The total solar irradiance, UV emission and magnetic flux during the last solar cycle minimum

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Abstract

We have analyzed the total solar irradiance (TSI) and the spectral solar irradiance as ultraviolet emission (UV) in the wavelength range 115-180 nm, observed with the instruments TIM and SOLSTICE within the framework of SORCE (The Solar Radiation and Climate Experiment) during the long solar minimum between the 23rd and 24th cycles. The wavelet analysis reveals an increase in the magnetic flux in the latitudinal zone of the sunspot activity, accompanied with an increase in the TSI and UV on the surface rotation timescales of solar activity complexes. In-phase coherent structures between the mid-latitude magnetic flux and TSI/UV appear when the long-lived complexes of the solar activity are present. These complexes, which are related to long-lived sources of magnetic fields under the photosphere, are maintained by magnetic fluxes reappearing in the same longitudinal regions. During the deep solar minimum (the period of the absence of sunspots) a coherent structure has been found, in which the phase between the integrated mid-latitude magnetic flux is ahead of the total solar irradiance on the timescales of the surface rotation.

Introduction

The minimum of the solar activity separating the activity cycles 23 and 24 is often called “an unusual minimum”. The annual sunspot number reached lower values: 7.5, 2.5 and 3.1 in 2007, 2008 and 2009, (8.6 in 1996 for comparison). A typical minimum lasts for about 486 spotless days (http://spaceweather.com), but since 2004 as many as 821 spotless days were observed. The total solar irradiance (TSI) was smaller in 2008 than that in 1996 by about 200 ppm [5]. The irradiance measured with the SOHO Solar EUV Monitor (SEM) at 26 to 34 nm was by about 15% lower in 2008 than that in 1996. This period is interesting, in addition, due to overlapping of the activity complexes of the solar cycles 23 and 24.

In this paper we study the impact of the magnetic flux of the sunspot activity on the solar irradiance, with the purpose to understand the role of the long-lived complexes of the solar activity. In this aspect, long and deep solar minimum gives a unique opportunity to analyze in detail variations of the total solar irradiance (TSI) and the spectral solar irradiance as a function of the magnetic flux and sunspot area. We can estimate the contribution of each complex of the solar activity to the TSI and UV, separately, taking into account a so-called TSI blocking effect, which makes it difficult to determine the relationship between the magnetic flux and the total solar irradiance. We can also compare these results with those for the time when the sunspots do not contribute to the TSI at all.

In addition, the distribution of the sources of the TSI and UV is particularly important for the development of empirical and semi-empirical irradiance models [6], for prediction of the solar luminosity.

Here, we use the data for TSI and UV (115-180 nm) obtained by the SORCE instruments (http://lasp.colorado.edu/sorce/), the data for XUV (0.1-7 nm) and EUV (33.5 nm, Fe XVI line) obtained by theTIMED-SEE instrument ftp://laspftp.colorado.edu/pub/SEE_Data . The sunspot areas are taken from the web page (http://solarscience.msfc.nasa.gov/greenwch.shtml). The magnetic data are represented by synoptic maps of the Wilcox Solar Observatory (WSO, http://wso.stanford.edu).

A non-axisymmetric pattern of the solar irradiance

The total solar irradiance (TSI) describes the total radiant energy, in the form of electromagnetic radiation emitted by the Sun at all wavelengths, that falls for each second on 1 square meter outside the Earth's atmosphere - a value proportional to the 'solar constant' introduced earlier in last century. TSI is a measure of the solar energy flux. The radiative flux decreases when dark sunspots are present on the disk and increases due to bright faculae or plages [4].

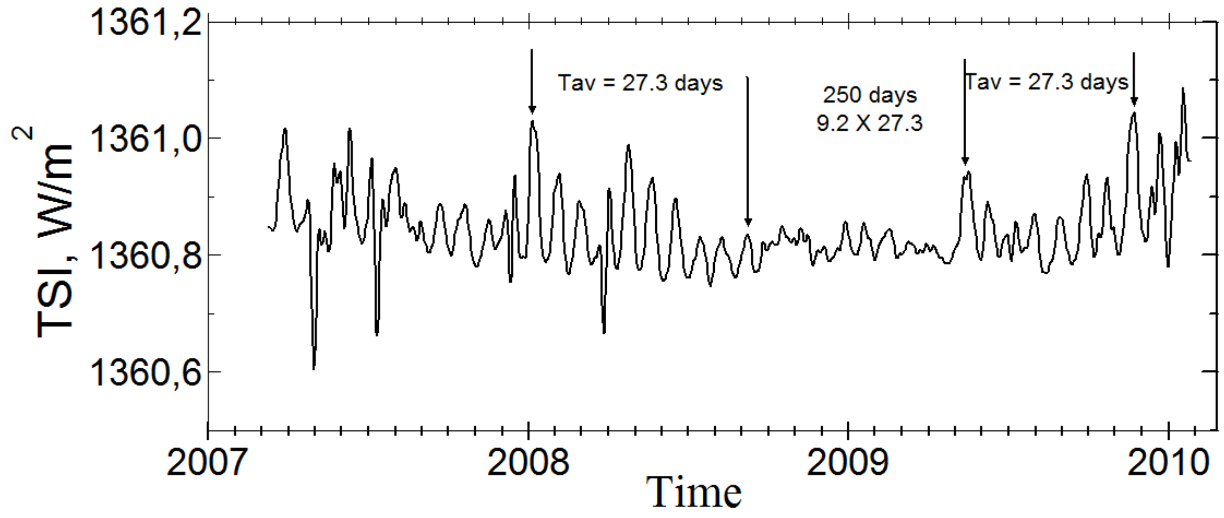

Figure 1.   The daily values of the total irradiance (TSI) during the time 10 March 2007 - 23 January 2010.

One can see a strong longitudinal non-uniformity in the TSI value during 27 solar rotations. Here we analyze sources of such non-uniformity.

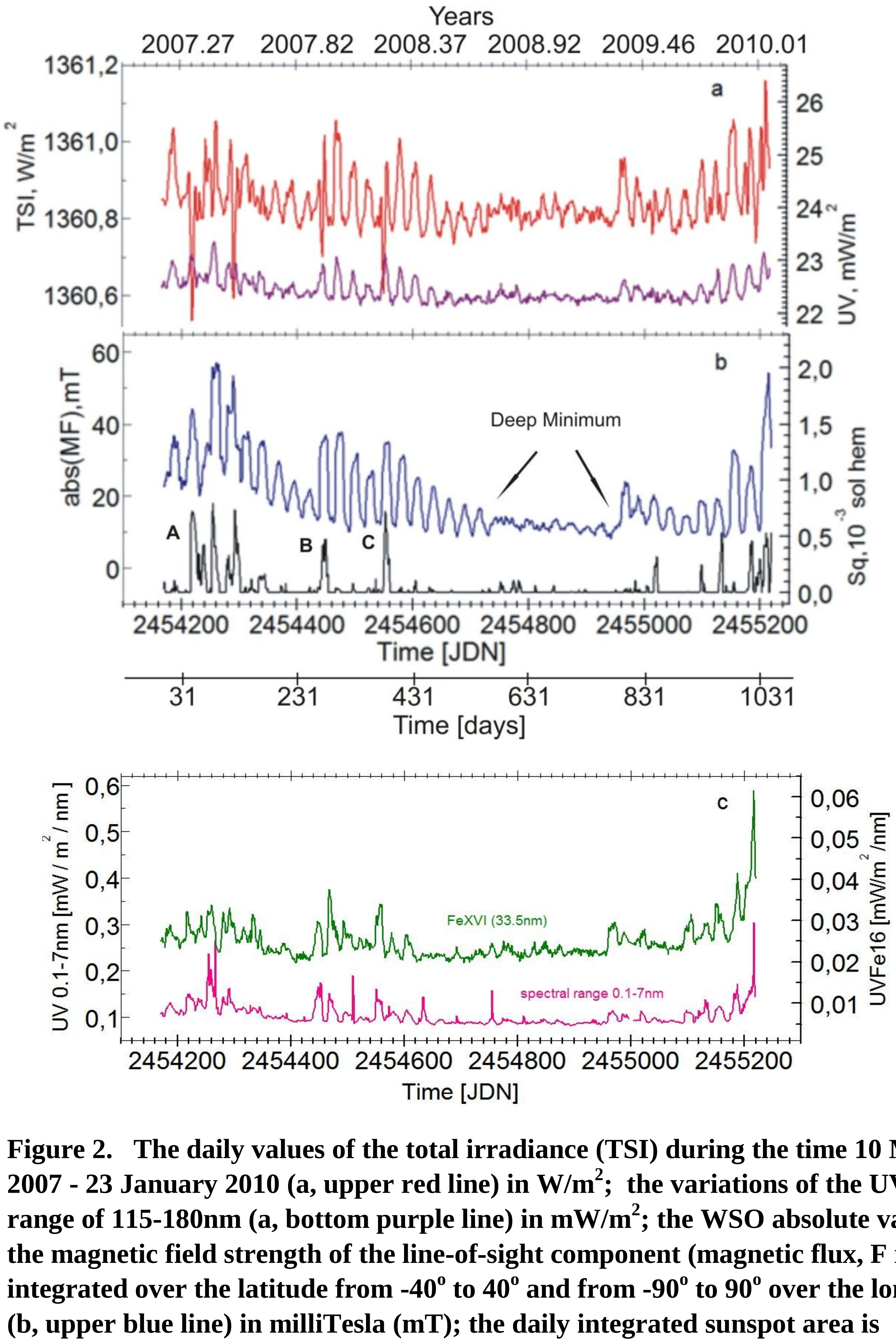

Figure 2. The daily values of the total irradiance (TSI) during the time 10 March 2007 - 23 January 2010 (a, upper red line) in W/m^2; the variations of the UV in the range of 115-180nm (a, bottom purple line) in mW/m^2; the WSO absolute values of the magnetic field strength of the line-of-sight component (magnetic flux, F mag) integrated over the latitude from -40^o to 40^o and from -90^o to 90^o over the longitude (b, upper blue line) in milliTesla (mT); the daily integrated sunspot area is represented as thousandths of the solar hemisphere (b, bottom black line); the variations of the EUV in the line FeXVI-33.5nm (c, upper green line) in mW/m^2; the variations of the EUV in the range of 0.1-7nm (c, bottom pink line) in mW/m^2; The beginning and the end of the deep minimum are marked by arrows.

A simple comparison of the variables TSI and F mag indicates their consistency, except for the times of strong TSI negative variations, which occurred due to the sunspot blocking effect. The increase in the daily integrated sunspot area corresponds to that in the integrated mid-latitude magnetic flux. There is a strong correlation between the F mag and the intensity of the UV. As we can see in Fig.2, during the deep minimum, the integrated mid-latitude magnetic flux corresponds to low luminosity in the total and UV irradiance.

We analyzed the TSI and magnetic data ($B_{||}$) in the form of Carrington maps (Fig.3) using the method described in [2]. It is clearly seen that during CR2055 - 2076 (March 2007 - November 2008) the strong magnetic activity exists in the longitudinal zone 200^o- 300^o and rotates with the velocity rate slightly exceeding that of the Carrington rotation. This magnetic structure, combined from 'A','B','C' activity complexes, contributes to the TSI due to the surrounding bright faculae.

The solar complex 'A' corresponds to the multiple strong variations of the sunspot area (Fig.2b, bottom plot), which occur during several Carrington rotations and are spread along the longitude. But only one of these fluctuations, the one related to the complexes of solar activity, exists inside the abovementioned longitudinal zone. The activity of B and C complexes is of special importance, as they belong to the overlapping cycles 23 and 24. According to the Hale's law, the polarity of the preceding and following parts in bipolar complexes of the solar activity alters from one solar cycle to the next. However, within the time interval of the so-called "cycles' overlap" the activity complexes of both polarities coexist. During 2008—2009, the `old' magnetic flux (which belonged to the cycle 23) was concentrated in longitudinal zones, and the largest part of the `new' flux (which belonged to the cycle 24) with reversed magnetic polarity emerged in the same zones, within the longitude interval 180^o - 270^o.

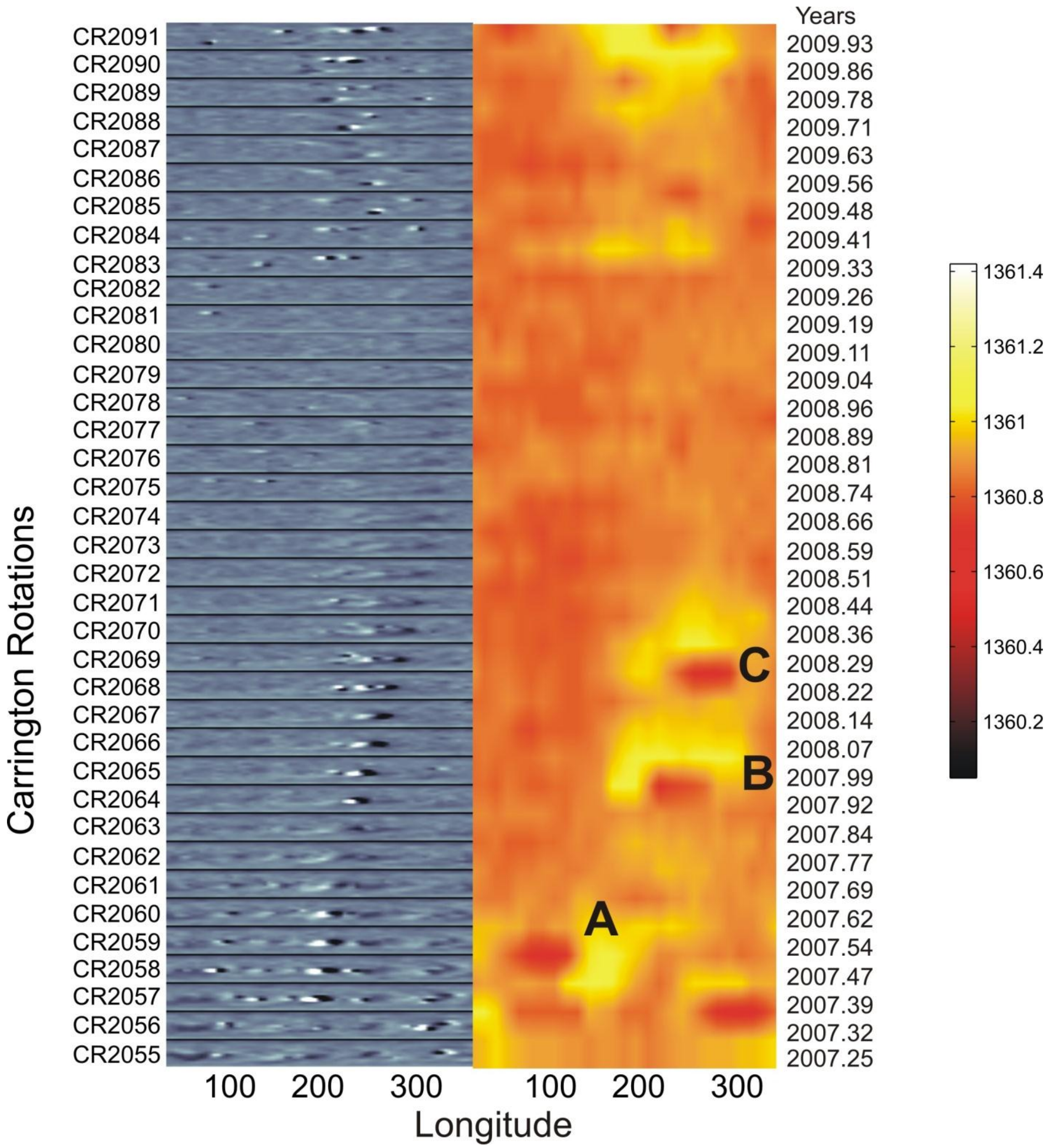

Figure 3. Left: stacked WSO synoptic maps, 10 March, 2007 to 23 January, 2010, in gray scale from -250 to 250 microTesla; Right: TSI as a function of the Carrington number and the Carrington longitude. Complexes of solar activity are marked with A, B, C. The time scale on the right indicates the beginnings of Carrington rotations. The color bar shows the TSI intensity in W/m^2.

At the beginning of the solar cycle 23, a similar longitudinal pattern existed from June, 1996 to June, 1998 [2]. During this time, the TSI distribution displayed an increase at longitudes $200^{o} – 300^{o}$. The EIT/SOHO data for the extreme UV irradiance indicated the increase in the coronal temperature associated with the activity complex at the beginning of the cycle 23. Therefore, the heating of the solar corona is closely related to long-lived complexes of the solar activity and to a corresponding source of the magnetic field under the photosphere.

Long-lived longitudinal non-uniformity in the solar activity (active longitudes) has been known for a long time, but generally, this phenomenon is related to active phases of solar cycles, when there are a number of (several) sunspot complexes and solar magnetic field has a complicated structure. Here, we observed a pronounced and stable longitudinal non-uniformity for the relatively weak solar magnetic flux during the long solar minimum and two cycles overlapping.

It is interesting that the long-lived longitudinal activity occurs at the ascending phase of the cycle 24 during the Carrington rotation CR2107 - CR2115 at the longitude 300^{o}-360^{o} and latitude $13^{o} – 22^{o}$ [1]. This complex produced a strong X-flare (X6.9) in September, 2011. It was the first long-lived complex in the cycle 24 and, possibly, (in some respects) it's appearance could be related to the activity complexes, discussed in this paper.

Cross wavelet transformation and coherence structure of TSI, UV, and F mag

A cross wavelet power transformation reveals areas with high common power spectrum in the time – frequency space; the wavelet coherence transformation finds local phase-locked behavior in this space. The cross wavelet transformation (XWT) of two series X and Y can be defined as $W_n^{XY}(s) = W_n^{X}(s)W_n^{Y*}(s)$, where * denotes complex conjugation. The wavelet transformations of the series X and Y are $W_n^{X}(s)$ and $W_n^{Y}(s)$, where *s* is the scale, so that $\eta = s \cdot t$; η is the dimensionless time. The cross wavelet spectrum is complex and can be defined as the cross wavelet power spectrum $|W_n^{XY}(s)|$. Another useful parameter derived from the wavelet analysis is the wavelet transformation coherence (WTC) defined as the square of the cross spectrum (XWT) normalized to the individual power spectrum. Phase coherence is defined as $\tan^{-1}[Im[|W_n^{XY}(s)|]/Re[|W_n^{XY}(s)|]]$ [3].

Figure 4a presents the cross wavelet power spectrum of the TSI and F mag. This Figure indicates strong correlation between the irradiance and the magnetic flux during the descending phase of the cycle 23 and during the overlap of cycles 23 an 24 (up to 500-th day of the time series) with the maximum at periods close to that of the solar activity surface rotation. Both time series are in phase during the evolution of the complexes of solar activity 'B' and 'C' (arrows pointing to the right). But there is no in-phase behavior of the TSI and F mag in the presence of the complex activity marked by 'A'. Note that this complex consists of several activity complexes separated in the Carrington longitude. Then, during the deep minimum (500 -- 800 days of the time series) the cross wavelet power spectrum of the TSI and F mag does not reveal strong common areas in the time-frequency space (Fig. 4a). Further, significant peaks appear again due to the development of the solar cycle 24. The cross wavelet of the UV and magnetic flux is slightly different (Fig. 4c) and indicates the in-phase behavior for all three complexes of solar activity on the rotational timescale (the synodic period is about 27-28 days).

In case of the wavelet transformation coherence there is a significant difference between the TSI, F mag series, on the one hand, and the UV, F mag series, on the other hand, in the coherence areas on periods of the surface rotation. The UV and magnetic flux coherence structures associated with the magnetic activity (Fig. 4d) are in-phase (arrows point to the right). The stronger magnetic flux causes stronger UV emission. The coherence structure related to the beginning of the cycle 24 appears slightly earlier then the development of sunspot activity begins (see Figs 4d and 2b).

The coherence structure of the TSI and the F mag on periods of the surface activity rotation is decomposed into several structures during the time of overlapping of cycles 23 and 24 (Fig. 4b) and during the solar cycle minimum.

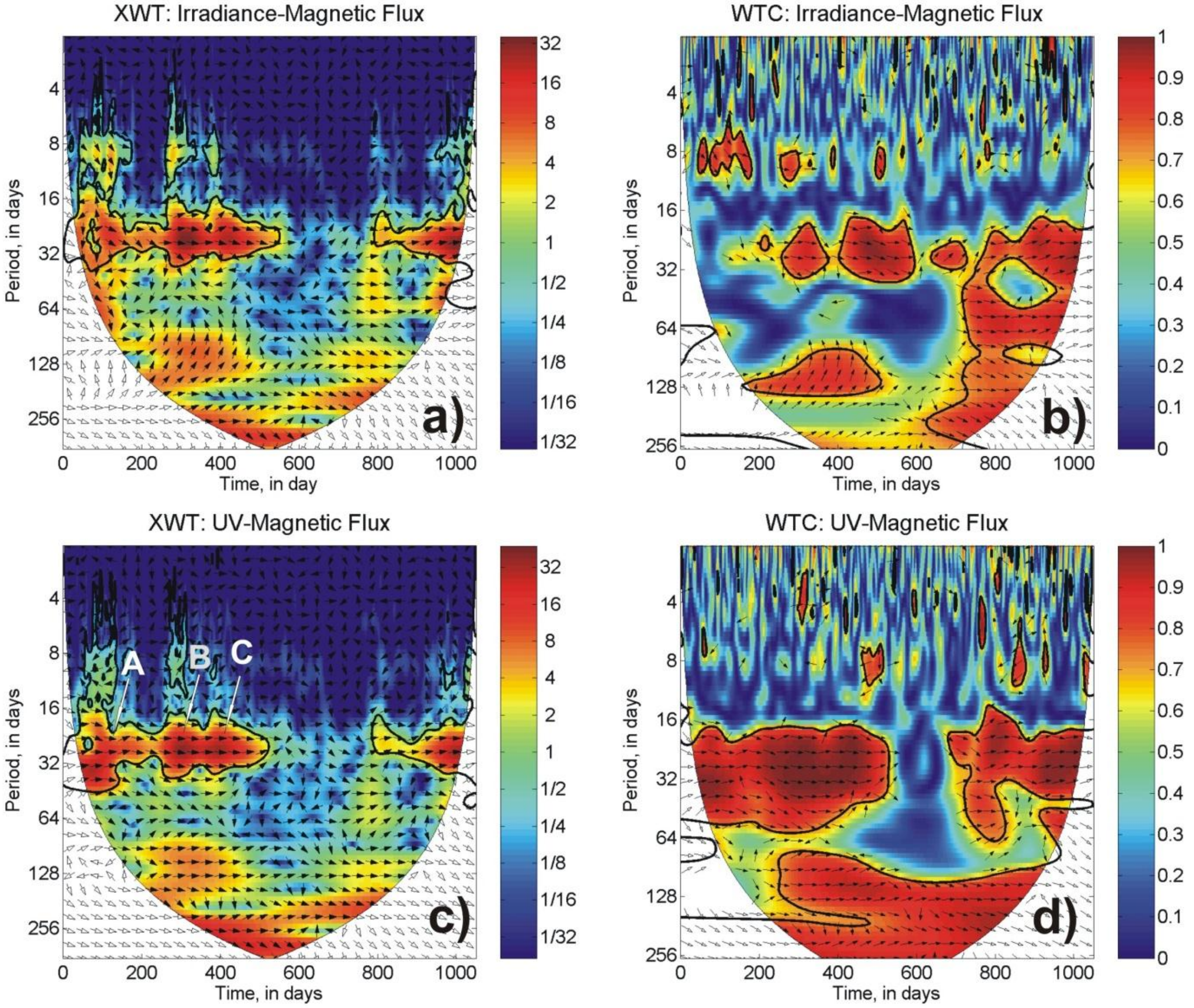

Figure 4. **a) Cross wavelet transformation of the irradiance and the magnetic flux; b) coherence of the irradiance and the magnetic flux; c) cross wavelet transformation of the ultraviolet and the magnetic flux; d) coherence of the ultraviolet and the magnetic flux. Arrows indicate the phase relationship between the two data series in time-frequency space: 1) arrows pointing to the right show the in-phase behavior; 2) arrows pointing to the left indicate the anti-phase behavior; 3) arrows pointing downward show that the first data series is by 90 ^{o} ahead of the second series; 4) arrows pointing upward indicate that the second data series is by 90 ^{o} ahead of the first series. Complexes of solar activity contributing to the TSI and UV are marked by A, B, C in panel c.**

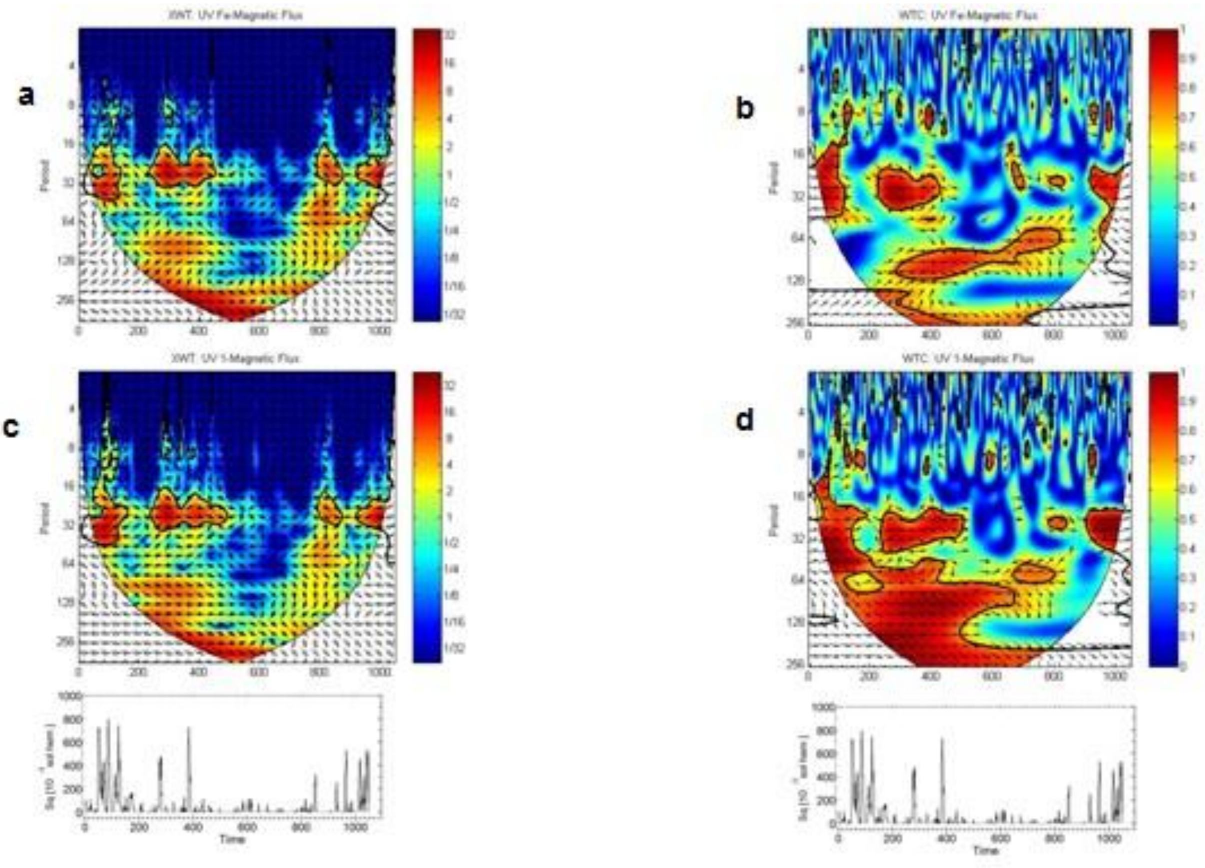

Figure 5. a) Cross wavelet transformation of the EUV FeXVI and the magnetic flux; b) coherence of the EUV FeXVI and the magnetic flux; c) cross wavelet transformation of the EUV in range 0.1-7nm and the magnetic flux; d) coherence of the EUV in range 0.1-7nm and the magnetic flux. Arrows indicate the phase relationship between the two data series in time-frequency space in the same way as in Figure 4. Time dependence of the sunspot areas is shown in the lowest graphs.

The coherent structures between the mid-latitude magnetic flux and EUV / XUV related to the appearance of sunspots in such complexes. Therefore, the non-uniform longitudinal distribution of the long-lived solar magnetic activity affects the solar irradiance.

Thus, complex ‘A’ does not create the coherent structure, but 'B' and 'C' display two coherent regions on periods of the surface activity rotation. The separation is related to the sunspot blocking effect. The coherent structure during the deep minimum shows, that the phase of the F mag is ahead of the total solar irradiance. This effect may be a result of the influence of the polar irradiance (due to bright polar faculae), which is in the anti-phase with the magnetic flux at mid-latitude during the solar minimum. In the case of the UV, the relationship between the polar irradiance and the mid-latitude magnetic flux is in phase due to the coronal holes visible in X-ray, UV, and EUV emissions.

Conclusions

A pronounced longitudinal non-uniform emerging of faculae and sunspots, and, as a result, a non-axisymmetrical distribution of the total and spectral solar irradiance was observed during the long minimum between cycles 23 and 24.

During the descending phase of the solar cycle 23, sunspots reappeared in the same plages, in a limited longitudinal zone, during 22 Carrington rotations. The Carrington longitude of these spots and faculae consecutively shifted from 180^o to 270^o, demonstrating the rotation rate slightly greater than the Carrington's. After the long minimum, sunspots of the cycle 24 tended to appear in the same longitudinal zone while the spots of the «old» cycle still exist.

The revealed tendencies make it possible to suppose that a long- lived local source of the emerging magnetic flux exists under solar photosphere. Our results also suggest that conditions for such a source to appear are stable relative to the process of cycle changing. According to the solar dynamo theory, the solar magnetic field during the minimum is expected to be a pure dipole. However, the existence of such a local long-lived subsurface source of magnetic field apparently indicates generation of a non-axisymmetrical component of the solar magnetic field due to dynamo process. And, possibly, such non-axisymmetrical component is the primary reason for the effect of the active longitudes, that is observed during active phases of the solar cycles.

Our comparative and cross wavelet analysis show that the increase in the magnetic flux in the latitudinal zone of the sunspot activity is accompanied with the increase in the TSI and UV on the timescale of the rotation of the solar activity complexes. The coherent structures between the mid-latitude magnetic flux and TSI / UV occurred in the case of the existence of the long-lived complexes of the solar activity. Therefore, the non-uniform longitudinal distribution of the long-lived solar magnetic activity affects the solar irradiance.

Indeed, the found coherent structures are associated with the development of such complexes of the solar activity. Moreover, coherent structures between the TSI and the magnetic flux confirm the idea about the interrelation of the activity processes going on the Sun in total.

A similar longitudinal pattern was observed at the beginning of the solar cycle 23 from June 1996 to June 1998 (Benevolenskaya, 2002). During this time, the longitudinal distribution of the total solar irradiance, EUV irradiance from the transition region and corona, and solar magnetic flux integrated over solar disk increase in the same longitudinal zone (200^o-300^o). We concluded that precisely the long-living complexes of sunspot activity associated with this longitudinal zone make a significant contribution to the variation of the total solar irradiance and to the heating of the solar corona.

Therefore, the revealed non-axisymmetrical character of the solar magnetic field turned out to be quite stable during the solar minimum and the solar irradiance is closely related to the nature of the solar magnetic field.

Acknowledgements

Authors thank -Dr. Grinsted, Prof. Moore, Dr. Jevrejeva, Dr. Torrence, Dr. Combo and Dr. Breitenberger for the development of the Wavelet Matlab package. Also we are thankful to the science team of SORCE, TIMED SEE and WSO for making their data available for free download. Part of this work is supported by the Program 22 of the Russian Academy of Science.

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