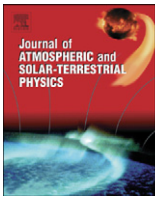
Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 235–240

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp



Changed relation between sunspot numbers, solar UV/EUV radiation and TSI during the declining phase of solar cycle 23

R. Lukianova [a,1], K. Mursula [b,*]

[a] Arctic and Antarctic Research Institute, St. Petersburg, Russia
[b] University of Oulu, Oulu, Finland

ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form
1 April 2010
Accepted 6 April 2010
Available online 11 April 2010

Keywords:
Solar cycle
Sunspot numbers
UV radiation
Ionospheric ionization

ABSTRACT

We study the mutual relation of sunspot numbers and several proxies of solar UV/EUV radiation, such as the F10.7 radio flux, the HeI 1083 nm equivalent width and the solar MgII core-to-wing ratio. It has been noted earlier that the relation between these solar activity parameters changed in 2001/2002, during a large enhancement of solar activity in the early declining phase of solar cycle 23. This enhancement (the secondary peak after the Gnevyshev gap) forms the maximum of solar UV/EUV parameters during solar cycle 23. We note that the changed mutual relation between sunspot numbers and UV/EUV proxies continues systematically during the whole declining phase of solar cycle 23, with the UV/EUV proxies attaining relatively larger values for the same sunspot number than during the several decennia prior to this time. We have also verified this evolution using the indirect solar UV/EUV proxy given by a globally averaged f_0(F2) frequency of the ionospheric F2 layer. We also note of a simultaneous, systematic change in the relation between the sunspot numbers and the total solar irradiance, which follow an exceptionally steep relation leading to a new minimum. Our results suggest that the reduction of sunspot magnetic fields (probably photospheric fields in general), started quite abruptly in 2001/2002. While these changes do not similarly affect the chromospheric UV/EUV emissions, the TSI suffers an even more dramatic reduction, which cannot be understood in terms of the photospheric field reduction only. However, the changes in TSI are seen to be simultaneous to those in sunspots, so most likely being due to the same ultimate cause.

1. Introduction

Modern observations of the Sun cover a large range of methods and produce a versatile set of parameters measuring different aspects of solar activity. Over longer time scales, solar activity has usually been studied by sunspots and the related sunspot numbers (SSN) that are available since four centuries. Sunspots are known to vary according to the roughly 11-year cycle (Schwabe, 1844) and most solar parameters also follow this cycle. Accordingly, in years when more sunspots are seen, i.e., when the Sun is more active, it emits more radiation in most spectral ranges. For example, the solar radio flux at 2800 MHz (10.7 cm wavelength, thus known as F10.7 index; Tapping, 1987) is closely correlated with SSN. The daily values of F10.7 have been measured by ground observatories since 1947. Similarly, the direct monitoring of total solar irradiance (TSI) made by continuous satellite experiments since 1978 have shown that total irradiance emitted by the Sun varies with the sunspot cycle. However, the two leading TSI composites, the PMOD (Fröhlich and Lean, 1998; Fröhlich, 2006), and the ACRIM (Willson, 1997; Scafetta and Willson, 2009) composites, differ in their detailed evolution since 1990 (see Section 4).

Overall, the various solar activity parameters correlate quite well with sunspot numbers and with each other, especially at long sampling times and over long time scales. Moreover, the mutual relations are also found to stay fairly stable in time. However, it was found some time ago (Floyd et al., 2005) that the mutual relation between sunspot numbers and three solar UV/EUV indices, the F10.7 flux, the MgII core-to-wing ratio (Viereck et al., 2001, 2004), which is an index of chromospheric UV irradiance near 280 nm (Heath and Schlesinger, 1986), and the HeI 1083 equivalent width (Donnelly et al., 1985), remained stable for roughly 25 years until the year 2000, but dramatically changed thereafter at the end of 2001. This change coincided with a large enhancement of solar activity in SC 23, which took place after the actual sunspot maximum of SC 23 and the subsequent intermediate relative quietness called the Gnevyshev gap (Gnevyshev, 1963, 1977; Storini et al., 2003). Floyd et al. (2005) noted that while the magnitude of the first maximum was larger

---

[*] Corresponding author. Tel.: +358 8 5531366; fax: +358 8 5531287.
E-mail address: kalevi.mursula@oulu.fi (K. Mursula).
[1] Also at Space Research Institute, Moscow.

1364-6826/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2010.04.002

according to sunspot numbers, the second maximum was significantly higher according to all three independent UV/EUV proxies, leading to the uniquely large discrepancy between sunspot numbers and solar UV/EUV proxies at this time.

The present paper studies the above mentioned discrepancy in the different solar proxies which appeared in 2001. We examine the sunspot numbers and the same three proxies of solar UV/EUV radiation (F10.7, HeI 1083 and MgII) as Floyd et al. (2005). (However, the MgII index studied here is not the same, original NOAA index, but rather a composite based on SORCE observations which aims to correct the problems of the NOAA index.) We find that the change in the mutual relation between sunspot numbers and all UV/EUV irradiance proxies is valid persistently during the whole declining phase of solar cycle 23. We also study the ionospheric response to UV/EUV radiation by using the F2 layer critical frequency f_0(F2) from different stations. We find that the ionosphere depicts the same change in its relation to sunspot numbers since 2001 as the more direct, solar-based UV/EUV proxies. Moreover, we show the relation between f_0(F2) and the solar-based UV/EUV proxies has remained the same. This gives strong support for the fact that, after the end of 2001, the UV/EUV irradiance has been higher than ever earlier for the same level of sunspot activity. We also note that similarly, the relation between sunspots and the total solar irradiance is changed since 2001. This change takes place in both leading TSI composites.

2. Relation between sunspot numbers and solar UV/EUV proxies

We depict in Fig. 1 the time series of sunspot numbers and the three solar UV/EUV proxies during the common measurement time of the UV/EUV proxies. As seen in Fig. 1, sunspots have their SC 23 maximum in 2000. However, the three UV/EUV proxies have a higher maximum (both in monthly values and in their 13-month running means) some 1.5 years later around the turn of 2001/2002. This fact was noted earlier (e.g., Kane, 2003; Floyd et al., 2005) but the reason is still unknown. Sunspots also show this peak but lower than the actual sunspot maximum in 2000. The dropout between these two maxima is the Gnevyshev gap of SC 23. A similar structure with two peaks and an intermediate dropout are seen in solar cycles 21 and 22 as well. The two peaks around the Gnevyshev gap are separated by roughly 1.5–2 years in all cases.

The two peaks in the smoothed sunspot curve (the sunspot maximum peak and the secondary peak thereafter) are more equal during SC 23 than other cycles, making this pattern particularly visible in this cycle. On the other hand, according to the solar UV/EUV proxies, the two peaks have more similar heights in SC 21 and 22 than in SC 23. Note also that while SC 23 is overall smaller than the two other cycles, the activity of the 2001/2002 peak reaches the level of the prior cycles in F10.7 flux, and even goes above them in HeI and MgII curves.

In order to examine the mutual relation between sunspot numbers and solar UV/EUV proxies and its temporal evolution, we have plotted in Fig. 2 the annual averages of the three proxies as a function of the simultaneous sunspot numbers. We have connected the successive years by a line depicting the time evolution. The top panel of Fig. 2 shows that, while sunspot numbers and the F10.7 flux follow a quite similar relation for the early part (1975–2000) of the depicted time interval, the relation is broken in 2001/2002. After this time, during the declining phase of SC 23, the F10.7 flux is systematically higher than the prior relation with sunspot numbers would suggest. The relative increase in the F10.7 flux in the early declining phase (in 2002–2004) is about 10–15% relative to the average, prior level. The difference is then reduced to about 5–10% in the later declining phase but remains until the last data point in 2008 where the annual sunspot numbers are lowest in the whole time interval included.

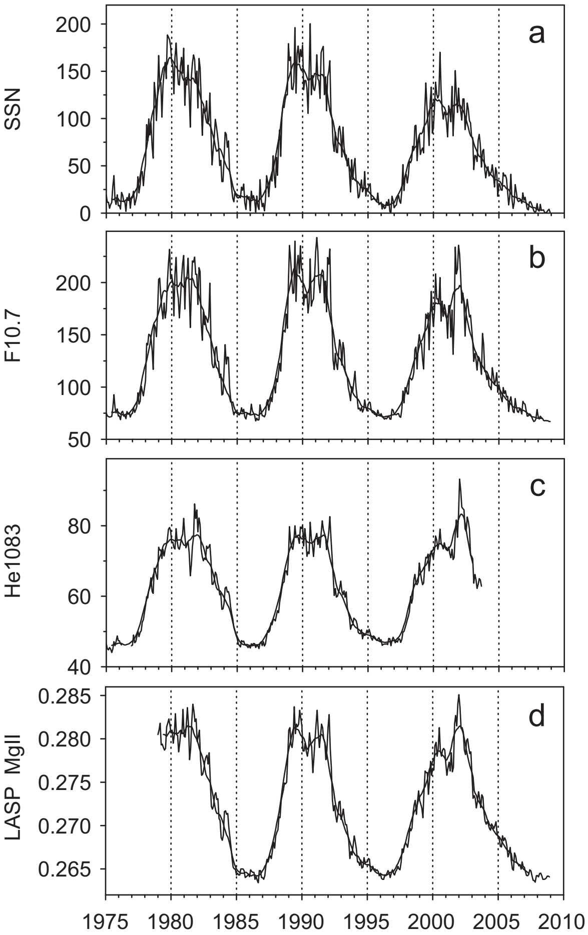


Fig. 1. The monthly averages and their 13-month running means for (a) sunspot numbers, (b) F10.7 radio flux, (c) He I 1083 equivalent width and (d) MgII core-to-wing ratio.

The same change in the early declining phase of SC 23 is also seen in the mutual relation between sunspot numbers and HeI 1083 equivalent width (middle panel of Fig. 2). The relative increase in 2002 is about 20%, i.e., even slightly larger than in F10.7. Unfortunately, to our information, this index was not continued after September 2003. Fig. 2 (bottom panel) shows that from 2001 onwards the annual means of the MgII index also depict significantly larger values than the prior relation with sunspot numbers would suggest. The relative increase to the earlier values is only about 1%, i.e., smaller than in the case of F10.7 flux, but the absolute increase of about 0.002 is roughly constant through the whole declining phase and forms a significant fraction (about 10–15%) of the total solar cycle variation (from 0.264 to 0.280) of this parameter. We note that the original NOAA MgII index depicts an even larger increase after 2001. However, this index suffers from calibration problems during the declining phase of SC 23. Therefore, we use here the LASP composite, which uses SORCE observations for this period.

3. Relation between sunspot numbers and ionospheric f_0(F2)

Because, as discussed above, some of the solar UV/EUV proxies that depict the unexpected evolution during the last few years are

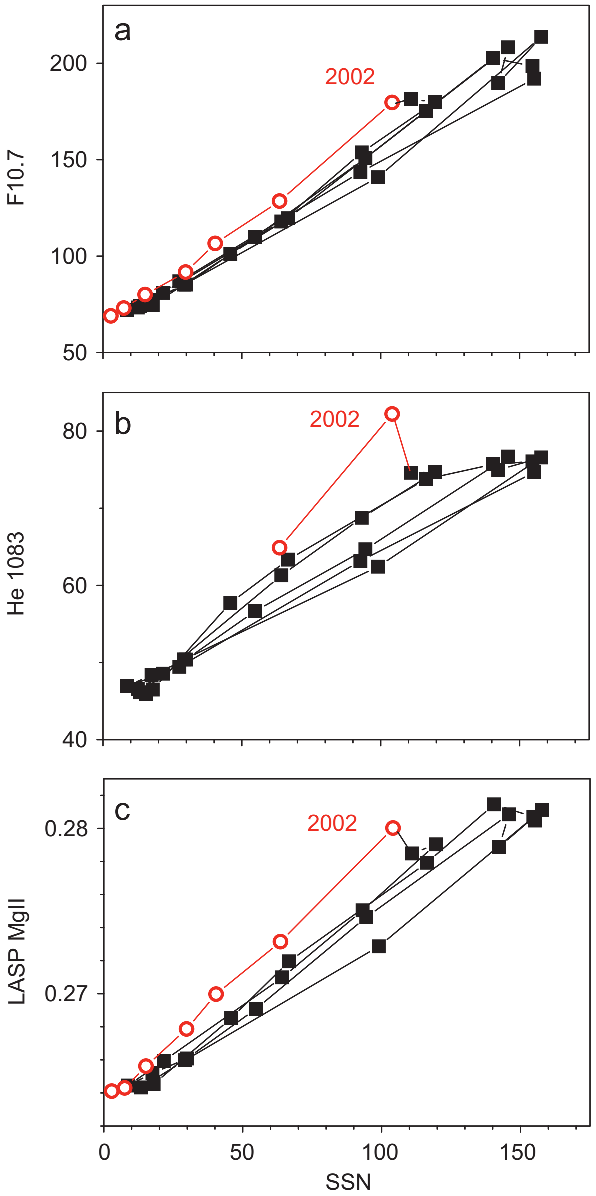


Fig. 2. Annual averages of (a) F10.7 radio flux in 1974–2008, (b) HeI 1083 equivalent width in 1974–2003 and (c) MgII core-to-wing ratio in 1978–2007, as a function of the simultaneous, annually averaged sunspot numbers. Line connects successive years. Years since 2002 are indicated by circles (red in color figures in web; grey in b&w figures in print).

at least partly in question, it is important to verify the same time evolution using a parameter that is completely independent of direct solar observations. Such parameters are offered by the Earth's ionosphere whose condition is regularly monitored by numerous observatories around the world. We use here the critical frequency of the ionospheric F2 layer called f_0(F2), which is a measure of the maximum electron density in the ionospheric F2 layer. Accordingly, the value of the f_0(F2) frequency is strongly correlated with the UV/EUV flux that produces ionization in the ionosphere and, thereby, with the UV/EUV proxies like F10.7, HeI and MgII indices. In this section, we examine if the ionospheric measurements can verify the curious change in the relationship between sunspots and the solar UV/EUV proxies after 2001/2002.

We have collected hourly f_0(F2) values from several mid-latitude observatories included in the NOAA SPIDR database (http://spidr.ngdc.noaa.gov/spidr/). We aimed for global coverage in longitude but did not include stations at high latitudes because auroral precipitation affects the ionosphere there, distorting the relationship between f_0(F2) and solar UV/EUV irradiance. We use here 8 stations (see Table 1) which have a good coverage of observations in the study period of 1975–2008. We use daily averaged f_0(F2) values in order to minimize the influence of various dynamical effects in the ionosphere and because the daytime maxima are often differently shifted from the noon at different stations and different seasons. We first calculated monthly averages from the daily averaged f_0(F2) values of each station. Then, in order to obtain a global measure of the f_0(F2) frequency, the monthly averages of all stations were normalized to Boulder using linear regression for all available data, and the normalized f_0(F2) values from the eight stations were averaged to a global f_0(F2) mean. Finally, a 13-month running mean of the monthly global f_0(F2) values was calculated in order to reduce the seasonal variation due, e.g., to an unequal number of stations from the two hemispheres.

Fig. 3 shows the monthly averaged curves of the eight stations and the 13-month running mean of the global f_0(F2) average. All stations verify the variation of the f_0(F2) values with solar cycle whose (normalized) amplitude is about 2–3 MHz around a typical average of about 6 MHz. Accordingly, the relative solar cycle variation in f_0(F2), about 30–50%, is considerably larger than in the MgII index and clearly smaller than in F10.7 but fairly close to the cycle variation in the HeI index. Note that a small amplitude of solar cycle variation (a small dynamical range) of a solar parameter like MgII makes it more vulnerable for random and systematic errors. This caveat is further emphasized when studying the consistency of the parameter over long time intervals. However, the ionospheric f_0(F2) frequency is safe for these arguments.

Note that cycle 23 is lower in the f_0(F2) average than the other two cycles and depicts a clear two-peak structure, with the second peak in 2002 being considerably higher than the first peak

Table 1
List of mid-latitude ionospheric stations.

Station name	Station code	Geographic Lat., Long
Boulder	BC840	40.1°, −105.8°
Juliusruh/Rugen	JR055	56.5°, 12.1°
Grahamstown	GR13L	−33.3°, 26.5°
Hobart	HO54K	−42.9°, 147.5°
Novosibirsk	NS355	55.1°, 88.9°
Point Arguello	PA836	37.5°, −124°
Tashkent	TQ241	41.3°, 69.6°
Wallops	WP937	40.3°, 76.2°

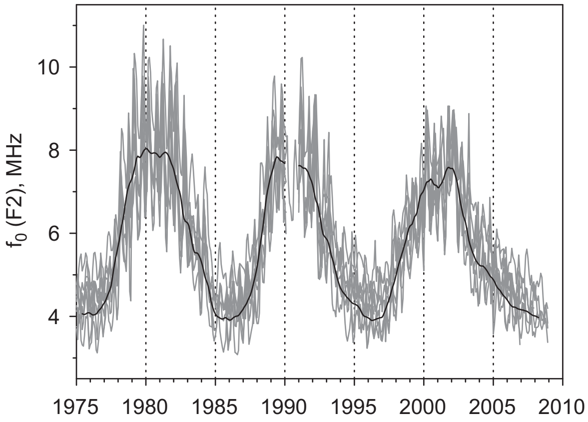


Fig. 3. Monthly means of f_0(F2) values from the 8 stations listed in Table 1 (grey curves) and the 13-month running mean curve of the global f_0(F2) average (in bold black line).

in 2000. These features are in good agreement with the solar based UV/EUV proxies. The detailed structure of cycle 22 is not very clear in f_0(F2) because of the unfortunate data gap in 1990 (only Boulder included data in this year), in the middle of the Gnevyshev gap of SC 22. However, the data show that the global f_0(F2) values in 1991 are lower than at the first maximum co-located with the sunspot maximum in 1989. Also, most interestingly, the global f_0(F2) level is clearly higher during the declining phase of SC 23 than during the corresponding times of the two previous cycles. This development is in agreement with F10.7, HeI 1083 and MgII indices and is responsible for the exceptional relation between sunspots and the various UV/EUV proxies at this time, as discussed above.

We have studied the temporal development of the f_0(F2) frequency and its relationship with sunspot numbers in more detail in Fig. 4, which depicts the annually averaged global f_0(F2) values in terms of the simultaneous sunspot numbers (cf. Fig. 2 for solar-based UV/EUV proxies). Fig. 4 shows that the values of the global f_0(F2) average are higher in the declining phase of SC 23 than in the two previous cycles included in the study period 1975–2008. The relative increase in global f_0(F2) with respect to the average level, nearly 10%, is largest in 2002. In the subsequent years this increase is considerably reduced but is quite large, about 5–7%, also in 2004. The temporal variation of f_0(F2) during SC 23 follows quite closely to that of F10.7 index, but the relative increase remains somewhat lower than in F10.7, which is understandable since f_0(F2) is clearly a less direct proxy of solar UV/EUV radiation than the solar-based proxies, depending on other factors like motion of the neutral air, station's latitude, etc. Most importantly, Fig. 4 gives strong, independent support for the conclusion based on solar-based UV/EUV parameters that the relation between sunspot numbers and solar UV/EUV irradiance experiences a significant change in 2001/2002, during and after which the Sun produces more UV/EUV radiation for the same sunspot level than before this time period.

We have studied in Fig. 5 the mutual relation between the global f_0(F2) (ground-based UV/EUV proxy) and F10.7 (solar-based UV/EUV proxy). Fig. 5 shows that f_0(F2) and F10.7 have a very consistent relation throughout the whole time interval studied, including the declining phase of SC 23. This proves that both of these UV/EUV parameters measure quite closely the same irradiance at all times. (Note that the relation between the two quantities experiences some saturation for large values of F10.7 because of ionospheric properties.)

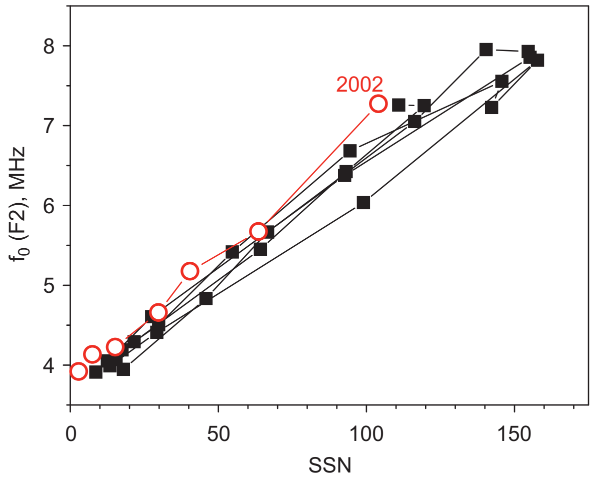


Fig. 4. Annual averages of the global f_0(F2) average in 1975–2008, as a function of the simultaneous, annually averaged sunspot numbers. Line connects successive years. Years since 2002 are indicated by circles (red in color figures in web; grey in b&w figures in print).

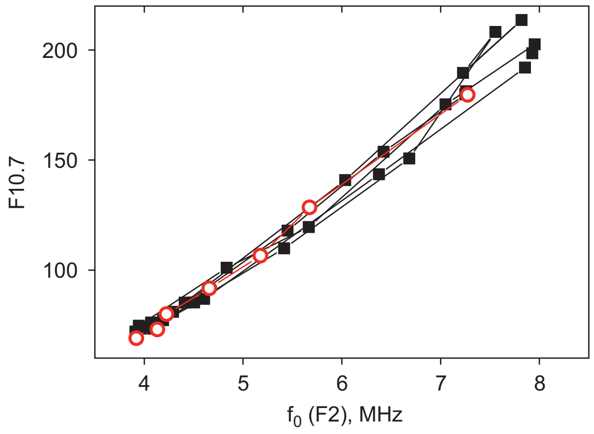


Fig. 5. Annual averages of F10.7 radio flux in 1975–2008 as a function of the simultaneous, annually averaged global f_0(F2) average. Line connects successive years. Years since 2002 are indicated by circles (red in color figures in web; grey in b&w figures in print).

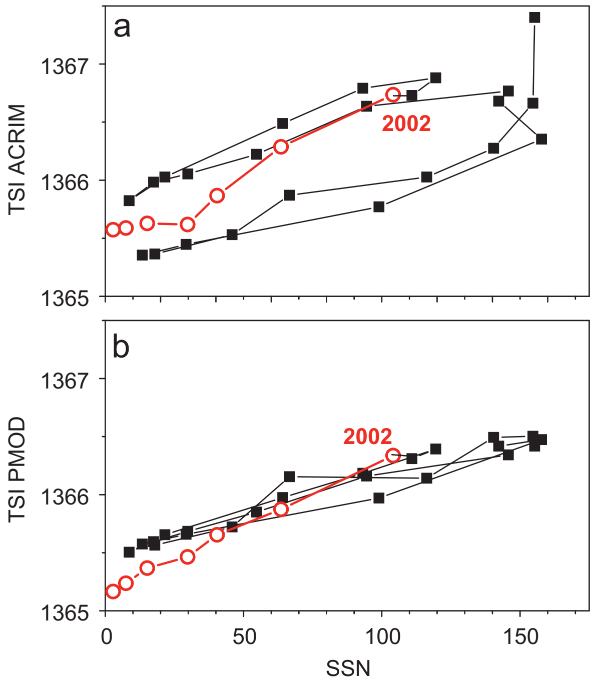


Fig. 6. Annual averages of three different estimates of the total solar irradiance (a) ACRIM and (b) PMOD in 1979–2008 as a function of the simultaneous, annually averaged sunspot numbers. Line connects successive years. Years since 2002 are indicated by circles (red in color figures in web; grey in b&w figures in print).

4. Total solar irradiance

We would like to conclude by noting that the observed change in the relation between sunspot numbers and solar UV/EUV radiation in 2001/2002 is not limited to UV/EUV radiation only but affects the total solar irradiance as well. Fig. 6 depicts the annual averages of two composites (ACRIM and PMOD) of the total solar irradiance in terms of the simultaneous sunspot numbers. Note first that, if we exclude the points of the recent declining phase, the linear correlation between PMOD and SSN in Fig. 6b is very high. On the other hand, the points of the recent years after 2002 fall into a line, which has a very different slope. Also, as seen in Fig. 6b, after 2004 the relation between SSN and PMOD diverges below the range of the normal linear fit, implying exceptionally small TSI values for given SSN thereafter. After this time, the difference between SSN and PMOD increases progressively with time, resulting in a record low "floor" in the current solar minimum. It is remarkable how closely the points in 2002–2008 follow the new regression line and how largely the slope of this line deviates from the best fit line of the prior solar history.

The relation between ACRIM TSI values and sunspot numbers (Fig. 6b) is more complicated than PMOD because their relation has a clear hysteresis pattern: the points in the declining phase of SC 21 and ascending phase of SC 22 follow a common, roughly linear relation which greatly deviates from the relation thereafter. This is due to the data gap between the ACRIM-I and ACRIM-II measurements around 1990, which raises the uncorrected ACRIM composite by roughly 0.3 W m^{-2} higher than the PMOD composite after this gap. This difference leads to two different data domains and the hysteresis of the ACRIM composite (Fröhlich, 2006; Scafetta and Willson, 2009; Krivova et al. 2009). Nevertheless, the new linear relationship between the ACRIM series and sunspots is violated in 2001. Instead of following the new regression line established after 1990, the ACRIM TSI values during the declining phase of SC 23 follow a new, considerably steeper regression line which crosses the intermediate region between the two prior regression lines. As in PMOD series, the points in 2002–2008 follow the new regression line remarkably well, and the slope of this line deviates largely from the best fit lines of prior ACRIM history. These developments suggest that the relation between the solar TSI and sunspot numbers is indeed greatly changed in the declining phase of SC 23.

The low TSI during the recent minimum, shown in Fig. 6b as a strong decrease of the PMOD composite since 2002 to a record low level, is in contrast with F10.7 and MgII index and may be explained by a global temperature decrease of the Sun, as suggested by Tapping et al. (2007) and studied by Fröhlich (2009). So, this may also indicate that the whole solar spectrum suffers an abrupt change in 2001/2002. This study is under progress.

5. Discussion and conclusions

We have studied here the mutual relation between sunspot numbers and different solar UV/EUV proxies in 1975–2008, including the period when direct measurements by satellites are available. Parameters measured from space include the MgII core-to-wing ratio, the HeI equivalent width and the two TSI composites while ground-based measurements provide the F10.7 radio flux and the ionospheric F2 layer critical frequency f_0(F2).

The time evolution of the statistical relationship between sunspot numbers and each of the above mentioned UV/EUV and TSI parameters shows two clearly different branches, the long-term, "normal" evolution until the year 2000, and the recent, "abnormal" evolution since 2001/2002. The change between the two different branches coincides with a large enhancement in solar activity, which was started during the last months of 2001 and lasted until the first months of 2002. This enhancement is seen as a secondary peak in sunspot numbers after the sunspot maximum in 2000 and a period of slightly reduced sunspot activity called the Gnevyshev gap. However, the enhancement in 2001/2002 was the highest peak in all UV/EUV proxies, marking the largest discrepancy with sunspot numbers during the measured period and continuing as an "abnormal" relation with sunspot numbers during the whole declining phase of SC 23.

We have found that the relative increase in the F10.7 radio flux in the early declining phase (in 2002–2004) is about 10–15% relative to the average "normal" level of sunspot activity, then decreasing to about 5–10% in the later declining phase. We have shown that the indirect measure of solar UV/EUV radiation, the ionospheric f_0(F2) frequency, also shows a change in its relation with sunspot activity after the enhancement in 2001/2002. The relative increase in the global f_0(F2) frequency with respect to the average prior level is nearly 10% in 2002, and remains above the normal level during the whole declining phase of SC 23. The temporal variation of f_0(F2) follows very closely to that of F10.7 index over the whole time interval studied. Accordingly, these two parameters observe the same changes in 2001/2002 in the relation between sunspots and solar UV/EUV radiation.

The same change in the early declining phase of SC 23 is also seen in two other satellite based indices of solar UV/EUV radiation, the HeI 1083 equivalent width and the MgII index. The relative increase in HeI in 2002 is largest of all studied UV/EUV parameters, about 20% (Floyd et al., 2005). Unfortunately, this proxy was not continued after 2003. In the MgII index the relative increase is, due to the nature of this parameter, smaller, only about 1% but this change is about 10–15% of average solar cycle variation of MgII.

We have also shown that the relation between sunspot numbers and the two composites of total solar irradiance, the PMOD series and the ACRIM series diverge from the normal evolution in 2001/2002. The annual averages of both TSI composites follow thereafter a new, steeper regression line than earlier, deviating from the earlier evolution. After 2004 the difference between sunspot numbers and PMOD increases progressively with time, resulting in a record low "floor" in the current solar minimum. The same evolution is seen in the ACRIM series, although ACRIM includes lower values from earlier years before the data gap. We note that it is remarkable how clearly the points in 2002–2008 in both PMOD and ACRIM series deviate from their earlier evolution and follow new, steeper regression lines. This further verifies the essential changes that have taken place in the solar magnetic field and solar irradiance in 2001/2002, continuing throughout the later declining phase of SC 23.

According to recent studies (Penn and Livingston, 2006; Livingston and Penn, 2009), the maximum temperatures of sunspot umbrae have become hotter and their maximum magnetic fields have reduced during the solar cycle 23. This would lead to a smaller background contrast and weakened visibility of sunspots. Assuming other factors unchanged, this would lead to having more UV/EUV activity for smaller sunspot numbers, exactly as observed after 2001/2002. Accordingly, our results indirectly support the above result of umbrae getting hotter and less magnetic during SC 23. However, while the UV/EUV proxies return roughly to the same minimum value in 2008, the TSI PMOD composite depicts uniquely low values. The smaller TSI values for a given sunspot number after 2001/2002 (Fig. 6) indicate that the faculae must, in order to balance the slightly increased TSI due to higher umbral temperatures, be severely reduced by the same processes that cause umbral field weakening. Accordingly, the exceptionally low level of TSI cannot be explained if the number of faculae is reduced by the same ratio as the field intensity of sunspots producing them. However, the mechanisms that cause the change in sunspots in 2001/2002 are simultaneous to the reduction of TSI, therefore indicating the same cause.

Summarizing, our results show that the earlier reported reduction in sunspot magnetic field intensity started quite abruptly in 2001/2002 and continued throughout the declining phase of solar cycle 23. This is verified by the modified mutual relation between sunspots and both satellite-based and ground-based UV/EUV proxies. Our results suggest that, whatever is the cause of the observed reduction in sunspot fields (or, more generally, photospheric fields), it does not similarly affect the chromosphere. On the other hand, TSI suffers an even more dramatic reduction, which cannot be understood in terms of the photospheric field reduction only. However, the changes in TSI are seen to be simultaneous to those in sunspots, most likely being due to the same ultimate cause. These differences, as well as the reasons to the observed changes will be examined in subsequent studies in more detail.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant agreement no. 218816 (Soteria project). K.M. acknowledges the financial support by the Academy of Finland to the HISSI Research Project no. 128189. R.L. acknowledges the support by the RFBR Grant 09-05-00232. We acknowledge the service of sunspots, F 10.7 index (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/) and the *f* 0(F2) data (http://spidr.ngdc.noaa.gov/spidr/) by NOAA/NGDC, and the MgII index (http://lasp.colorado.edu/lisird/mgii/mgii.html) by LASP, University of Colorado. The TSI composites were obtained from PMOD (http://www.pmodwrc.ch/) and ACRIM groups (http://www.acrim.com/). He1083 data are produced by NSF/NOAO, NASA/GSFC and NOAA/SEC (http://nsokp.nso.edu/).

References

Donnelly, R.F., Repoff, T.P., Harvey, J.W., Heath, D.F., 1985. Temporal characteristics of the solar UV flux and He I line at 1083 nm. J. Geophys. Res. 90, 6267–6273.

Fröhlich, C., Lean, J., 1998. The Sun's total irradiance: cycles, trends, and related climatic change uncertainties since 1976. Geophys. Res. Lett. 25, 4377–4380.

Fröhlich, C., 2006. Solar irradiance variability since 1978: revision of the PMOD composite during solar cycle 21. Space Sci. Rev. 125, 53–65, doi:10.1007/s11214-006-9046-5.

Fröhlich, C., 2009. Evidence of a long-term trend in total solar irradiance. Astron. Astrophys. 501, L27–L30, doi:10.1051/0004-6361/200912318.

Floyd, L., Newmark, J., Cook, J., Herring, L., McMullin, D., Solar, E.U.V., 2005. UV spectral irradiances and solar indices. J. Atmos. Sol. Terr. Phys. 67, 3–15.

Gnevyshev, M.N., 1963. The corona and the 11-year cycle of solar activity. Sov. Astron. 7, 311.

Gnevyshev, M.N., 1977. Essential features of the 11-year solar cycle. Sol. Phys. 51, 175–183, doi:10.1007/BF00240455.

Heath, D.F., Schlesinger, B.M., 1986. The Mg 280-nm doublet as a monitor of changes in solar ultraviolet irradiance. J. Geophys. Res. 91, 8672–8682.

Kane, R.P., 2003. Dissimilarity in the evolution of solar EUV and solar radio emission (2800 MHz) during 1999–2002. J. Geophys. Res. 108 (A12), 1455, doi:10.1029/2003JA009869.

Krivova, N.A., Solanki, S.K., Wenzler, T., 2009. ACRIM-gap and total solar irradiance revisited: is there a secular trend between 1986 and 1996? Geophys. Res. Lett. 36 L20101, doi:10.1029/2009GL040707.

Livingston, W., M.J. Penn, 2009. Are sunspots different during this solar minimum? EOS, Transactions, AGU, 90, no. 30, 28 July, pp. 257–264.

Penn, M.J., Livingston, W., 2006. Temporal changes in sunspot umbral magnetic fields and temperatures. Astrophys. J. 649, L45–L48, doi:10.1086/508345.

Scafetta, N., Willson, R.C., 2009. ACRIM-gap and TSI trend issue resolved using a surface magnetic flux TSI proxy model. Geophys. Res. Lett. 36, L05701, doi:10.1029/2008GL036307.

Schwabe, M.,1844. Sonnenbeobachtungen im Jahre 1843 von Herrn Hofrath Schwabe in Dessau. Astronomische Nachrichten 21, 233.

Storini, M., Bazilevskaya, G.A., Fluckiger, E.O., Krainev, M.B., Makhmutov, V.S., Sladkova, A.I., 2003. The Gnevyshev gap: a review for space weather. Adv. Space Res. 31, 895–900, doi:10.1016/S0273-1177(02)00789-5.

Tapping, K.F., 1987. Recent solar radio astronomy at centimeter wavelength—the temporal variability of the 10.7-cm flux. J. Geophys. Res. 92, 829–838.

Tapping, K.F., Boteler, D., Charbonneau, P., Crouch, A., Manson, A., Paquette, H., 2007. Solar magnetic activity and total irradiance since the Maunder minimum. Sol. Phys. 246, 309–326.

Viereck, R., Puga, L., McMillin, D., Judge, D., Weber, M., Tobiska, K., 2001. The MgII index: a proxy for solar EUV. J. Geophys. Res. 28 (7), 1343–1346.

Viereck, R.A., Floyd, L.E., Crane, P.C., Woods, T.N., Knapp, B.G., Rottman, G., Weber, M., Puga, L.C., DeLand, M.T., 2004. A composite Mg II index spanning from 1978 to 2003. Space Weather 2, S10005, doi:10.1029/2004SW000084.

Willson, R.C., 1997. Total solar irradiance trend during solar cycles 21 and 22. Science 277, 1963–1965.