Chapter 2
Models of Solar Total and Spectral Irradiance Variability of Relevance for Climate Studies

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Abstract The variable radiative output of the Sun is a prime external driver of the Earth's climate system. Just how effective this driver is has remained relatively uncertain, however, partly due to missing knowledge on the exact variation of the Sun's irradiance over time in different parts of the solar spectrum. Due to the limited length of the time series of measured irradiance and inconsistencies between different measurements, models of solar irradiance variation are particularly important. Here we provide an overview of progress over the last half decade in the development and application of the SATIRE family of models. For the period after 1974, the model makes use of the full-disc magnetograms of the Sun and reproduces up to 97 % of the measured irradiance variation. Over this time frame, there is no evidence for any non-magnetic change in the solar irradiance on time scales longer than about a day. We have also been able to compute total solar irradiance since the Maunder minimum and further into the past throughout the whole Holocene. The Sun's spectral irradiance from the Lyman α line in the UV to the far infrared has also been reconstructed throughout the telescopic era.

2.1 Introduction

The Earth's global surface temperature has being growing rapidly over the last decades [see, e.g., *Solomon et al.*, 2007]. This has in large measure been attributed to human activity. However, a quantitative assessment of the anthropogenic contribution to the change in climate is still hampered by inadequate understanding of the relative roles of different climate drivers, both internal and external [e.g., *Hansen et al.*, 2002, 2005; *Jungclaus et al.*, 2010; *Schmidt et al.*, 2011].

The main external driver of the Earth's climate system is the solar radiative output [e.g., *Eddy*, 1976; *Reid*, 1987; *Hansen*, 2000; *Bond et al.*, 2001; *Neff et al.*, 2001;

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Hansen et al., 2002; *Camp and Tung*, 2007; *Gray et al.*, 2010]. The strength of Sun's influence and which process plays the main role remain, however, unclear. Variations in solar total and/or spectral irradiance are the prime suspects. Solar total (i.e. integrated over all wavelengths) irradiance (TSI) is the total solar energy flux at the top of the Earth's atmosphere, and thus any changes in the TSI affect the overall energy balance of the climate system. Variations in the spectral distribution of the irradiance, in particular in the UV but also in the visible and IR, have a pronounced effect on the chemistry and dynamics of the Earth's atmosphere [e.g., *Haigh*, 1994, 2007; *Haigh et al.*, 2010; *Rozanov et al.*, 2004; *Kodera and Kuroda*, 2002, 2005; *Langematz et al.*, 2005; *Matthes et al.*, 2006; *Gray et al.*, 2010].

Space-based instruments have being monitoring solar total and spectral (SSI) irradiance since 1978 [e.g., *Willson et al.*, 1981; *Fröhlich et al.*, 1997; *Floyd et al.*, 2003; *Willson and Mordvinov*, 2003; *Skupin et al.*, 2005; *Kopp et al.*, 2005; *Fröhlich*, 2006; *Harder et al.*, 2009]. Different mechanisms have been proposed to explain the observed changes in the irradiance [see review by *Domingo et al.*, 2009], of which most successful was the modulation by the solar surface magnetic field. Models assuming that solar brightness changes due to the varying relative contributions of dark sunspots, bright faculae and the bright network explain over 90 % of the measured TSI variation on time scales of days up to the solar cycle [*Fröhlich and Lean*, 1997; *Fligge et al.*, 2000; *Preminger et al.*, 2002; *Ermolli et al.*, 2003; *Krivova et al.*, 2003; *Wenzler et al.*, 2006, 2009; *Ball et al.*, 2011].

Despite the great success of the models in reproducing TSI measurements, a number of open questions remain, including the presence and the magnitude of the secular trend in the irradiance during the last 3 cycles [*Fröhlich*, 2009; *Scafetta and Willson*, 2009; *Krivova et al.*, 2009a, 2011a], the absolute level of the TSI [*Kopp et al.*, 2007; *Kopp and Lean*, 2011] or the contribution of different spectral ranges to the irradiance variation [*Krivova et al.*, 2006; *Harder et al.*, 2009; *Pagaran et al.*, 2009; *Morrill et al.*, 2011].

Understanding the mechanisms of the irradiance variability is not of purely theoretical interest. Only when the physical origin of the variation is recognised and the measured changes are reproduced with high accuracy, can a reconstruction of the past solar irradiance be trustworthy. Such longer-term reconstructions are prerequisites for a reliable evaluation of the connection between solar variability and the Earth's climate change, since the time series of direct measurements is just over 30 years long and is too short for this.

Extension of the models back in time poses additional challenges. Available historical data featuring solar activity become sparser and of lower quality when going further back in time. The magnitude of the secular trend in the irradiance has remained by far the most speculative aspect of long-term reconstructions [cf. *Lean et al.*, 1992; *Hoyt and Schatten*, 1993; *Zhang et al.*, 1994; *Soon et al.*, 1996; *Mendoza*, 1997; *Foster*, 2004; *Wang et al.*, 2005; *Krivova et al.*, 2007, 2010; *Schrijver et al.*, 2011; *Shapiro et al.*, 2011].

Here we describe our recent progress in modelling solar irradiance on time scales of days to millennia using the SATIRE set of models. We refer to *Domingo et al.* [2009] for a recent review of different irradiance models on time scales of days to the solar cycle. The present paper is structured as follows. Section 2.2 sketches out essentials of the SATIRE model. Section 2.3 describes our efforts in modelling solar total and spectral irradiance over the satellite era, whereas Sects. 2.4 and 2.5 deal with reconstructions of solar irradiance for the telescope and pretelescopic eras, respectively. Section 2.6 summarises the results.

2.2 SATIRE

SATIRE (Spectral And Total IRradiance REconstructions) is a set of routines developed for calculations of solar irradiance from other magnetic activity proxies [*Solanki et al.*, 2005; *Krivova and Solanki*, 2008; *Krivova et al.*, 2011b]. SATIRE is based on the assumption that all irradiance variation on time scales longer than a day is entirely due to the changes in the number and distribution of magnetic features (such as sunspots or faculae) on the solar surface.

Irradiance changes on shorter time scales are dominated by other sources, such as the p-mode oscillations peaking at a period of around 5 minutes [see review by *Christensen-Dalsgaard*, 2002] or solar granulation, i.e. the convective cells on the surface of the Sun [e.g., *Seleznyov et al.*, 2011] and are not described by the SATIRE. These variations are, however, of no importance for climate studies. On time scales related to climate variability, no evidence for other mechanisms of intrinsic (i.e. not related to changes in the Earth's orbit) solar irradiance modulation has yet been provided [see, e.g., *Domingo et al.*, 2009, as well as Sect. 2.3].

Magnetic features that can be observed on the solar surface are divided in SATIRE into various classes. Sunspot umbrae and sunspot penumbrae, that are cooler than the surrounding quiet photosphere, appear dark and reduce solar brightness. Faculae and the network (represented by a single component in SATIRE) are bright. Solar surface essentially free (above the noise and detectability thresholds) of magnetic field is called 'the quiet Sun'. Thus, SATIRE currently distinguishes four different photospheric components.

The brightness of each component is assumed to be time-invariant but depends (as attested by observations) on the wavelength and the position on the solar disc. These brightnesses were calculated [*Unruh et al.*, 1999] in the LTE approximation using the ATLAS9 code by *Kurucz* [1993].

The area covered by different features on the solar surface changes with time, which leads to the irradiance modulation. To describe the surface coverage by each component and its evolution in time, we employ different observational data. Most detailed information is provided by the direct measurements of the solar photospheric magnetic field, i.e. by the full-disc magnetograms. The version of SATIRE which makes use of the magnetograms is called SATIRE-S (S stands for Satellite era; *Krivova et al.*, 2003; *Wenzler et al.*, 2005, 2006) and is discussed in Sect. 2.3. Magnetograms with sufficient quality and cadence have been recorded for less than four decades. Thus reconstructions of solar irradiance over longer periods have to content themselves with data having lower quality and resolution (both spatial and temporal). For the period after 1610, the sunspot number can be employed to reconstruct the evolution of the solar surface magnetic field and thus irradiance. This is done in the SATIRE-T (for the Telescope era; *Solanki et al.*, 2002; *Balmaceda et al.*, 2007; *Krivova et al.*, 2007, 2010) model described in Sect. 2.4. Finally, before 1610 even the sunspot number is not available. Then, concentrations of cosmogenic isotopes in terrestrial archives can be employed as a proxy of solar magnetic activity if the effect of the Earth's magnetic field is taken into account. This is possible for the Holocene [*Solanki et al.*, 2004; *Usoskin et al.*, 2006a; *Vieira and Solanki*, 2010]. The SATIRE-M model [*Vieira et al.*, 2011] deals with solar irradiance on millennial time scales (Sect. 2.5). Knowing brightnesses of individual features and their surface coverage, it is then possible to calculate solar irradiance as the sum of the contributions of all components.

Since brightnesses of the photospheric components depend on the wavelength, calculations are done on a grid of wavelengths from 10 to 160 000 nm. An integral over all wavelengths gives the total solar irradiance (TSI). The LTE approximation involved in calculations of the brightness spectra of photospheric components is not valid in some spectral lines, mainly in the UV (see also *Danilovic et al.*, 2007, 2011 for an example of SATIRE's performance in spectral lines in the visible) and below roughly 200–250 nm. The contribution of these short wavelengths to the TSI is less than 1 % [*Krivova et al.*, 2006] and the computed TSI is still quite accurate. However, the calculated UV fluxes are not reliable. We therefore correct the model at shorter wavelength in the following way. *Krivova and Solanki* [2005] and *Krivova et al.* [2006] found that SATIRE reproduces quite accurately variations of solar spectral irradiance in the range between 220 and 240 nm as observed by the UARS/SUSIM instrument. Thus we have derived empirical relationships between the measured irradiance in this range and irradiance at other wavelengths covered by SUSIM (115–410 nm). Applying these relationships to the modelled irradiance at 220–240 nm, SATIRE is extended down to 115 nm.

2.3 Satellite Era

2.3.1 TSI

Employment of the solar full-disc magnetograms for irradiance modelling turned out to be very successful in reproducing the measured irradiance variations. *Krivova et al.* [2003] and *Ball et al.* [2011] employed the SoHO/MDI magnetograms and continuum images to model solar irradiance over the ascending (1996–2002) and descending (2003–2009) phases of cycle 23, respectively. The model captures 92 to 97 % of the TSI variation (given by the squared correlation coefficient r_c^2, with maximum r_c values reaching 0.984) measured by the SoHO/VIRGO and SORCE/TIM instruments (see Fig. 2.1). Employment of the ground-based NSO KP magnetograms and continuum images [*Wenzler et al.*, 2004, 2005, 2006] results in a somewhat lower correlation of $r_c = 0.91$ ($r_c^2 = 0.83$) over the period 1974–2003. Taking

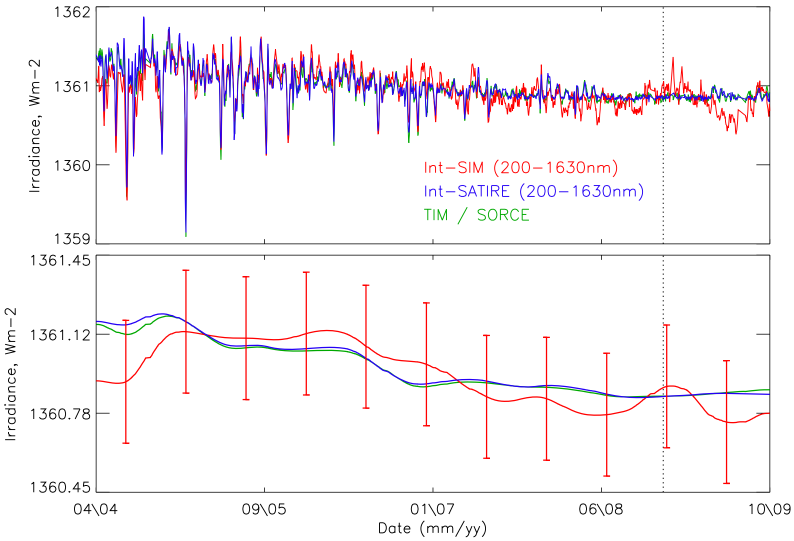

Fig. 2.1 TSI measured by SORCE/TIM (*green line*) and irradiance integrated (Int) over the range 200–1630 nm (i.e. the spectral range covered by SORCE/SIM) as measured by SORCE/SIM (*red*) and modelled with SATIRE-S (*blue*). The Int-SIM and Int-SATIRE curves are shifted in absolute levels to compensate for the missing contributions from the spectral ranges below 200 nm and above 1630 nm. *Top*: daily values; *bottom*: smoothed to remove short-term fluctuations. Error bars represent one standard deviation in the long-term stability of Int-SIM and are 0.259 $\mathrm{W\,m^{-2}}$ or 212 ppm. This figure is taken from *Ball et al.* [2011]

into account the significantly lower quality of the ground-based data, which suffer from numerous artefacts, such a good agreement of the model with the measurements provides strong support for surface magnetism as the dominant driver of irradiance variations on time scales from about a day to the solar cycle.

The space-based TSI measurements started in 1978 and were carried out by a number of different experiments, whose observing time span partly overlapped. Each of the instruments suffered from its individual degradation, calibration or other problems, making a construction of a composite time series nontrivial. The three currently available composites, PMOD [*Fröhlich*, 2009], ACRIM [*Willson and Mordvinov*, 2003] and IRMB [*Dewitte et al.*, 2004] show significantly different long-term trends (i.e. differences in the relative irradiance levels during different activity minima). This initiated the debate on the presence and magnitude of a secular trend in the TSI during the satellite era [e.g., *Fröhlich*, 2006, 2009; *Scafetta and Willson*, 2009].

Whereas the ACRIM and IRMB composites show an increase in the TSI between the minima preceding cycles 22 and 23 (though the increase is not statistically significant in the IRMB composite), the PMOD composite suggests a slight decrease (by 0.053 $\mathrm{W/m^2}$, given by *Fröhlich*, 2011, to 0.123 $\mathrm{W/m^2}$, from *Fröhlich*, 2009). From the minimum in 1996 preceding cycle 22 to the most recent minimum in 2008, TSI has been found to decrease by a further 0.22 to 0.273 $\mathrm{W/m^2}$ [*Fröhlich*,

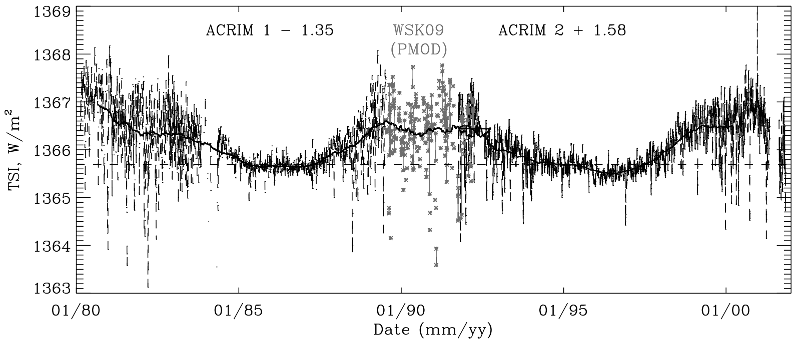

Fig. 2.2 'Mixed' TSI composite constructed from ACRIM-1 and ACRIM-2 data (*black dashed line*), with the gap bridged using the SATIRE-S (PMOD-optimised) model (asterisks connected by *grey solid line* when there are no gaps). The *heavy solid line* is the 1-year smoothed TSI, and the *horizontal dashed line* shows the level of the minimum preceding cycle 22. From *Krivova et al.* [2009a]

2009, 2011]. Note that SORCE/TIM measures a shallower decrease [*Kopp and Lean*, 2011]. This most recent decrease appears unusual when compared to other solar magnetic activity proxies according to *Fröhlich* [2009], which has been interpreted by him as a sign of non-magnetic origin in the TSI secular change. We have therefore tested whether the SATIRE-S model is able to reproduce all the observed TSI changes within the surface magnetism concept.

First, *Wenzler et al.* [2009] have compared the TSI reconstructed from the NSO KP magnetograms with all three available composites. They found a significantly better agreement with the PMOD composite than with the other two records. Both the correlation coefficients were significantly higher (over 0.91 for PMOD compared to 0.79–0.82 for ACRIM and IRMB) and the slopes of the linear regressions between the data and the model were closer to 1 (0.98 compared to 0.81–0.82). In particular, the upward trend between the minima in 1986 and 1996 in the ACRIM and IRMB composites could not be reproduced.

The main moot point in the discussion on the trend between the minima 21/22 and 22/23 is the question on the 'cross-calibration' of the ACRIM-1 and ACRIM-2 instruments caused by an unplanned 2-year long gap between their operations. Therefore *Krivova et al.* [2009a] have used the TSI reconstructed by SATIRE-S to bridge this gap, as proposed by *Scafetta and Willson* [2009]. Such a 'mixed' (observations—model—observations) composite is shown in Fig. 2.2 and suggests that the TSI has decreased between the two minima by 0.15–0.38 W/m^2. The exact value of the change depends somewhat on the SATIRE-S optimisation (i.e. whether it is optimised to best fit the PMOD, ACRIM or IRMB composite). But independently of the optimisation (1) an increase in the minima levels could not be achieved, and (2) the decrease of 0.15–0.38 W/m^2 in the TSI from 1986 to 1996 is slightly larger than is shown by the PMOD composite (0.053–0.12 W/m^2; the 1-σ uncertainty of the PMOD composite for the minimum in 1996 is listed as 0.1 W/m^2; *Fröhlich*, 2009).

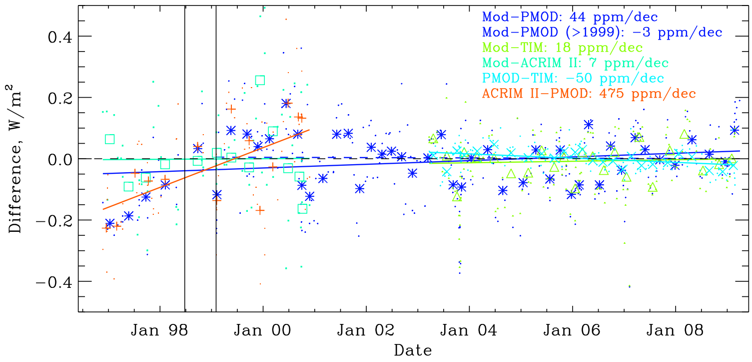

Fig. 2.3 The difference, in W/m^2, between the model and the data: PMOD (*blue*), ACRIM II (*pine green*), TIM (*light green*), and between the PMOD and the two other data sets: ACRIM II (*orange*) and TIM (*cyan*). *Dots* represent values for individual days, whereas *bigger symbols* represent bins of five individual points. The corresponding trends with time are indicated by the *straight lines* and their slopes are listed in the *right top corner*. The *vertical black lines* show the beginning and the end dates of the period without regular contact with SoHO. From *Krivova et al.* [2011a]

Finally, *Krivova et al.* [2011a] have used 60-min averaged MDI magnetograms sampled roughly every two weeks to reconstruct the TSI over the period November 1996 to April 2009. They have compared the modelled TSI with the PMOD composite and with the measurements by two individual instruments, UARS/ACRIM-2 and SORCE/TIM that monitored the TSI over the minimum in 1996 and during the declining phase of cycle 23, respectively. Excellent agreement has been found between the model and all sets of measurements with the exception of the early (1996–1998) PMOD data. The difference between the model and all sets of measurements as well as between the PMOD and the other two records is plotted in Fig. 2.3.

Whereas the agreement between the SATIRE-S and the PMOD composite between 1999 and 2009 is essentially perfect, the modelled TSI increases faster from the end of 1996 to 1999 than implied by the PMOD composite. On the other hand, model's steeper trend agrees remarkably well with the ACRIM-2 data. This is further supported by the fact that the shallower trend of the PMOD data is only seen in the measurements of one VIRGO radiometer, the PMO6V, whose data are used in the composite, whereas the other VIRGO radiometer, the DIARAD, shows a steeper trend in agreement with ACRIM-2 and SATIRE-S results. This all suggests that the TSI level during 1997–1998 might be overestimated in the PMOD data set by roughly 0.1–0.15 W/m^2. This inconsistency of the PMOD composite with other measurements and the model around the minimum preceding cycle 23 explains why the earlier study by *Steinhilber* [2010] found a discrepancy between the observed and modelled TSI in the minima preceding cycles 23 and 24. At the same time, the study of *Krivova et al.* [2011a] clearly demonstrates that there is no evidence for any non-magnetic long-term change in the TSI over the period of satellite measurements.

2.3.2 SSI

Although regular monitoring of solar spectral irradiance (SSI) in the UV also started in 1978, a consistent time series does not exist. The reason is that, in addition to different absolute levels, degradation trends and other problems in the data from various instruments depend strongly on the wavelength, which makes a proper self-consistent cross-calibration of measurements by different instruments essentially impossible [cf. *DeLand and Cebula*, 2008]. Regular observations in a broader spectral range covering the visible and the near-IR began only in 2002/2003 with ENVISAT/SCIAMACHY and SORCE/SIM.

Poorer spectral data is one of the factors hindering SSI models in their development. Another one is the failure of the LTE approximation in the UV part of the spectrum. Non-LTE models still need to mature to provide SSI reconstructions over a broad spectral range [e.g., *Fontenla et al.*, 2004, 2006] although significant progress has been made recently [*Shapiro et al.*, 2010].

As described earlier in Sect. 2.2, SATIRE makes use of the empirical relationships derived from SUSIM observations at wavelength below 270 nm and thus allows a reconstruction of the solar spectral irradiance over essentially the whole range that is of interest for climate models (115–160 000 nm). Detailed comparisons of the SATIRE-S results with different spectral data can be found in *Krivova et al.* [2003, 2006, 2009b]; *Krivova and Solanki* [2005]; *Unruh et al.* [2008]; *Danilovic et al.* [2007, 2011]; *Ball et al.* [2011]. Reconstructions of the SSI from magnetograms over cycles 21–23 were presented by *Krivova et al.* [2006, 2009b, 2011b]. They have shown that the contribution of the UV radiation below 400 nm to the TSI variation might be significantly higher than was previously estimated from UARS/SOLSTICE and UARS/SUSIM data [see, e.g., *Lean*, 1989; *Lean et al.*, 1997; *Krivova et al.*, 2006]. The reason is that the long-term stability of these (and earlier) instruments above 250–300 nm was comparable to or even lower than the solar cycle changes in this range.

The relative contributions of different wavelength ranges to the TSI and its solar cycle variation obtained by *Krivova et al.* [2006] are listed in Table 2.1 together with the values obtained by other authors from both observations and models. All recent estimates suggest a relatively high contribution of the UV wavelengths to the TSI changes. At the same time, considerable uncertainty remains.

In particular, Table 2.1 makes it apparent that, of the recent estimates of the contribution of the UV wavelengths below 400 nm to the total change in the TSI, all but SIM are lying in the range 47–63 %. At the same time, the SIM estimate of roughly 180 % is by a factor of 3 higher. The results based on the SORCE/SIM measurements [*Harder et al.*, 2009] are particularly surprising, since they imply that the total change in the irradiance at 200–400 nm is roughly a factor of 2 higher than the TSI change over the same period, which is almost compensated by the negative trends in the visible and the IR. If confirmed, this may have a significant effect on climate models [*Haigh et al.*, 2010; *Garcia*, 2010]. Note that values from *Harder et al.* [2009] listed in the table are rough estimates from their plot and depend strongly

Table 2.1 The relative contribution of different spectral ranges to the TSI variation ($\Delta F_\lambda / \Delta F_{\mathrm{TSI}}$) as measured or modelled by different authors (listed in the 1st column). The solar cycle upon which the results are based is identified in the 2nd column. The last line lists the contribution of the irradiance in the corresponding intervals, F_λ, to the total solar irradiance, F_{TSI}, according to *Krivova et al.* [2006]. If only a part of the corresponding wavelength interval or a larger range was considered, then the exact range is given in brackets (for PWB-09 and MFM-11)

Ref	Cycle	Wavelength range, nm				
		200–400	400–700	700–1000	1000–3000	> 3000
Lea-97	22	30.8				
KSF-06	23	61.8	26.1	15.4	−5.5	1.4
Hea-09	23	≈ 180	≈ −90	≈ 10	≈ −50	
PWB-09	23	47 (> 240)	20.6	5.6 (< 900)	3.2 (1100–1600)	
MFM-11	21–23	63.3 (> 150)				
$F_\lambda / F_{\mathrm{TSI}}$, %		7.7	38.7	22.7	28.8	2.0

Lea-97 *Lean et al.* [1997]
KSF-06 *Krivova et al.* [2006]
Hea-09 *Harder et al.* [2009]
PWB-09 *Pagaran et al.* [2009]
MFM-11 *Morrill et al.* [2011]

on whether the SORCE/TIM data are used as a measure for the TSI change or an integral over the SORCE/SIM data (corrected for the missing wavelengths).

The unusual behaviour displayed by the SORCE/SIM data can also be seen in Fig. 2.1. In this figure, the red line shows the data integrated over the entire SORCE/SIM spectral range (200–1630 nm) shifted to account for the missing wavelengths, the blue line shows the same quantity, but now provided by the SATIRE-S model [*Ball et al.*, 2011], and the red line represents the SORCE/TIM TSI measurements. In the bottom panel, all data are smoothed to emphasise the long-term trends. Whereas SATIRE-S results agree amazingly well with the TIM data, the long-term behaviour of the integrated SIM data is rather different. A comparison of the SATIRE-S with the SIM data in individual spectral bands reveals that most significant differences between the modelled and measured trends appear at the beginning of the considered period, i.e. before 2006–2007 [*Ball et al.*, 2011]. Since SATIRE-S also reproduces UV measurements by UARS/SUSIM between 1991 and 2002 [*Krivova and Solanki*, 2005; *Krivova et al.*, 2006, 2009b; *Ball et al.*, 2011; *Morrill et al.*, 2011] this implies that either the mechanism of SSI variation fundamentally changed around the peak of cycle 23 or there is an inconsistency between SUSIM and SIM measurements. Thus the origin of the very different trends measured by SIM needs to be further investigated.

We note that the estimate of the relative changes in different spectral ranges by *Pagaran et al.* [2009] based on SCIAMACHY measurements should be considered as a lower limit. The reason is that their normalisation to the TSI change is not self-consistent (the total change in the irradiance used for the normalisation is taken from the PMOD composite and is not estimated from SCIAMACHY data). As a result, the sum of the contributions of all the wavelength ranges they list is only 76 % of the TSI. The missing wavelengths (below 240 nm and above 1600 nm) are unlikely to contribute the remaining 24 % if other studies are to be believed (see Table 2.1 and *Krivova et al.*, 2006). We therefore believe that the real numbers should be roughly 20 % higher, i.e. the contribution of the 240–400 nm range to the TSI variation, as derived from SCIAMACHY data, is most probably lying around 60 %.

2.4 Telescope Era

Since high-quality full-disc magnetograms of the Sun are not available before the 1970s, reconstructions on longer time scales have to rely on disc-integrated quantities. To describe the evolution of sunspots, the records of their areas and numbers have widely been employed. Sunspot areas and positions have regularly been measured by the Royal Greenwich Observatory between 1874 and 1976. *Balmaceda et al.* [2009] have combined these data with more recent observations from a number of other observatories taking into account their systematic differences to provide a homogeneous record covering more than 130 years. The historic sunspot number record goes back to 1610. A long, reliable proxy of facular areas is not yet available. However their evolution is related to that of sunspots, since both are found in active regions. Hence, a given relationship of the magnetic flux emerging in plage to that in sunspots (such as that found by *Chapman et al.*, 1997) can be employed. The changes of the weak magnetic field on the solar surface, however, are not well represented by the sunspot proxies, which makes an estimate of the secular trend in the irradiance a particularly challenging task. It is this secular trend that is of particular interest for climate studies.

Most of the early reconstructions of TSI back to the Maunder minimum [e.g., *Lean et al.*, 1992; *Zhang et al.*, 1994] relied on indirect estimates of the secular change in irradiance derived from a comparison with other Sun-like stars. The basis for these estimates turned out to be flawed [e.g., *Hall and Lockwood*, 2004; *Wright*, 2004] and they have later been strongly criticised. A physical mechanism that produces a secular change in the irradiance has been identified by *Solanki et al.* [2000, 2002]. *Harvey* [1992] has shown that a significant amount of fresh flux in ephemeral active regions (smaller than normal active regions and spread over the whole solar surface) appears at the surface already during the decay phase of the previous cycle, so that consecutive cycles of ephemeral region emergence overlap. Significant background magnetic flux is thus present on the solar surface even at activity minima. This flux is actually comparable to the flux in active regions at activity maximum [*Harvey*, 1994; *Krivova and Solanki*, 2004]. Since the length and the strength of the solar cycle vary with time, so does the overlap between the ephemeral region flux from different activity cycles. This should lead to a secular change in the background field.

This idea underlies our reconstructions of the open and total solar magnetic flux back to the Maunder minimum [*Solanki et al.*, 2000, 2002; *Krivova et al.*, 2007;

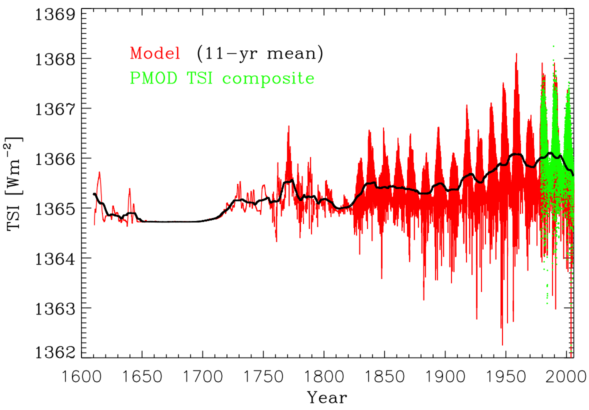

Fig. 2.4 Solar total irradiance since 1610 reconstructed using the SATIRE-T model (*red line*). Also shown are the 11-yr smoothed TSI (*thick black line*) and PMOD composite of measurements since 1978 (*green*). From *Krivova et al.* [2010]

Vieira and Solanki, 2010] from the sunspot number. The total flux agrees well with observations available for the last 4 cycles, while the open flux closely follows the empirical reconstruction by *Lockwood et al.* [2009]. Moreover, if the modelled open flux is used to calculate ^{44}Ti activity following *Usoskin et al.* [2006b], the latter agrees well with ^{44}Ti activity measured in stony meteorites [*Vieira et al.*, 2011].

Using the modelled solar surface magnetic flux as input to SATIRE-T (see Sect. 2.2), *Balmaceda et al.* [2007] and *Krivova et al.* [2007, 2010] have reconstructed solar total and spectral irradiance since the Maunder minimum. The reconstructed TSI is shown in Fig. 2.4. We find that between the end of the Maunder minimum and the end of the 20th century, the cycle-averaged TSI has increased by 1.25 W/m^2 or about 0.9 %. *Krivova et al.* [2007] have estimated the possible range of the secular increase as 0.9–1.5 W/m^2. This range is consistent with most other recent estimates derived under various assumptions [*Foster*, 2004; *Wang et al.*, 2005; *Crouch et al.*, 2008; *Steinhilber et al.*, 2009], although two different, fairly controversial estimates have recently been published by *Schrijver et al.* [2011] and *Shapiro et al.* [2011]. This is because they considered rather extreme assumptions about the solar activity state during the Maunder minimum. *Schrijver et al.* [2011] assumed that the minimum solar activity state, similar to that reached during the Maunder minimum, was globally approached during the last minimum in 2008, which suggests a decrease of only about 0.014–0.036 % compared to the minimum in 1996. *Shapiro et al.* [2011], in contrast, assumed that during the Maunder minimum the entire solar surface had the intensity that is currently observed only in the darkest parts of supergranule cells, which results in a value of 0.4 % (6 ± 3 W/m^2) for the TSI change between the Maunder minimum and the present. Therefore these two extreme estimates may be considered as lower and upper limits.

Figures 2.5 and 2.6 show solar irradiance in Ly-α and several other spectral intervals of special interest for climate models reconstructed by *Krivova et al.* [2010]. Interestingly, the irradiance variation in the IR, between 1500 and 2500 nm, is reversed compared to other spectral ranges, as also seen in SORCE/SIM data [*Harder et al.*, 2009], which, however, also displays such a reversed behaviour in the visible.

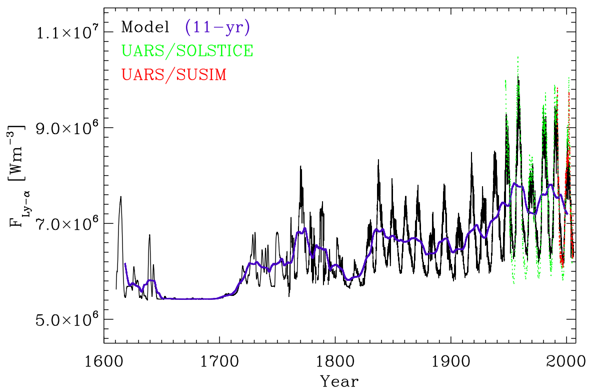

Fig. 2.5 Solar irradiance in Ly-α reconstructed using the SATIRE-T model (*black solid line*). Also shown are the 11-yr smoothed Ly-α irradiance (*dark blue*), measurements by the UARS/SUSIM instrument (*red*) as well as the composite (*green*) of UARS/SOLSTICE measurements and proxy models by *Woods et al.* [2000]

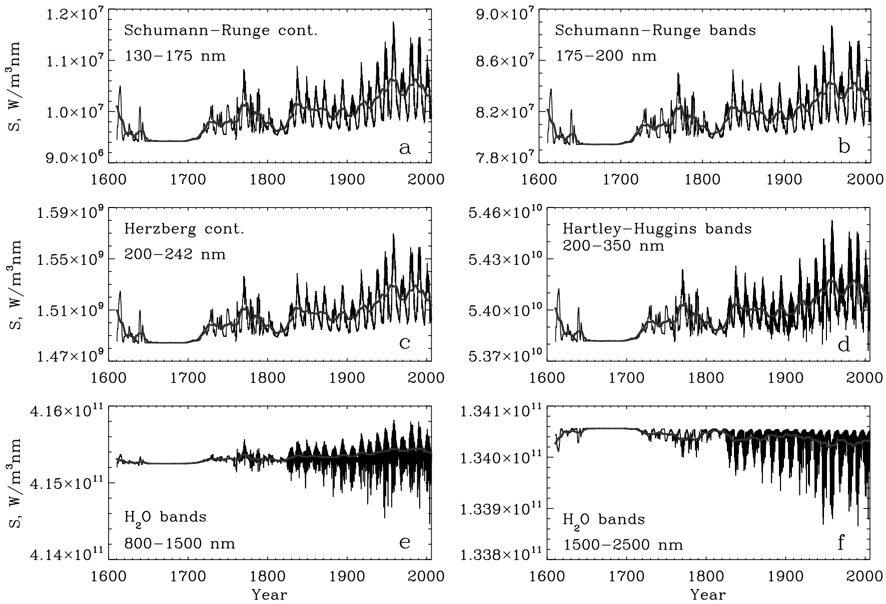

Fig. 2.6 Reconstructed solar irradiance in selected spectral intervals of special interest for climate models: daily (*thin lines*) and smoothed over 11 years (*thick lines*). (**a**) Shumann-Runge oxygen continuum; (**b**) Schumann-Runge oxygen bands; (**c**) Herzberg oxygen continuum; (**d**) Hartley-Huggins ozone bands; (**e**) and (**f**) water vapour infrared bands. The exact wavelength ranges are indicated in each panel. From *Krivova et al.* [2010]

Potentially, information on the magnitude of the secular change in irradiance can be provided by full-disc solar images in the Ca II line. A number of observatories around the globe carried out such observations since the beginning of the 20th century, and some of these archives have recently been digitised. Unfortunately, these images suffer from numerous problems and artefacts (e.g., plate defects and aging, geometrical distortions, degradation and changes of the instrumentation etc.), some of which, such as photometric uncertainties, are difficult to correct [*Ermolli et al.*, 2009]. Thus more work is needed before the Ca II archives can be employed for reliable irradiance reconstructions, although their potential remains very large. A simultaneous analysis of different archives would be advantageous.

2.5 Pretelescopic Era

The sunspot number record goes back to 1610. Information on the solar magnetic activity prior to 1610 is provided by concentrations of cosmogenic isotopes, such as ^{14}C or ^{10}Be, in natural archives. These can be used to calculate the Sun's open and total magnetic flux and the sunspot number [*Solanki et al.*, 2004; *Usoskin et al.*, 2006a; *Steinhilber et al.*, 2009; *Vieira and Solanki*, 2010].

The main complication for the irradiance reconstructions is that only cycle-averaged values can be derived. Thus the SATIRE-T model cannot be applied directly. *Vieira and Solanki* [2010] and *Vieira et al.* [2011] have reconstructed the evolution of the decadally averaged magnetic flux from decadal values of ^{14}C concentrations employing a series of physics-based models connecting the processes from the modulation of the cosmic ray flux in the heliosphere to the isotope records in natural archives. They have also found that the variation in the TSI is produced by contributions of the magnetic flux from two cycles. This result suggests that reconstructions of TSI based on linear relationships between the open flux and TSI [e.g., *Steinhilber et al.*, 2009] are not justified physically, although the practical consequences are expected to be significant mainly for time scales shorter than 40–50 years. *Vieira et al.* [2011] thus compute the TSI (Fig. 2.7) as a linear combination of two consecutive decadal values of the open magnetic flux and employ different paleomagnetic models to evaluate the uncertainties.

Note that the TSI reconstructed in this way shows a stronger increase since the Maunder minimum than the reconstruction by *Steinhilber et al.* [2009] from the ^{10}Be data. This is expected to be largely due to the difference in the methods employed by the two groups, although differences in the input data, ^{10}Be vs. ^{14}C, may also contribute. In particular, the linear relationship between the TSI and the open flux employed by *Steinhilber et al.* [2009] is based on the measurements for the last 3 minima only [*Fröhlich*, 2009]. Of these, the levels of the last two in the TSI are rather uncertain (see Sect. 2.3.1).

2.6 Summary

The SATIRE models have been used to reconstruct solar total and spectral irradiance on time scales ranging from a day up to millennia from different available proxies of solar magnetic activity. Most accurate are reconstructions from the full-disc magnetograms and continuum images (SATIRE-S) covering the period after 1974. Reconstructions from the sunspot number (SATIRE-T) go back to 1610, while the

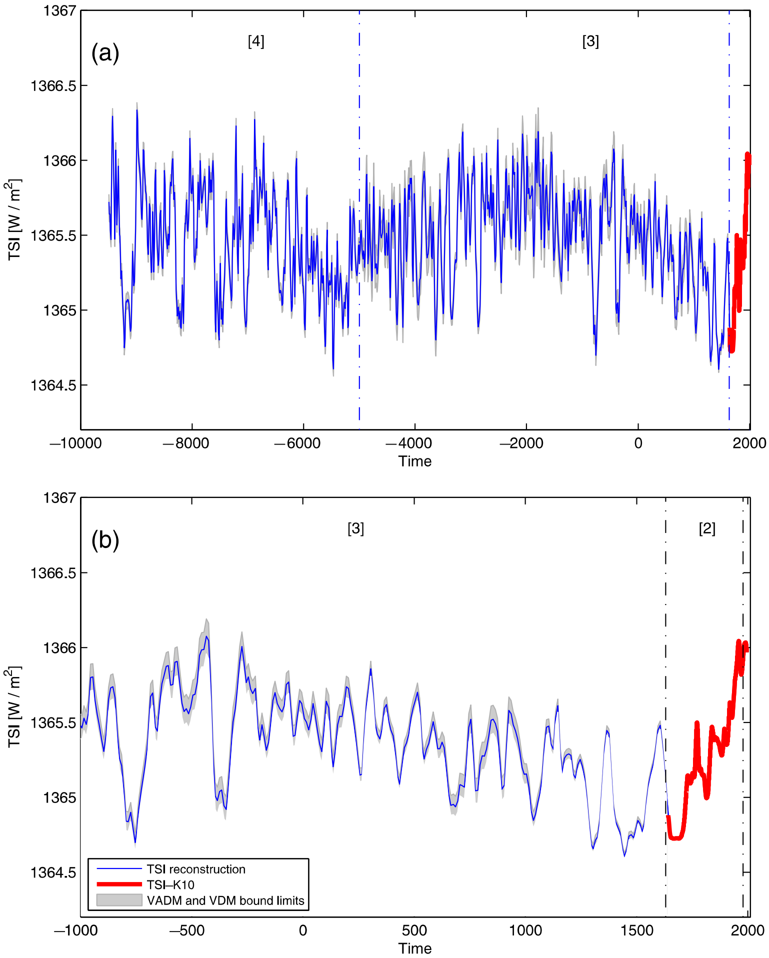

Fig. 2.7 (**a**) TSI reconstruction since 9500 BC from the SATIRE-M (*blue*) and SATIRE-T (*red*) models. (**b**) Enlargement of panel a for the last 3000 years. From *Vieira et al.* [2011]

SATIRE-M version, relying on the cosmogenic isotope concentrations, has provided TSI over the whole Holocene. The following data sets produced in the framework of the CAWSES/SOLIVAR project described here are available from the MPS Sun-Climate web page http://www.mps.mpg.de/projects/sun-climate/data.html:

- the solar spectral UV irradiance at 115–400 nm between 1 Jan 1974 and 31 Dec 2007 reconstructed from magnetograms [*Krivova et al.*, 2006, 2009b];
- TSI and SSI since 1610 reconstructed from the sunspot number [*Balmaceda et al.*, 2007; *Krivova et al.*, 2007, 2010];
- TSI for the Holocene reconstructed from the ^{14}C data [*Vieira et al.*, 2011];
- the composite of daily sunspot areas and the PSI index calculated after cross-calibration of measurements by different observatories [*Balmaceda et al.*, 2009].

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