climate Experiment (SORCE; Harder et al., 2022). Criscuoli et al. (2018); Criscuoli (2019); Berrilli et al. (2020) and Criscuoli et al. (2023) reconstructed the variability

in UV (2300–4000 Å) and Balmer lines ($H\alpha$, β , γ , δ), respectively, with MLSO/PSPT Ca II K observations. For the time being SRPM has only been applied on CCD-based Ca II K observations, but in principle, it has the potential of using historical Ca II K data provided they are accurately processed.

4 Synopsis of TSI reconstructions based on Ca II K data

Table 2 compares several Ca II K-based TSI reconstructions to the PMOD, ACRIM, ROB, and Montillet et al. (2022) TSI composites. In particular, we list the RMS differences and the linear correlation coefficients between all series. Due to the different cadence of the series we give them separately for annual, monthly, and daily values when available. The performance of the models is in general very good, with RMS difference to the TSI composites typically below 0.3 and the correlation coefficients higher than 0.7. The performance varies slightly

among the models when compared to different composites and depending on the cadence. For example, the daily SATIRE-Ca reconstruction from Rome/PSPT data performs slightly better than the Meudon-based version when compared to PMOD and Montillet et al. (2022) series, while the opposite is seen when comparing to ROB for annual and monthly values. Such differences might provide some information on the quality and the stability of the input Ca II K data. Noteworthy, for all models, the agreement to the ACRIM composite is worse than with the other composites, hinting at issues with the ACRIM series, as also indicated by numerous earlier studies (Lockwood & Fröhlich, 2008; Lockwood & Ball, 2020; Krivova et al., 2009; Ball et al., 2012; Chapman et al., 2013; Yeo et al., 2014, 2017a; Mauzeri et al., 2019; Chatzistergos et al., 2020a, 2021a; Lean et al., 2020; Chatzistergos, 2024).

A comparison between the various published TSI series is, however, affected by numerous different aspects of the reconstructions, including, in particular, differences in the employed Ca II K data (choice and number of archives, how data from different sources are combined, data sampling and processing), the reference TSI measurements, and of course the model architecture. In the following, we briefly address some of these issues.

4.1 Combining different Ca II K data

Combining Ca II K data from different sources is not only required to increase the temporal coverage of the reconstructions but also has the advantage of understanding long-term changes in the quality of the data and potential systematic trends. Yet, most of the available TSI reconstructions used Ca II K data from a single archive. This is largely due to the intrinsic differences among the archives rendering it difficult to combine them in a consistent way. The few exceptions were the studies by Foukal (2002, 2012); Ambelu et al. (2011); Fontenla & Landi (2018) and Chatzistergos et al. (2021a).

Foukal (2002, 2012) and Ambelu et al. (2011) used plage areas and an emission index from Mt Wilson observatory, which was extended with those from Sacramento Peak and the MPSI index from Mt Wilson (see Sect. 2.2 for the definition), respectively. Potential inconsistencies between the archives were not addressed however, and as Figure 5 demonstrates, there is significant disagreement between the plage areas from different studies which can lead to significant differences in the resulting TSI.

The studies by Fontenla & Landi (2018) and Chatzistergos et al. (2021a) have attempted to account for the differences. In particular, Fontenla & Landi (2018) combined data from three archives for which they had adjusted the segmentation parameters for each archive separately to minimise the differences in the plage areas they derived from the three archives. This adjustment was, however, done through visual inspection of the produced masks, which might introduce biases. Chatzistergos et al. (2021a) accounted for the differences in the archives by normalising the level of the quiet-Sun regions prior to their conversion to unsigned magnetograms. Also, the free parameter of the model (see Sect. 3.1) was set individually for different archives (which essentially reflects the somewhat different sensitivity of the different archives to the magnetic field).

An important step in moving forward with TSI (or magnetogram) reconstructions employing Ca II K data is to identify and account for all possible inconsistencies within the archives,

as well as to improve their cross-calibration. Inaccurate stitching of the Ca II K archives can introduce spurious long-term trends when reconstructing TSI variations or magnetograms from them.

4.2 Comparing different models using same input data

To help highlight the differences between the models, in Figure 10 we show five TSI reconstructions using different models that employed exactly the same Ca II K data processed in the same way with the methods by Chatzistergos et al. (2018b). In particular, we use the SATIRE-Ca (Chatzistergos et al., 2021a), RIM (Ermolli & Chatzistergos, 2023), photometric sum (PHSUM, hereafter; Chatzistergos et al., 2020a) as well as two regression models based on plage areas (Linear Regression Irradiance reconstruction from Ca II K plage Areas, LIRICA) and integrated intensity (Linear Regression Irradiance reconstruction from Ca II K integrated Intensity, LIRICI) series produced by us here for the sake of this comparison. The reconstruction follows the well-known linear regression approach (e.g. Lean, 2000; Foukal, 2002). Both models use the Photometric Sunspot Index (PSI) by Mandal et al. (2020) to account for the sunspot contribution. For the facular contribution, LIRICA and LIRICI use plage areas by Chatzistergos et al. (2020c) and the Chatzistergos et al. (2020a) Ca II K photometric sum series, respectively. The regression is performed on monthly mean values. All models were applied on exactly the same Rome/PSPT Ca II K observations. In a separate panel we also show the residuals between the reconstructions and the Montillet et al. (2022) TSI composites. The shading shows the range of TSI values obtained when using different TSI composites (namely, Montillet et al., 2022, PMOD, ACRIM, and ROB) as the reference for the reconstruction (that is to fix the free parameters of the models, see Sect. 4.3). The differences between the various reconstructions are rather small. The most prominent differences are for cycle 23, where all reconstructions shown here slightly underestimate TSI, as represented by the composite by Montillet et al. (2022), during the ascending and descending phases, while SATIRE-Ca slightly overestimates it during the ascending phase. The differences are, however, rather small and are within the differences between the different TSI composites. The instrumental changes and relocation of the Rome/PSPT in 2001 (Ermolli et al., 2022), might partly explain the higher disagreement of TSI reconstructions with these data over the earlier period. Over cycle 24, differences between the various models are yet smaller. Table 3 shows the correlation coefficients and RMS differences between these reconstructions and the Montillet et al. (2022) TSI composite.

4.3 Effect of reference TSI series

All models, whether empirical or semi-empirical, have free parameters that need to be set by comparing their output to actual TSI measurements (The only exception of a TSI model which does not require this is the new-generation SATIRE-3D model by Yeo et al., 2017b, which however, cannot, at least at the time being, be adapted to use Ca II K data). While there is no clear consensus on the TSI composite record, different reconstructions might use a different TSI reference to fix their parameters. This can in principle also lead to differences among the various reconstructions.

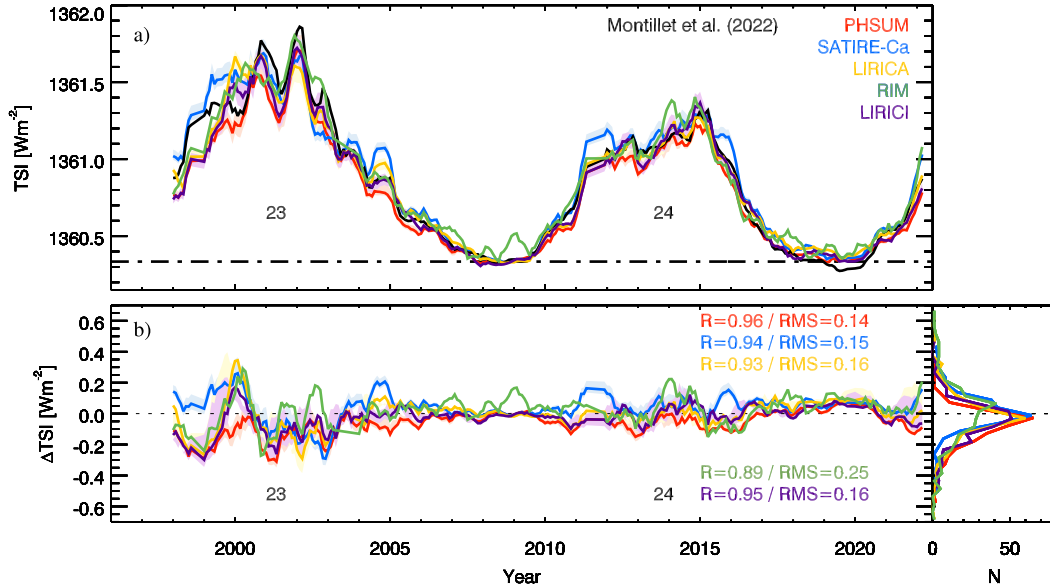


Figure 10. *Top:* TSI variations reconstructed using different models employing the same Rome/PSPT Ca II K data. The shaded surfaces show the range of reconstructions when using ACRIM, ROB, and PMOD TSI composites to set the free parameters of the models (except for RIM). All series were offset to match the value of the Montillet et al. (2022) TSI composite over 2009 (marked with a horizontal line). *Bottom:* Difference between the TSI reconstructed with the various models and the Montillet et al. (2022) TSI composite. The right panel shows the histogram of the residuals in bins of 0.05 Wm^{-2} . Shown are 3-month running mean values, while the numbers in each panel give the linear coefficient (R) and RMS differences in Wm^{-2} between the models and the Montillet et al. (2022) TSI composite series for monthly values. The running means are computed only over the common days in all series. The horizontal line denotes differences of 0 Wm^{-2} . The numbers in the lower part of the figure denote the conventional cycle numbering.

Table 3. Comparison between TSI reconstructions employing the same Ca II K data and the Montillet et al. (2022) TSI composite.

	SATIRE-Ca	RIM	PHSUM	LIRICA	LIRICI
SATIRE-Ca	–	0.215	0.175	0.138	0.162
RIM	0.879	–	0.189	0.183	0.189
PHSUM	0.949	0.925	–	0.140	0.115
LIRICA	0.955	0.910	0.952	–	0.097
LIRICI	0.941	0.911	0.968	0.974	–

Note. The values above the diagonal are RMS differences in Wm^{-2} , while the ones below the diagonal are the linear correlation coefficient, R .

Some of the studies have evaluated the effect of the choice of the TSI reference series on their reconstructions. In particular, Wenzler et al. (2009); Krivova et al. (2009); Yeo et al. (2014), and Chatzistergos et al. (2021a,b) showed that the effect of using a different reference series has only a minor effect on the final reconstruction when using the SATIRE model. In particular and most importantly, the long-term trend of the reconstruction is only minutely affected. Also, Chapman et al. (2013) considered different TSI reference series (PMOD, ROB, and ACRIM) for their empirical reconstruction with the photometric sums. However, they did not discuss differences in the resulting reconstructions. Chatzistergos et al. (2020a), who also used the photometric sums method, evaluated the effect of the reference TSI record and showed that it was negligible also for this model, and the minimum-to-minimum change was essentially unaffected.

To our knowledge, the effect of the reference TSI series was not evaluated by any of the empirical regression models using Ca II K plage areas. To demonstrate the effect of such models, in Figures 7c and 10, we show also LIRICA, a linear regression TSI reconstruction based on Ca II K plage areas. In particular, in Figures 7c and 10, we show reconstructions with LIRICA employing the Chatzistergos et al. (2020c) Ca II K plage area composite series produced in this study (see Sect. 4.2) and plage areas from only Rome/PSPT, respectively. We also show, as a shaded surface, the range of the reconstructions produced when using the TSI composites by Montillet et al. (2022), PMOD, ACRIM, and ROB as the reference. The result is consistent with that for SATIRE and empirical photometric sum models previously reported. Namely, the activity minimum-to-minimum trend remains essentially unaffected.

5 Long-term trends in TSI derived from Ca II K based models

The unique potential of Ca II K data is that they can help reduce the uncertainty of the estimates of the amplitude of the secular variability of TSI. Firstly, modern reliable Ca II K archives allow for reducing the uncertainties due to the cross-calibration issues of direct TSI measurements. Secondly, combined with longer-running historic archives, they can allow estimating the variability since the late 19th century.

Chatzistergos et al. (2020a, 2021b), updated by Chatzistergos et al., (2023b) estimated the minimum-to-minimum change since 1996 using Rome/PSPT Ca II K data to reconstruct TSI

Table 4. TSI differences between solar cycle minima in various models.

TSI series	1913–2019	1913–1996	1923–1996	1923–1964	1964–1996	1996–2008	2008–2019
	SC 15–25	SC 15–23	SC 16–23	SC 16–20	SC 20–23	SC 23–24	SC 24–25
Ambelu et al. (2011)	–	–	1.14 (0.83)	0.76 (0.31)	1.63 (0.52)	–13.72 (–1.69)	–
Foukal (2012)	–	–	–1.34 (–0.98)	–0.72 (–0.30)	–2.13 (–0.68)	–16.15 (–1.99)	–
Xu et al. (2021)	–	0.56 (0.47)	0.76 (0.55)	2.24 (0.92)	–1.16 (–0.37)	–8.59 (–1.06)	–
Penza et al. (2022)	–	14.05 (11.67)	10.90 (7.96)	20.08 (8.27)	–0.97 (–0.31)	–	–
LIRICA	–0.89 (–0.95)	0.87 (0.72)	–0.34 (–0.25)	0.96 (0.39)	–2.01 (–0.64)	–20.52 (–2.53)	7.81 (0.86)
LIRICI	–	–	–	–	–	–5.50 (–0.68)	3.97 (0.44)
Chapman et al. (2013)	–	–	–	–	–	–5.90 (–0.73)	–
Puiiu (2019)	–	–	–	–	–	–	–1.56 (–0.17)
PHSUM Rome/PSPT	–	–	–	–	–	–18.33 (–2.26)	–0.39 (–0.04)
PHSUM SFO	–	–	–	–	–	–11.83 (–1.46)	–
RIM	–	–	–	–	–	–	–0.26 (–0.03)
SATIRE-Ca Rome/PSPT	–	–	–	–	–	–17.60 (–2.17)	3.76 (0.41)
SATIRE-Ca SFO	–	–	–	–	–	–7.19 (–0.89)	–

Note. The values are given as the TSI trends (difference) between the start and the end years in $\text{mW m}^{-2} \text{y}^{-1}$ ($\times 10 \text{ W m}^{-2}$). Underneath the periods we also list the corresponding cycle numbers (where the years refer to the cycle start).

variations with the PHSUM and SATIRE-Ca models, respectively. They reported trends of $-18 \text{ mW m}^{-2} \text{y}^{-1}$ (same for both models) between the 1996 and 2008 minima and -0.4 and $3.8 \text{ mW m}^{-2} \text{y}^{-1}$ between the 2008 and 2019 minima for the PHSUM and SATIRE-Ca reconstructions, respectively. Table 4 lists the minimum-to-minimum change for all TSI reconstructions, for which we have the data and could determine the trend between at least two solar cycles. We considered seven periods, two over the satellite period (1996–2008 and 2008–2019), three covering the longest possible extent (1913–2019, 1913–1996, and 1923–1996), and finally splitting the entire period into two halves (1923–1964 and 1964–1996). Table 4 also gives the corresponding cycle numbers, which refer to the preceding minima. All models considered here show a decreasing trend between cycles 23 and 24, although they differ in the exact value, ranging from -5.5 to $-20.5 \text{ mW m}^{-2} \text{y}^{-1}$. Negative values mean TSI decreases with time. Between cycles 24 and 25, the estimates of the change range from -1.56 to $7.81 \text{ mW m}^{-2} \text{y}^{-1}$. For comparison, direct TSI measurements suggest a trend between cycles 24 and 25 of $13 \text{ mW m}^{-2} \text{y}^{-1}$ (Woods et al., 2022) from SORCE/TIM (Total Irradiance Monitor onboard the Solar Radiation and Climate Experiment mission; Kopp, 2021) and $-15 \pm 26 \text{ mW m}^{-2} \text{y}^{-1}$ (Finsterle et al., 2021) from SOHO/VIRGO (Variability of solar IRadiance and Gravity Oscillations experiment onboard the Solar and Heliospheric Observatory; Fröhlich et al., 1997).

The differences become more significant when considering longer periods. Several studies used Ca II K plage areas or 1 Å emission index for long-term TSI reconstructions (Solanki & Fligge, 1998; Lean, 2000; Foukal, 2002, 2012; Ambelu et al., 2011; Xu et al., 2021; Penza et al., 2022). Most of those models used solely Ca II K data for the facular contribution, while the models by Solanki & Fligge (1998) and Lean (2000, 2018) combined the Ca II K data with other chromospheric indices. In particular, Solanki & Fligge (1998) used a composite proxy of facular emission (Fligge & Solanki, 1998), which was produced by combining four series, namely sunspot areas, 10.7cm radio flux, white-light facular areas, and Ca II K plage areas by Foukal (1996, yellow curve in Fig. 5), while also

considering a cycle length series (cf. Chatzistergos, 2023). Similarly, the NRLTSI model (Lean, 2000, 2018) combined various indices including the F10.7 index and Ca II K plage areas from SGD and Foukal (1998) as presented by Lean et al. (2001). We do not show these two series because they combine observed records with proxies derived from different alternative sources, which makes it difficult to assess the role of the Ca II K data in the outcome.

Long-term reconstructions using only Ca II K data to describe the facular contribution are those by Foukal (2002, 2012); Ambelu et al. (2011); Xu et al. (2021); Penza et al. (2022). They all used different Ca II K data, and as mentioned before, besides the series by Penza et al. (2022) all Ca II K data were photometrically uncalibrated. In particular, Foukal (2012); Ambelu et al. (2011); Xu et al. (2021); Penza et al. (2022) used the plage fractional areas by Foukal (2002, ciel curve in Fig. 5), the Ca II K index by Bertello et al. (2010, black curve in Fig. 5), the 1 Å emission index by Bertello et al. (2016, purple curve in Fig. 5), and the Chatzistergos et al. (2019b) plage area composite series, respectively. Penza et al. (2022) additionally included the modulation potential by Muscheler et al. (2007) to allow for long-term variations which they ascribe to the quiet Sun. Due to the magnetic origin of the variability of the modulation potential, this essentially means that they use the modulation potential to describe the evolution of the network not represented by the employed plage area record. Whereas their reconstruction goes back to 1513, only the period after 1874 and 1893 was based on actual sunspots and plage areas, respectively. To estimate plage and sunspot areas at earlier times, they used the modulation potential derived from cosmogenic radioisotopes.

All available long-term TSI reconstructions with Ca II K data, along with a new empirical TSI reconstruction produced here (see Sect. 4.2), are shown in Figure 7c over the period for which actual Ca II K observations exist, that is since 1892. The complete TSI reconstruction by Penza et al. (2021) back to 1513 is shown in Figure 2. The series exhibits variations that are typically less than 0.5 W m^{-2} for annual median values. Between cycles 16 and 23, the long-term reconstructions, except the one by Penza et al. (2022), suggest a very weak overall trend

of $\pm 1 \text{ mW m}^{-2} \text{ y}^{-1}$, which is rather stable over the entire 20th century (see Table 4). The TSI reconstructed by Penza et al. (2022), however, shows a comparatively strong increase. The significant difference between the reconstruction by Penza et al. (2022) and the others is entirely due to their inclusion of an additional long-term trend scaled with the modulation potential derived from cosmogenic radioisotope data. It should be noted that Vieira and Solanki (2010) and Vieira et al. (2011) showed that the link between the TSI and the radionuclide concentrations is non-linear. While most reconstructions (except that by Foukal, 2012) suggest that TSI has been increasing in the first half of the 20th century, the trend turned to decline in the 2nd half of the century (although the decline started a bit later in the model by Ambelu et al., 2011). This is probably not very surprising and is in agreement with the overall evolution of the solar magnetic activity, as evidenced, e.g., by the sunspot number or areas. Interestingly, the strongest trend (of the order of or even exceeding $10 \text{ mW m}^{-2} \text{ y}^{-1}$) is found over the more recent period, especially over cycles 23–24 (except for the model by Penza et al., 2022).

6 Conclusions

Ca II K observations comprise one of the longest archives of direct solar observations, with photographic data extending back to 1892 and modern observations acquired with CCD devices continuing to this day. Ca II K observations are a treasure trove for solar irradiance studies, which can significantly improve our understanding of past irradiance variations and, in particular, help reduce the existing uncertainty in the magnitude of the secular variability. However, owing to various intricacies of the Ca II K data they have not been exploited to their fullest yet. In this paper, we reviewed the progress that has been achieved over the last decades aiming at utilizing Ca II K observations to reconstruct irradiance variations.

Extensive efforts over the last two decades have resulted in most of the prominent Ca II K data to have been digitised and made available to the public. Modern techniques have been developed and optimised to process the Ca II K observations and to correct them for limb darkening as well as artefacts (e.g. Ermolli et al., 2009b; Chatterjee et al., 2016; Chatzistergos et al., 2018b; Bertello et al., 2020). Chatzistergos et al. (2018b, 2019b) have also evaluated the accuracy of their processing and their study was the first to do so, to the best of our knowledge. These studies demonstrated that historical Ca II K observations can be processed with sufficient accuracy to account for the majority of artefacts affecting the images, even in rather severe cases, and thus open them for studies of past solar activity and irradiance reconstructions. Methods to accurately perform the photometric calibration of historical data were also developed (Chatzistergos et al., 2018b), something that was previously lacking for photographic data. All these efforts brought us to the state where Ca II K observations can enter irradiance models with significantly lower uncertainties and fewer artefacts than in the past.

Ca II K data have been used in the literature to study the temporal evolution of plage areas and various disc-integrated emission indices. Unfortunately, differences in the processing of Ca II K images led to some discrepancies between the published results of plage areas (Ermolli et al., 2009b, 2018;

Chatzistergos et al., 2022b). This highlights the importance of accurate processing of Ca II K images and accounting for the differences between the archives when stitching data from different sources together. Understanding the intrinsic differences among Ca II K data taken with different passbands is essential to consistently combine data from various sources. This task remains the main challenge on the way to a reliable reconstruction of the solar irradiance from historical Ca II K data.

Ca II K data have also been used to reconstruct total and spectral solar irradiance, with both empirical and semi-empirical models (e.g. Solanki & Fligge, 1998; Lean et al., 1998; Foukal, 2002, 2012; Ambelu et al., 2011; Ermolli et al., 2011; Chapman et al., 2013; Fontenla & Landi, 2018; Harder et al., 2019; Berrilli et al., 2020; Xu et al., 2021; Penza et al., 2022; Criscuoli et al., 2023), including some of the most prominent models such as SATIRE and SRPM. The majority of existing reconstructions were restricted to CCD-based Ca II K observations, which cover an even shorter period than direct irradiance measurements. The various existing TSI reconstructions show a good agreement with composites of direct TSI measurements, with the exception of ACRIM. Long-term reconstructions from Ca II K data are so far limited to empirical regression models using Ca II K plage areas or disc-integrated emission indices (Solanki & Fligge, 1998; Lean, 2000; Foukal, 2002, 2012; Ambelu et al., 2011; Xu et al., 2021; Penza et al., 2022). That means that potential spurious trends in the plage area series due to inaccurate processing would be plaguing the irradiance reconstructions too. There has been only one semi-empirical TSI reconstruction with photometrically calibrated historical Ca II K data (Chatzistergos et al., 2021a). This demonstrated that recovering accurate TSI reconstructions from historical data is indeed possible, provided accurate and consistent processing of Ca II K data is used.

Finally, on one hand, we would like to stress that despite the huge effort put into the digitisation of the Ca II K data, there still remain observations that have not been digitised. Availability in digital format of these data is important not only for preservation purposes, but it could help improve the temporal coverage of existing datasets as well as help resolve issues with the existing archives. Thus, the digitisation of further archives would also be greatly beneficial for irradiance studies. On the other hand, the continuation of the few running modern series of Ca II K observations is also extremely important, to continue exploring and understanding the solar variability from short- to increasingly longer-term scales.

Acknowledgements

We thank the observers at the Baikal, Brussels, Calern, Kanzelhöhe, Kodai-kanal, Meudon, Mt Wilson, Pic du Midi, Rome, and San Fernando sites for their enormous efforts to create and preserve such an important archive of solar data. Our special thanks go to Isabelle Bualé for her continued efforts to digitise the archive of the Meudon observatory. We further thank Francesco Berrilli, Angela Cookson, and Tatiana Egorova for providing their data. The TSI reconstructions with SATIRE by Dasi-Espuig et al. (2016) and Wu et al. (2018a), PHSUM by Chatzistergos et al. (2020a) as well as the CEA20 plage area composite and the MEA20 sunspot area composite are available at <http://www2.mps.mpg.de/projects/sun-climate/data.html>. The TSI series by Steinhilber et al. (2012) is available at https://www.ncmi.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/. The Foukal (1996, 2002) and SGD plage areas are available at <https://www.ngdc.noaa.gov/stp/solar/calciumplages.html>. The Lyman- α composite series by Machol et al. (2019) is available at https://lasp.colorado.edu/lisird/data/composite_lyman_alpha/. TC and NAK acknowledge support by the

German Federal Ministry of Education and Research (Project No. 01LG1909C). This work was partly supported by the European Union's Horizon 2020 Research and Innovation program under grant agreement No 824135 (SOLAR-NET). This research has made use of NASA's Astrophysics Data System. The editor thanks three anonymous reviewers for their assistance in evaluating this paper.

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Cite this article as: Chatzistergos T, Krivova NA & Ermolli I 2024. Understanding the secular variability of solar irradiance: the potential of Ca II K observations. *J. Space Weather Space Clim.* **14**, 9. <https://doi.org/10.1051/swsc/2024006>.