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Reconstruction of solar UV irradiance since 1974

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[1] Variations of the solar UV irradiance are an important driver of chemical and physical processes in the Earth's upper atmosphere and may also influence global climate. Here we reconstruct solar UV irradiance in the range 115–400 nm over the period 1974–2007 by making use of the recently developed empirical extension of the Spectral And Total Irradiance Reconstruction (SATIRE) models employing Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) data. The evolution of the solar photospheric magnetic flux, which is a central input to the model, is described by the magnetograms and continuum images recorded at the Kitt Peak National Solar Observatory between 1974 and 2003 and by the Michelson Doppler Imager instrument on SOHO since 1996. The reconstruction extends the available observational record by 1.5 solar cycles. The reconstructed Ly-α irradiance agrees well with the composite time series by Woods et al. (2000). The amplitude of the irradiance variations grows with decreasing wavelength and in the wavelength regions of special interest for studies of the Earth's climate (Ly-α and oxygen absorption continuum and bands between 130 and 350 nm) is 1–2 orders of magnitude stronger than in the visible or if integrated over all wavelengths (total solar irradiance).

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1. Introduction

[2] Solar irradiance variations show a strong wavelength dependence. Whereas the total (integrated over all wavelengths) solar irradiance (TSI) changes by about 0.1% over the course of the solar cycle, the irradiance in the UV part of the solar spectrum varies by up to 10% in the 150–300 nm range and by more than 50% at shorter wavelengths, including the Ly-α emission line near 121.6 nm [e.g., *Floyd et al.*, 2003a]. On the whole, more than 60% of the TSI variations over the solar cycle are produced at wavelengths below 400 nm [*Krivova et al.*, 2006; cf. *Harder et al.*, 2009].

[3] These variations may have a significant impact on the Earth's climate system. Ly-α, the strongest line in the solar UV spectrum, which is formed in the transition region and the chromosphere, takes an active part in governing the chemistry of the Earth's upper stratosphere and mesosphere, for example, by ionizing nitric oxide, which affects the electron density distribution, or by stimulating dissociation of water vapor and producing chemically active HO(x) that destroy ozone [e.g., *Frederick*, 1977; *Brasseur and Simon*, 1981; *Huang and Brasseur*, 1993; *Fleming et al.*, 1995; *Egorova et al.*, 2004; *Langematz et al.*, 2005a]. Also, radiation in the Herzberg oxygen continuum (200–240 nm) and the Schumann-Runge bands of oxygen (180–200 nm) is important for photochemical ozone production [e.g., *Haigh*, 1994, 2007, accessed March 2009; *Egorova et al.*, 2004; *Langematz et al.*, 2005b; *Rozanov et al.*, 2006; *Austin et al.*, 2008]. UV radiation in the wavelength range 200–350 nm, i.e., around the Herzberg oxygen continuum and the Hartley-Huggins ozone bands, is the main heat source in the stratosphere and mesosphere [*Haigh*, 1999, 2007; *Rozanov et al.*, 2004, 2006].

[4] The record of regular measurements of the solar UV irradiance spectrum, accurate enough to assess its variations, goes back to 1991, when the Upper Atmosphere Research Satellite (UARS) was launched. Among others, it carried two instruments for monitoring solar radiation in the UV, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) [*Brueckner et al.*, 1993] and the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) [*Rottman et al.*, 1993]. These data sets are of inestimable value, but remain too short to allow reliable evaluation of solar influence on the Earth's climate and need to be extended back in time with the help of models.

[5] Reconstructions of solar UV irradiance have earlier been presented by *Fligge and Solanki* [2000] and by *Lean* [2000]. The first one was based on LTE (Local Thermodynamic Equilibrium) calculations of the solar spectrum and the latter on UARS/SOLSTICE measurements. The LTE approximation gives inaccurate results below approximately 200 nm and in some spectral lines, whereas the long-term uncertainty of SOLSTICE (as well as of all other instruments that measured solar UV irradiance before SORCE) exceeded the solar cycle variation above approximately 250 nm, thus leading to incorrect estimates of the UV

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irradiance variability at longer wavelengths [see *Lean et al.*, 2005; *Krivova et al.*, 2006].

[6] Whereas considerable advance has recently been made in modeling the variations of the total solar irradiance and the irradiance at wavelengths longer than about 300 nm [e.g., *Unruh et al.*, 1999; *Ermolli et al.*, 2003; *Krivova et al.*, 2003; *Wenzler et al.*, 2004, 2005, 2006], models at shorter wavelengths have not kept apace. This is because the LTE approximation usually taken in calculations of the brightness of different photospheric components fails in this wavelength range and non-LTE calculations are much more arduous [e.g., *Fontenla et al.*, 1999, 2006; *Haberreiter et al.*, 2005].

[7] An alternative approach has been developed by *Krivova and Solanki* [2005a] and *Krivova et al.* [2006] that allows an empirical extrapolation of the successful Spectral and Total Irradiance Reconstruction (SATIRE) models [*Krivova and Solanki*, 2005b; *Solanki et al.*, 2005] down to 115 nm using available SUSIM measurements. *Krivova et al.* [2006] have combined this technique with the model of *Krivova et al.* [2003] to reconstruct the variations of the solar UV irradiance over the period 1996–2002, i.e., the rising phase of cycle 23, using MDI (Michelson Doppler Imager on SOHO) [*Scherrer et al.*, 1995] magnetograms and continuum images. Here we employ the data from the National Solar Observatory Kitt Peak (NSO KP), in order to reconstruct the solar UV irradiance spectrum back to 1974. We then combine this KP-based reconstruction for the period 1974–2002 with the reconstruction based on MDI data [*Krivova et al.*, 2006], which has now been extended to 2006. In order to fill in the gaps in daily data and to extend the time series to 2007, when MDI continuum images displayed deteriorating quality, we employ the Mg II core-to-wing ratio and the solar F10.7 cm radio flux. Hence the present paper extends the work of *Krivova et al.* [2006] to three cycles, i.e., the whole period of time over which high-quality magnetograms are available.

[8] The model is described in section 2, the results are presented in section 3 and summarized in section 4.

2. Model

[9] We take a similar approach as *Krivova et al.* [2006]. This means that variations of the solar total and spectral irradiance on time scales of days to decades are assumed to be entirely due to the evolution of the solar surface magnetic field. Under this assumption, *Krivova et al.* [2003] and *Wenzler et al.* [2005, 2006] have successfully modeled the observed variations of the total solar irradiance. *Krivova et al.* [2006] showed that this (SATIRE) model also works well in the spectral range 220–240 nm (hereinafter, the reference range). They then analyzed SUSIM data and worked out empirical relationships between the irradiance in this range and irradiances at all other wavelengths covered by the SUSIM detectors (115–410 nm). Thus if the irradiance in the range 220–240 nm is known, it is also possible to calculate irradiance at other wavelengths in the UV down to 115 nm.

2.1. Solar Irradiance at 220–240 nm

[10] In a first step, we apply the SATIRE model [*Solanki et al.*, 2005; *Krivova and Solanki*, 2008] to NSO KP magnetograms and continuum images, in order to reconstruct solar irradiance in the reference range for the period 1974–2003. In SATIRE, the solar photosphere is divided into four components: the quiet Sun, sunspot umbrae, sunspot penumbrae and bright magnetic features (describing both faculae and the network). Each component is described by the time-independent spectrum calculated from the corresponding model atmospheres in the LTE approximation [*Unruh et al.*, 1999]. Since the distribution of the magnetic field on the solar surface evolves continuously, the area covered by each of the components on the visible solar disc also changes. This is represented by the corresponding filling factors, which are retrieved from the magnetograms and continuum images. In the period 1974–2003, such data were recorded (nearly daily) with the 512-channel Diode Array Magnetograph (before 1992) [*Livingston et al.*, 1976] and the Spectromagnetograph (after 1992) [*Jones et al.*, 1992] on Kitt Peak [see also *Wenzler et al.*, 2006]. Since 1996 magnetograms and continuum images were also recorded by the MDI instrument on SOHO. More details about the SATIRE model have been given by *Fligge et al.* [2000], *Krivova et al.* [2003], and *Wenzler et al.* [2005, 2006].

[11] This model has one free parameter, B_{sat}, denoting the field strength below which the facular contrast is proportional to the magnetogram signal, while it is independent (saturated) above that. It depends on the quality (noise level and spatial resolution) of the employed magnetograms. From a comparison with the PMOD composite [*Fröhlich*, 2006] of the TSI measurements, *Wenzler et al.* [2006, 2009] found the value of B_{sat} = 320 G for the KP data, whereas *Krivova et al.* [2003] obtained a value of B_{sat} = 280 G for the MDI data. In this work we use the same values of this parameter and do not vary them any more in order to fit the spectral data.

[12] The solar irradiance integrated over the wavelength range 220–240 nm reconstructed from the KP magnetograms and continuum images is shown in Figure 1 by the red pluses connected by the dashed line where there are no gaps in the daily sequence of data. The measurements by the SUSIM instrument are represented by the green line. We use daily level 3BS V22 data with a sampling of 1 nm [*Floyd et al.*, 2003b; L. Floyd, personal communication, 2007]. A similar plot obtained with MDI data was given by *Krivova et al.* [2006]. The apparent change in the behavior between cycles 22 and 23 seen in Figure 1a is due to the incorrect estimate of the degradation during the solar minimum period (L. Floyd, personal communication, 2007). This is, for example, confirmed by a comparison with the Mg II core-to-wing ratio, which is free of such problems, and is discussed in more detail by *Krivova et al.* [2006]. The fact that a single shift in absolute values applied to the SUSIM data before 1996 is sufficient in order to bring the data in agreement with the model also supports this conjecture. Indeed, in Figure 1b the period before 1996 is shown on an enlarged scale. Here the measurements by SUSIM were shifted in the absolute level by a fixed value (-5.0×10^6 W m^{-3} nm), and a good correspondence between the model and the data is seen.

[13] This is also demonstrated by Figure 2, where the measured irradiance at 220–240 nm is plotted against the modeled values. Dots and pluses are used for the data from

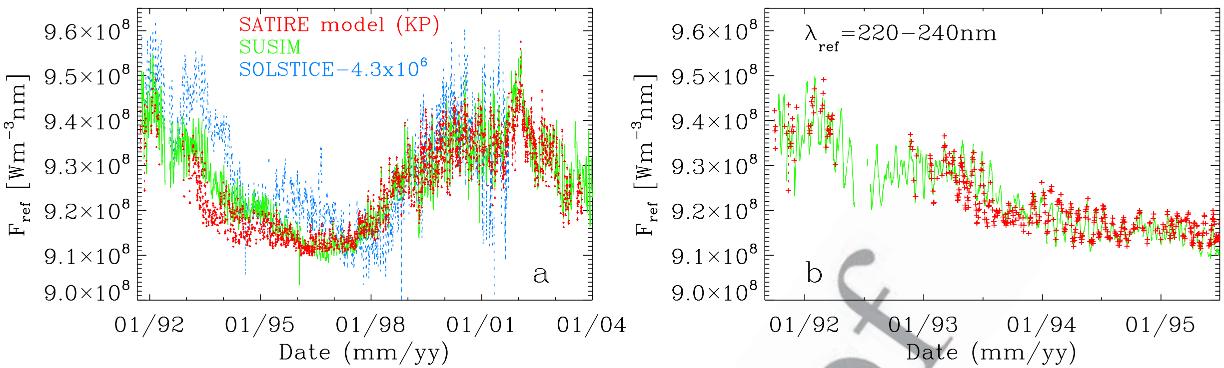

Figure 1. (a) Solar irradiance integrated over the wavelength range 220–240 nm as a function of time for the period 1991–2003. The green line shows SUSIM measurements [*Floyd et al.*, 2003b], and the red pluses (connected by the dashed line where there are no gaps) show the values reconstructed using SATIRE models and KP magnetograms. SOLSTICE data [*Woods et al.*, 1996] shifted by -4.3×10^6 W m^{-3} nm are shown by the blue dashed line. (b) Enlargement of Figure 1a restricted to the period before 1996 showing only SUSIM data and the reconstruction. Here SUSIM data were shifted by -5.0×10^6 W m^{-3} nm.

cycles 22 and 23, respectively (no correction to the absolute level has been applied). The dashed straight line with a slope of 0.95 represents the regression to all points. The correlation coefficient is 0.93. The solid line with a slope of 1.02 is the regression to the cycle 23 data only. It is hardly distinguishable from the thick dotted line with a slope of 1.0 expected for a perfect fit. The corresponding correlation coefficient is 0.94, i.e., the same as found by *Wenzler et al.* [2006] for the modeled TSI compared to the PMOD composite for the period since 1992. We stress that the value of the free parameter, B_{sat}, was the same in both cases. This means that SATIRE reproduces independent SUSIM data without any further adjustments, which is yet another success of the model.

[14] In Figure 1a, we also plot SOLSTICE data [*Woods et al.*, 1996] represented by the blue dashed line. Note that for comparison sake the SOLSTICE absolute values have been shifted by -4.3×10^6 W m^{-3} nm. It is clear that at 220–240 nm the model is in a better agreement with the SUSIM data, even if the correction due to the degradation is not taken into account, than with the measurements by SOLSTICE, which also show a higher scatter.

[15] Solar irradiance in the reference range for the period 1996–2002 was also reconstructed by *Krivova et al.* [2006, Figure 2] using MDI magnetograms and continuum images. We have updated their model through the beginning of 2006 and combined it with the KP-based reconstruction shown in Figure 1. On the days when both models are available, the preference was given to the MDI-based values, since they were found to be more accurate [cf. *Krivova et al.*, 2003; *Wenzler et al.*, 2004, 2006].

[16] Unfortunately, the flat field distortion progressively affecting MDI continuum images requires a correction of all images recorded after approximately 2005 before they can

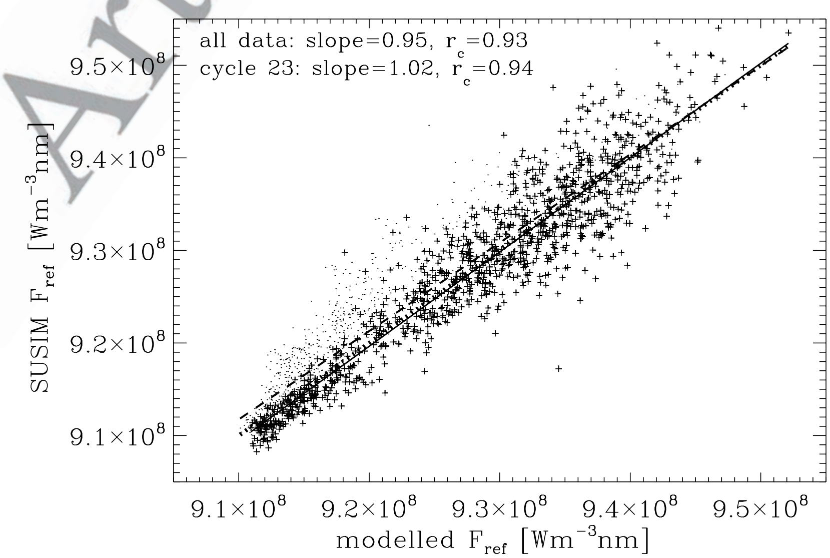

Figure 2. Solar irradiance in the range 220–240 nm as measured by SUSIM versus reconstructed by SATIRE. Dots and pluses are used for cycles 22 and 23, respectively. The dashed straight line is the regression to all points (with no correction applied to SUSIM's absolute level). The solid line is the regression for cycle 23 only. The thick dotted line almost coinciding with the solid line shows the expectation value, i.e., a slope of 1.0 and no offset. Correlation coefficients and slopes are indicated.

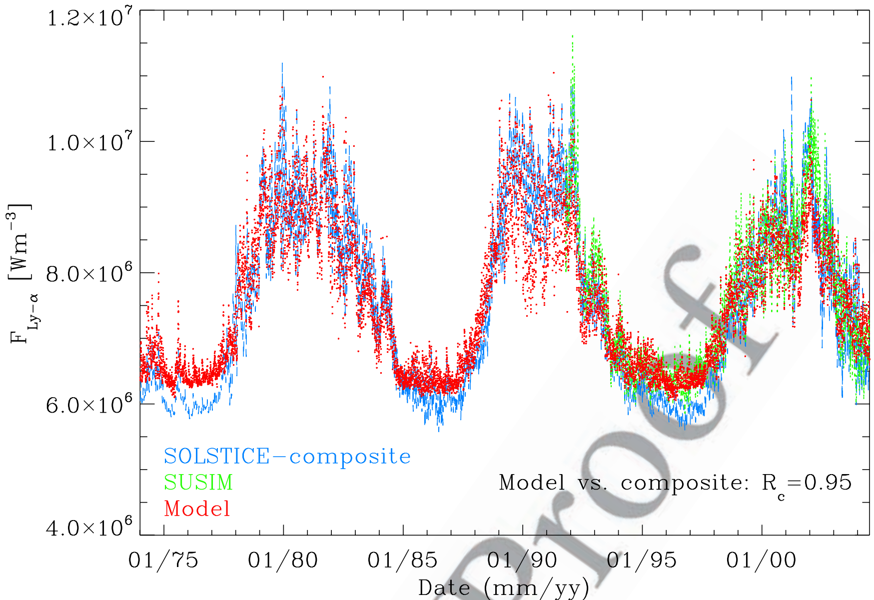

Figure 3. Solar Ly-α irradiance since 1974 reconstructed by SATIRE (red), measured by the SUSIM instrument (green), and compiled by *Woods et al.* [2000] (blue).

be employed for the irradiance reconstructions. Such a correction is being attempted, but the outcome is not certain and it seems advisable to complete the reconstruction instead of waiting an unknown length of time.

[17] There are also some gaps in the daily reconstructions, when no magnetograms and continuum images were recorded, in particular, in the 1970s. On the other hand, climate models often require solar signal input with a daily cadence. Therefore, we have employed the Mg II core-to-wing ratio [*Viereck et al.*, 2004] and the solar F10.7 cm radio flux [*Tanaka et al.*, 1973] in order to fill in the gaps and to extend the data to 2007. This has been done by using a linear regression between the irradiance in the reference range (220–240 nm) and the Mg II index (the linear correlation coefficient is R_c = 0.98) and a quadratic relationship between the irradiance in the reference range and the F10.7 flux (R_c = 0.92). Mg II and F10.7 cm flux data are obtained from the National Geophysical Data Center (NGDC; http://www.ngdc.noaa.gov/ngdc.html).

2.2. UV Spectral Irradiance

[18] In order to extrapolate the SATIRE model based on KP NSO and MDI magnetograms and continuum images to other UV wavelengths, we made use of the relations between irradiances, F_λ, at a given wavelength, λ, and in the reference interval, $F_{\rm ref}$ (220–240 nm). These relationships in the range 115–410 nm were deduced by *Krivova et al.* [2006] using daily SUSIM data recorded between 1996 and 2002. We have repeated this analysis with the data set extended to 2005, but did not find any significant difference to the earlier derived values and therefore employed the relationships from the previous work for consistency.

[19] Using the calculated irradiances at 220–240 nm and empirical relationships $F_\lambda/F_{\rm ref}$ versus $F_{\rm ref}$, solar UV irradiance at 115–270 nm was reconstructed for the whole period 1974–2007. Since the long-term uncertainty of SUSIM measurements becomes comparable to or higher than the solar cycle variation at around 250 and 300 nm, respectively [*Woods et al.*, 1996; *Floyd et al.*, 2003b], above 270 nm SATIRE is found to be more accurate than the measurements [*Krivova et al.*, 2006; cf. *Unruh et al.*, 2008], Therefore spectral irradiance values at these wavelengths are calculated directly from SATIRE.

3. Results

3.1. Ly-α Irradiance

[20] The Ly-α line is of particular interest not just for its prominence in the solar spectrum and its importance for the Earth's upper atmosphere, but also because for this line a composite of measurements is available for the whole period considered here. In Figure 3 we compare the reconstructed solar Ly-α irradiance (red) with the composite time series (blue) compiled by *Woods et al.* [2000]. The latter record comprises the measurements from the Atmospheric Explorer E (AE-E, 1977–1980), the Solar Mesosphere Explorer (SME, 1981–1989), UARS SOLSTICE (1991–2001), and the Solar EUV Experiment (SEE) on TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamic Mission launched in 2001). The gaps are filled in using proxy models based on Mg core-to-wing and F10.7 indices, and the F10.7 model is also used to extrapolate the data set back in time. The UARS SOLSTICE data are used as the reference, and other measurements and the models are adjusted to the SOLSTICE absolute values. Although this time series is thus only partly based on direct Ly-α observations, it is the nearest we found to an observational time series to compare our model with.

[21] For comparison, the SUSIM measurements are also plotted in Figure 3 (green). The model agrees well with the SUSIM data, which confirms that our semiempirical technique works well. Note that there is no change in the behavior around the minimum in 1996. This is yet another indication of the instrumental origin of the jump in the

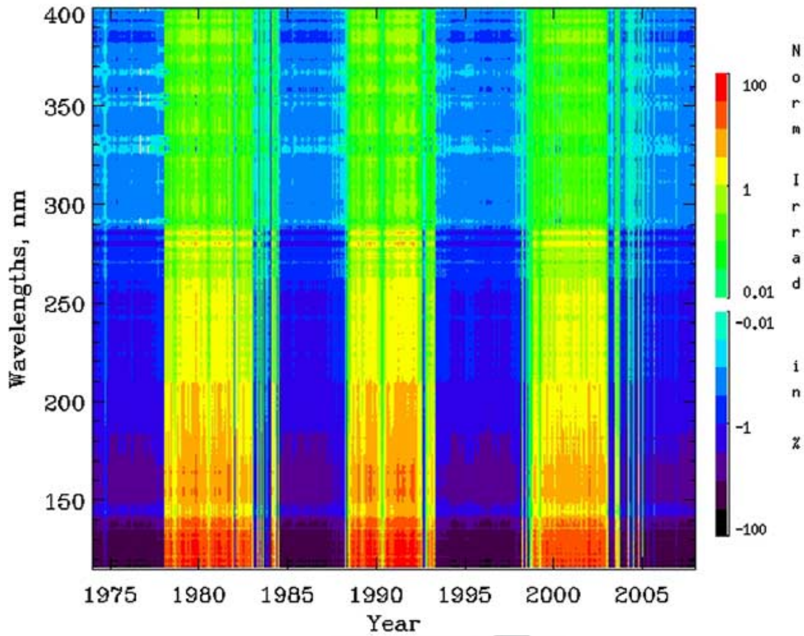

Figure 4. Reconstructed solar UV irradiance at 115–400 nm in the period 1974–2007 normalized to the mean at each wavelength over the whole period of time.

absolute values seen in SUSIM's irradiances at 220–240 and many other wavelengths [see *Krivova et al.*, 2006].

[22] As Figure 3 shows, there is some difference (about 5%) in the magnitude of the Ly-α solar cycle variations between SOLSTICE and SUSIM. Since our model agrees with SUSIM (by construction), a difference of this magnitude remains also between our model and SOLSTICE. Other than that, the model agrees with the completely independent composite time series very well, with a correlation coefficient of 0.95 (remember that the free parameter of the SATIRE model was fixed from a comparison with the PMOD composite of the TSI and not varied to fit the UV data).

[23] The solar Ly-α irradiance has also been modeled by *Haberreiter et al.* [2005] using the filling factors derived from the MDI and KP NSO magnetograms and continuum images in combination with the brightness spectra for the quiet Sun, sunspots and faculae calculated with their NLTE code COSI. The calculated variability was about a factor of 2 lower than the measured one. NLTE calculation are, in principal, better suitable for calculations of the solar UV irradiance and they have recently made significant progress [e.g., *Fontenla et al.*, 2006, 2007; *Haberreiter et al.*, 2008]. Their complexity and the number of processes to be accounted for do not, however, as yet allow an accurate reconstruction of the solar spectral irradiance over broader spectral ranges and longer periods of time.

3.2. Solar UV Irradiance at 115–400 nm in 1974–2007

[24] Figure 4 shows the reconstructed solar UV irradiance in the range 115–400 nm over the period 1974–2007 (i.e., covering cycles 21–23), normalized to the mean at each wavelengths over the complete time period. At all considered wavelengths, the irradiance changes in phase with the solar cycle, in agreement with recent results based on 4 years of SIM/SORCE measurements [*Harder et al.*, 2009]. The variability becomes significantly stronger toward shorter wavelengths: from about 1% over the activity cycle at around 300 nm to more than 100% in the vicinity of Ly-α.

[25] Figure 5 shows the solar UV irradiance integrated over spectral ranges of particular interest for climate studies as a function of time: 130–175 nm (Figure 5a), 175–200 nm (Figure 5b), 200–242 nm (Figure 5c), and 200–350 nm (Figure 5d). Solar radiation at 130–175 nm (Schumann-Runge continuum) is completely absorbed in the thermosphere. Over activity cycles 21–23, solar radiative flux in this spectral range varied by about 10–15% (Figure 5a), i.e., by more than a factor of 100 more than solar cycle variations in the solar total energy flux (total solar irradiance). In the oxygen Schumann-Runge bands (175–200 nm) and Herzberg continuum (200–242 nm), important for photochemical ozone production and destruction in the stratosphere and mesosphere, solar irradiance varied on average by about 5–8% (Figure 5b) and 3% (Figure 5c), respectively. In the Hartley-Huggins ozone bands between 200 and 350 nm, solar radiation is the main heat source in the stratosphere. At these wavelengths, the amplitude of the solar cycle variation is of the order of 1%, which is still an order of magnitude stronger than variations of the total solar irradiance.

[26] The complete data set of the reconstructed solar irradiance at 115–400 nm over the period 1974–2007 is available as auxiliary material and at http://www.mps.mpg.de/projects/sun-climate/data.html.[1]

4. Summary

[27] *Krivova et al.* [2006] have developed an empirical technique, which allows an extrapolation of the magnetogram-based reconstructions of solar total and spectral

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/jd/2009jd012375.

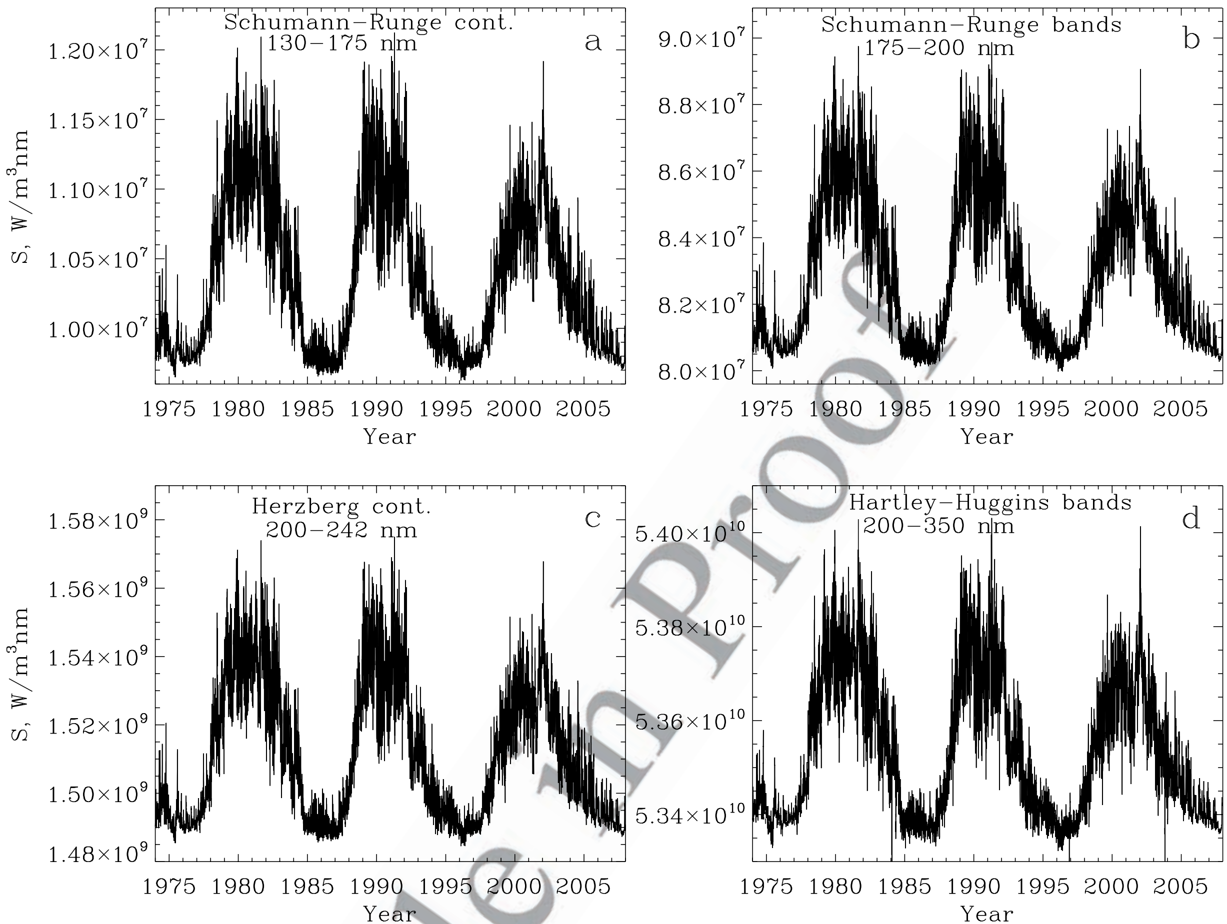

Figure 5. Reconstructed solar irradiance in the period 1974–2007 integrated over the wavelength ranges (a) 130–175 nm (Schumann-Runge continuum), (b) 175–200 nm (Schumann-Runge bands), (c) 200–242 nm (Herzberg continuum), and (d) 200–350 nm (Hartley-Huggins bands).

irradiance to shorter wavelengths, down to 115 nm. They applied this technique to obtain variations of solar UV irradiance between 1996 and 2002. We have now extended their model to both earlier and more recent times. Thus we provide a reconstruction of the solar UV irradiance spectrum between 115 and 400 nm over the period 1974–2007. This extends the available observational record by about 1.5 solar cycles, i.e., roughly doubles the available record.

[28] As a test of the quality of our model, we have compared the reconstructed solar Ly-α irradiance with the completely independent composite of measurements and proxy models by *Woods et al.* [2000]. There is a small (about 5%) difference in the solar cycle amplitude between our model and that composite. This difference is also present between the SUSIM and SOLSTICE data, which are the reference sets for the model and the composite, respectively. Aside from that, the modeled and composite records closely agree with each other.

[29] Solar UV irradiance varies in phase with the solar cycle at all wavelengths between 115 and 400 nm, in agreement with the recent finding of *Harder et al.* [2009] based on SIM/SORCE measurements over 2004–2007. The relative amplitude of the variations grows with decreasing wavelength. In the wavelength regions important for studies of the Earth's climate (e.g., Ly-α and oxygen absorption continuum and bands between 130 and 350 nm), the relative variation is 1–2 orders of magnitude stronger than in the visible or if integrated over all wavelengths (i.e., TSI).

[30] SATIRE-based reconstructed UV irradiance in the spectral range 115–400 nm between 1 January 1974 and 31 December 2007 is available as auxiliary material and at http://www.mps.mpg.de/projects/sun-climate/data.html.

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