New Astronomy 60 (2018) 7–13

Contents lists available at ScienceDirect

New Astronomy

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

The quasi-biennial oscillation of 1.7 years in ground level enhancement events

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ARTICLE INFO

Keywords:
Solar flares
Ground level enhancements
Cosmic rays
Wavelet analysis

PACS:
Physics
Astronomy

ABSTRACT

The so-called Ground Level Enhancement events are sporadic relativistic solar particles measured at ground level by a network of cosmic ray detectors worldwide. These sporadic events are typically assumed to occur by random chance. However, we find that by studying the last 56 ground level enhancement events reported from 1966 through 2014, these events occur preferentially in the positive phase of the quasi-biennial oscillation of 1.7 year periodicity. These discrete ground level enhancement events show that there is another type of solar emission (i.e., wavelike packets) that occurs only in a specific phase of a very particular oscillation. We interpret this empirical result to support that ground level enhancement events are not a result of purely stochastic processes. We used the Morlet wavelet to analyze the phase of each of the periodicities found by the wavelet analyses and local variations of power spectral density in these sporadic events. We found quasi-regular periodicities of 10.4, 6.55, 4.12, 2.9, 1.73, 0.86, 0.61, 0.4 and 0.24 years in ground level enhancements. Although some of these quasi-biennial oscillation periodicities (i.e., oscillations operating between 0.6 and 4 years) may be interpreted as simply harmonics and overtones of the fundamental solar cycle from the underlying sun-spot magnetism phenomenon. The sources of these periodicities are still unclear. Also there is no clear mechanism for the variability of the quasi-biennial oscillation periodicities itself. The quasi-biennial oscillation periodicities are broadly considered to be a variation of solar activity, associated with the solar dynamo process. Also, the intensity of these periodicities is more important around the years of maximum solar activity because the quasi-biennial oscillation periodicities are modulated by the solar cycle where the Sun is more energetically enhanced during activity maxima. To identify the relationships among ground level enhancement, solar, and cosmic rays indices in time-frequency framework, we apply the wavelet coherence analysis. The fingerprints of solar activity and galactic cosmic rays on these phenomena can also be discerned in terms of the prominent quasi-biennial oscillation of about 1.7 years.

1. Introduction

The occurrence of solar proton events is a rather frequent phenomenon, which up to now is considered as a random event associated mostly with solar flares. At the same time, their close relations to magnetically active centers on the surface of the Sun and even to shock wave phenomena in the heliosphere is also presently recognized. In broad extent, their occurrence rate follows the 11-year Schwabe cycle of solar activity intimately related to the sunspot phenonemon.

Sporadically, with an average rate of 1.1 year^{-1}, a relativistic solar proton event occurs when protons acquire energies above 433 MeV (up to ≥ 10 GeV). This particular kind of events are also known as ground level enhancements of relativistic solar particles. These sporadic events are associated with solar flares and eventually with shock waves, and are assumed to be quasi-random in nature. Their study turns out to be very important for both astrophysical and terrestrial aspects: the study of their energy spectrum and intensity-time profile gives us important information about their physical sources and propagation processes, respectively. To a certain extent, these occasional phenomena follow the time behaviour of the 11-year cycle of solar activity; however, they do not strictly follow the intensity of the solar activity cycle.

In a preliminary work (Pérez-Peraza et al., 2009) we established, for the first time, the intrinsic periodicities modulating ground level enhancement events: mid-term periodicities, in the range of months to years, short-term periodicities in the order of months and ultra-short term in the order of days. Most of them are seemingly harmonics of the

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http://dx.doi.org/10.1016/j.newast.2017.09.007
Received 19 May 2017; Received in revised form 25 August 2017; Accepted 17 September 2017
Available online 20 September 2017
1384-1076/

11 year solar activity cycles. Many of these periodicities are quite similar to those existing in sub-photospheric and coronal layers (i.e., sunspot and coronal activity indices) as well as in solar activity phenomena.

Later, an exhaustive study of the periodicities of ground level enhancement and galactic cosmic rays was given in Miroshnichenko et al. (2012). Recently, in Pérez-Peraza et al. (2015) it was established that some of the dominant periodicities that are present in galactic cosmic rays 11, 4.7, 2.8, 1.7, 0.4, 0.25 and 0.075 years, which in turn coincide with those of solar activity 11, 7, 4.7, 3.5, 1.3, 0.9 and 0.4 years based on the sunspot number. With the exclusion of the 11 years periodicity of the solar cycle, it was determined that the most prominent periodicity in galactic cosmic rays and the sunspot number is that of 4.7 years. We claim that such similarity is a necessary condition, but it is however not sufficient to draw physical inferences on the phenomena that are taking place in the solar atmosphere.

The periodicities between 0.6 and 4 years are broadly categorized as the quasi-biennial oscillation of solar activity (see Bazilevskaya et al. (2014, 2016)), speculated to be associated with the underlying solar dynamo processes. In addition, the inter-relationship between quasi-biennial variations of solar activity and galactic cosmic rays was also analyzed by Bazilevskaya et al. (2014), Bazilevskaya et al. (2016).

In the analysis of quasi-biennial oscillation of solar activity, different filters are usually adopted (for more details, see e.g., Rivin (1989); Bazilevskaya et al. (2016)). But there is a practical problem, it is not clear what are the criteria to choose the correct and appropriate filters. Here we propose to use the wavelet coherence to resolve this problem Velasco Hererra (2008a). A first wavelet coherence analysis was performed by Velasco Hererra (2008b) and those authors found that many of the relativistic solar particles periodicities are in common with different facets of the solar atmosphere. Following this work, in Pérez-Peraza et al. (2011) we proposed a classification of ground level enhancement of relativistic solar particles on the basis of their spectral content: we delimited three main groups according to the level of enhancement over the galactic cosmic rays background.

Based on the ground works established previously, we have advanced the idea that the agreement in the modulation timescales found with wavelet coherence analysis between ground level enhancement periodicities and those of different layers of the solar atmosphere, indicates that ground level enhancement phenomena are not locally isolated phenomena but that there is apparently a well organized synchronization involving the whole Sun and even including the associated modulation of the incoming galactic cosmic rays fluxes. This empirical evidence argues against the pure stochasticity of ground level enhancement production.

It should be emphasized that even if the sunspot number is a representative proxy of solar activity phenomena, sunspots are not the ultimate source of ground level enhancement, which in turn is generally placed in the context of solar flare activity phenomenon (see e.g., attempts to connect solar flares to the underlying magnetic sunspot features in Eren et al. (2017)). A more direct proxy is now available from the Boğaziçi University Kandilli Observatory, Istanbul, Turkey which we will use in this paper.

Following our synchronization hypothesis, we attempt in this work by considering the effect of the source itself of ground level enhancement, that is the generating mechanisms of solar flare. We study, using the wavelet coherence analysis, directly the solar flare index for the period 1966 to 2014, which is a close-enough proxy of the particle acceleration source itself. We ignore here the ground level enhancement statistics available from 1942–1965 interval mainly because the solar flare index dates only from 1966 onward. In addition, we also carry out here a wavelet coherence analysis pairwise among galactic cosmic rays, ground level enhancement and solar flare index indices.

2. Data

The network of neutron monitors stations worldwide furnishes data of the ground level enhancement and galactic cosmic rays. Data since 1964 with high reliability are available from many neutron monitors stations; for the period from 1966 up to 2014 we have used monthly averaged galactic cosmic rays data from the Oulu neutron monitor station: http://cosmicrays.oulu.fi/.

The fact that the solar flare index is available only since 1966, we consider here 57 events (see Table 3 below) from the ground level enhancement-event no. 15 (July 07, 1966) up to ground level enhancement-event no. 71 (May 17, 2012) and digitally transformed into a binary signal (Velasco Herrera and Cordero, 2016), as follows:

$$F = \begin{cases} 1 & \text{there are GLE in given month} \\ 0 & \text{no GLE or no reported} \end{cases} \quad (1)$$

We note that the use of the binary function (F) does not produce spurious or fictitious periodicities but only influence the decrease in amplitude of spectral power per scale.

In our previous works, we have studied the coherence between the sunspot number and ground level enhancement activity variations. Since the relativistic solar protons are basically produced in solar flares and only indirectly through the sunspot index, in this work we take a new step forward by using the source of the phenomenon itself, that is, solar flare, solar flare index, statistics.

The solar flare index is a value related to the measure of this short-lived explosive activity on the Sun (Ataç, 1987; Özgüç and Ataç, 1989; 1996; 2003; Ataç and Özgüç, 1996; 1998; 2001). Here we used the monthly averaged data on total solar flare index from the Boğaziçi University Kandilli Observatory, Istanbul, Turkey http://www.koeri.boun.edu.tr/astronomy), from 1966 up to 2014.

3. Wavelet analysis

Concerning the methodology employed, let us remind here that in order to analyze local variations of power within a single non-stationary time series at multiple periodicities, (such as the galactic cosmic rays, ground level enhancement and solar flare index), we apply the wavelet tool using the Morlet wavelet (Torrence and Compo, 1998) because it provides a relatively higher resolution of the periodicity (frequency) scales. And because the basis analyzing function for the wavelet transform is a complex function, we are also able to calculate the phase information accurately (e.g. Velasco Herrera et al., 2015).

Meaningful wavelet periodicities (confidence level greater than 95%) must be contained inside the cone of influence (lightly shaded zones in Figs. 1 and 2) of solar flare index and the interval of 95% confidence (Torrence and Compo, 1998) is marked by red dotted lines (left panels in all figures). The global spectra (left panels in all figures) have been included in the wavelet plot in order to show the power contribution of each periodicity inside the cone of influence. To determine the statistical significance levels of the global wavelet power spectrum, it is necessary to choose an appropriate background spectrum. For many phenomena, an appropriate background spectrum is either white noise (with a flat Fourier spectrum) or red noise (increasing power with decreasing frequency). We established our significance levels in the global wavelet spectra with a simple red noise model (Gilman et al., 1963).

The uncertainties of each meaningful periodicities (peak in global wavelet spectrum) are obtained from the full-width at half maximum values (Mendoza et al., 2006).

The squared coherency is used to identify frequency bands within which two time series are covarying and is a measure of the intensity of the covariance of the two series in time-frequency space. The wavelet transform coherence (WTC) is especially useful in highlighting the time and periodicity intervals, when the two phenomena (X and Y) have a

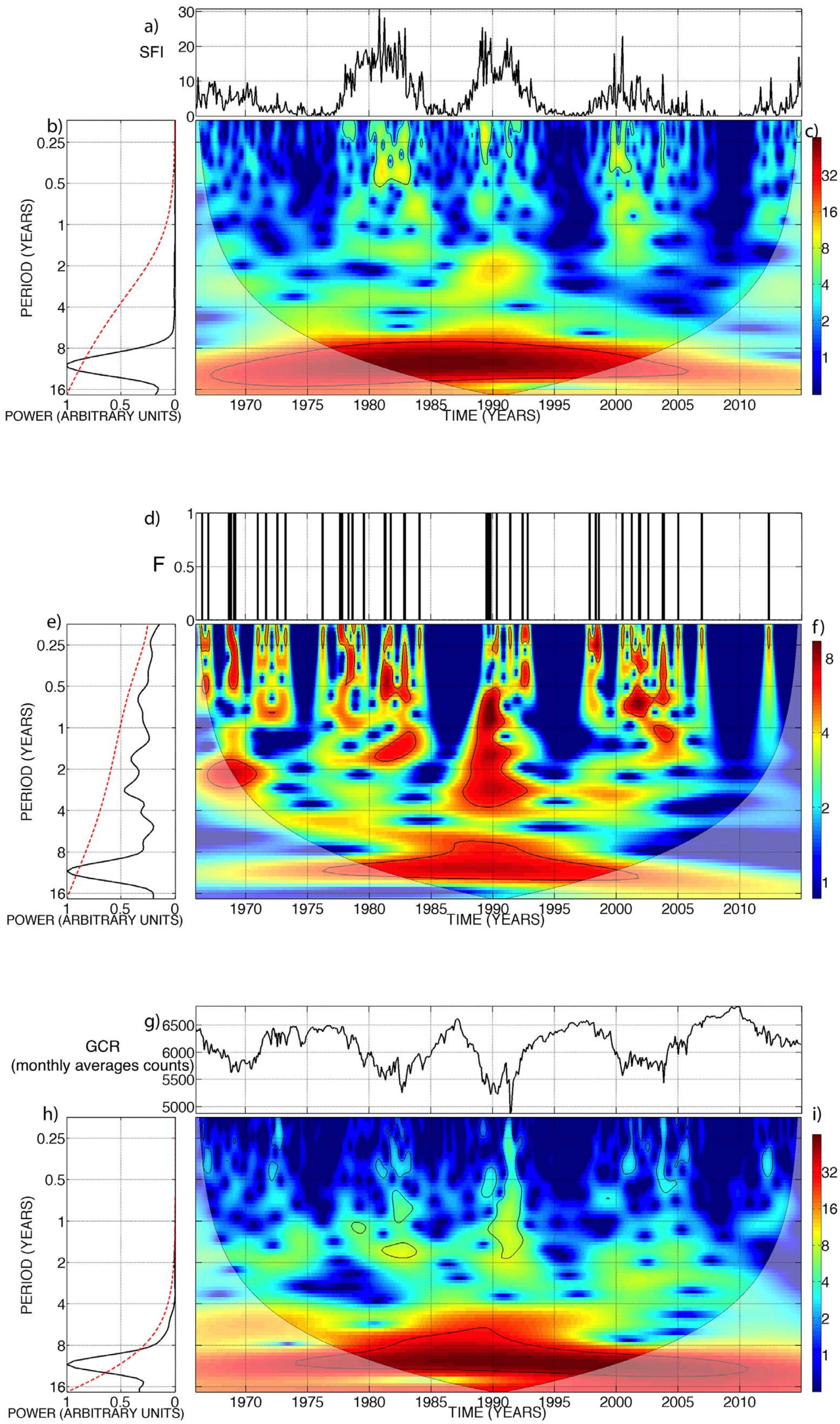

Fig. 1. Wavelet transform analysis of solar flare index (SFI), ground level enhancements (F) and galactic cosmic rays (GCR) time series (black line in a, d, and g) between 1966 and 2014. The wavelet powers are shown in the central panel (c, f, and i), where the curved outlines mark zones of the cone of influence. The color bar scale shows the wavelet spectral power in arbitrary normalized units. The thick contour is the 95% confidence level for the corresponding red-noise spectrum. The global wavelet is shown in the left panel (b, e, and h). The red dotted lines marked the 95% red-noise levels of the global spectra. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strong coupling, and is defined (Torrence and Compo, 1998) as:

$$WTC_n^{XY}(s) = \frac{\langle |W_n^{XY}(s)|^2 \rangle}{\langle s^{-1}|W_n^X(s)|^2 \rangle \langle s^{-1}|W_n^Y(s)|^2 \rangle} \quad (2)$$

where $W_n^{XY}(s)$ is the cross wavelet spectrum of two time series X and Y, with wavelet transforms $W_n^X(s)$ and $W_n^Y(s)$ respectively, $\langle . \rangle$ indicates smoothing both in time and scale (e.g. Grinsted et al., 2004; Velasco Hererra et al., 2017), n is the time index and s is the wavelet scale. The factor s^{-1} is used to convert to energy density.

The global wavelet coherence spectrum (GWTC) is defined (Velasco and Mendoza, 2008) as:

$$GWTC = \sum_n WTC_n^{XY}(s)$$

The statistical significance level of the wavelet coherence is estimated using Monte Carlo methods with red noise to determine the 5% significance level (Torrence and Webster, 1999). The Monte Carlo estimation of the significance level uses on the order of 1000 surrogate data set pairs (Grinsted et al., 2004).

If the wavelet spectrum is calculated individually for two or more time series and these spectra show that they have some periodicities in common, this does not necessarily means there is a physical relationship between them. However, if the global wavelet coherence spectrum shows that there are common periodicities; this implies that there is a physical mechanism and/or certain medium connecting these two phenomena. It is precisely such frequency synchronization that may indicate that there is coupling, modulation and/or resonance between these two distinct phenomena studied.

Broadly speaking, the WTC metric measures the degree of similarity between the input (X) and the system output (Y), as well as the consistency of the output signal (X) due to the input (Y) for each frequency component. If the coherence between two series is high, the arrows in the coherence spectra show the phase between the phenomena: arrows at 0° (horizontal right) indicate that both phenomena are in phase and arrows at 180° (horizontal left) indicate that they are in anti-phase. It is very important to point out that these two cases imply a linear relationship between the considered phenomena; arrows at 90° and 270° (vertical up and down, respectively) indicating an out of phase situation which means that the two phenomena have a non-linear relationship (i.e., see Soon et al., 2014; Velasco Herrera and Cordero, 2016; Velasco Herrera, 2016; Velasco Herrera et al., 2017).

4. Results and discussion

Fig. 1 shows the wavelet spectra of the solar flare index , the ground level enhancement and the galactic cosmic rays records, respectively. The time series are shown in the top panels (black line in Fig. 1a, d, and g), and the wavelet powers are shown in the central panels in time-frequency representation (Fig. 1c, f, and i). The global-averaged wavelet spectra (GWS) indicating the main periodicities appears in the left panel of each figure (Fig. 1b, e, and h).

In Fig. 1a, we show the wavelet analysis of the solar flare index from 1966 to 2014. The GWS (Fig. 1b) presents periodicities of 10.4, 5.2, 3.27, 2.45, and 1.73 years and of 262, 146, and 76 days. It is noted that in the central panel where a periodicity of 10.4 years is shown, the spectral power is distributed evenly throughout the whole time interval (1966–2014), whereas the spectral powers of periodicities under 10.4 years are most visible only around the time of solar activity maxima (Fig. 1c).

The wavelet analysis of the ground level enhancement from 1966 to 2014 is shown in Fig. 2d. The GWS (Fig. 1e) presents periodicities of 10.4, 6.55, 4.12, 2.9, and 1.73 years and of 313, 222, 146, and 87 days. The frequency spectral power for 10.4 years is present throughout the time interval. Once again, the modulations of ground level enhancement events on periodicities shorter than 10.4 years mainly occur around the phase of solar activity maxima (Fig. 1f).

The wavelet analysis of the galactic cosmic rays between 1966 and 2014 is shown in Fig. 1g. The GWS (Fig. 1g) presents periodicities of 10.4, 5.2, 3.09, 1.83, and 1.22 years and of 281 and 156 days. For the periodicity of 10.4 years, the spectral power is distributed evenly throughout the whole record from 1966 to 2014, whereas the spectral powers of the periodicities under 10.4 years are most prominent only around solar maxima (Fig. 1i).

The periodicity of 10.4 years corresponds to the Schwabe cycle and is present in all of the time series, with the main power concentrated in this periodicity. This periodicity has been detected at a confidence level greater than 95%. The periodicity of 5.2 years corresponds to the quasi-quinquennial cycle Velasco Hererra (2008a), while the periodicities between 0.6 and 4 years are noted as the quasi-biennial oscillation of solar activity (Bazilevskaya et al., 2014; 2016), presumably associated with the solar dynamo process. Regarding the 4.7–5.5 years periodicity, Djurović and aquet (1996) reported these periodicities in sunspot areas, as well as in the coronal activity index, Wolf numbers and solar flux at 10.7 cm.

We wish to note that the periodicity of 1.8 years in Total Solar Irradiance index has been contemplated and reported by Li et al. (2010). The plausible connection of such short-term periodicity to the underlying instrinsic solar magnetism or solar dynamo operation can be further motivated by the recent exciting discovery of such a mid-term periodicity by Egeland et al. (2015) in a young (about 1 Gyr old) Sun analog, HD 30495. Apparently, the solar and stellar dynamo generation and/or modulation of such mid-term 1.7–1.8 years oscillation is nearly universal.

The periodicity of 146 days is the Rieger-type cycle, and 76 days is a short periodicity. The intensity of these periodicities is more important around the years of maximum solar activity because the mid-term, short and ultra-short periodicities are modulated by the solar cycle where the Sun is more energetically enhanced during activity maxima Valdés-Galicia and Velasco (2008). The intermediate-term periodicities (87–106, 159–175, 194–219, 292–318 and $\sim$ 389 days) in sunspot areas has been reported by Chowdhury et al. (2009). In Table 1, we summarize the main periodicities with their uncertainties for the solar flare index, ground level enhancement and galactic cosmic rays records deduced in our analyses.

The pairwise wavelet coherence analyses between solar flare index , ground level enhancement, and galactic cosmic rays time series from 1966 to 2014 are shown in Fig. 2. Fig. 2a and c illustrates the wavelet coherence (WTC) spectrum between solar flare index and ground level enhancement statistics (black line and black bars, respectively). It can be seen from the corresponding global wavelet coherence spectra (Fig. 2b) that the common periodicities between these two phenomena are 10.4, 4.74, 3.04, 1.67 0.9 and 0.59 years. All these periodicities have confidence levels greater than 95%, with the exception of the periodicity of 4.74. Other than the 11 years periodicity of the solar cycle, the most prominent one is that of 1.67 years, called hereafter as the 1.7 years periodicity (taking into account the uncertainty margin for the wavelet basis in resolving this timescale/period). It should be noted that this periodicity divides the ground level enhancement into five intervals, each of which are well defined within solar Schwabe Cycles 20–24: 1966–1972, 1975–1985, 1986–1994, 1996–2006 and 2011–2014. It can be seen that they are linearly correlated most of time with the exception of Cycle 22 where the correlation is of a rather complex nature.

Fig. 2d and f shows the wavelet coherence spectrum between galactic cosmic rays and ground level enhancement (black line and blue bars, respectively): the common periodicities in this case are 10.4, 4.52, 2.89, 1.59, 0.7 and 0.44 years. Here the periodicities between galactic cosmic rays and ground level enhancement are in anticorrelation and all these periodicities have confidence levels greater than 95%, with the exception of the periodicity of 4.79 The 1.59 years periodicity (confidence level greater than 95%) designated from here on as the 1.7-year

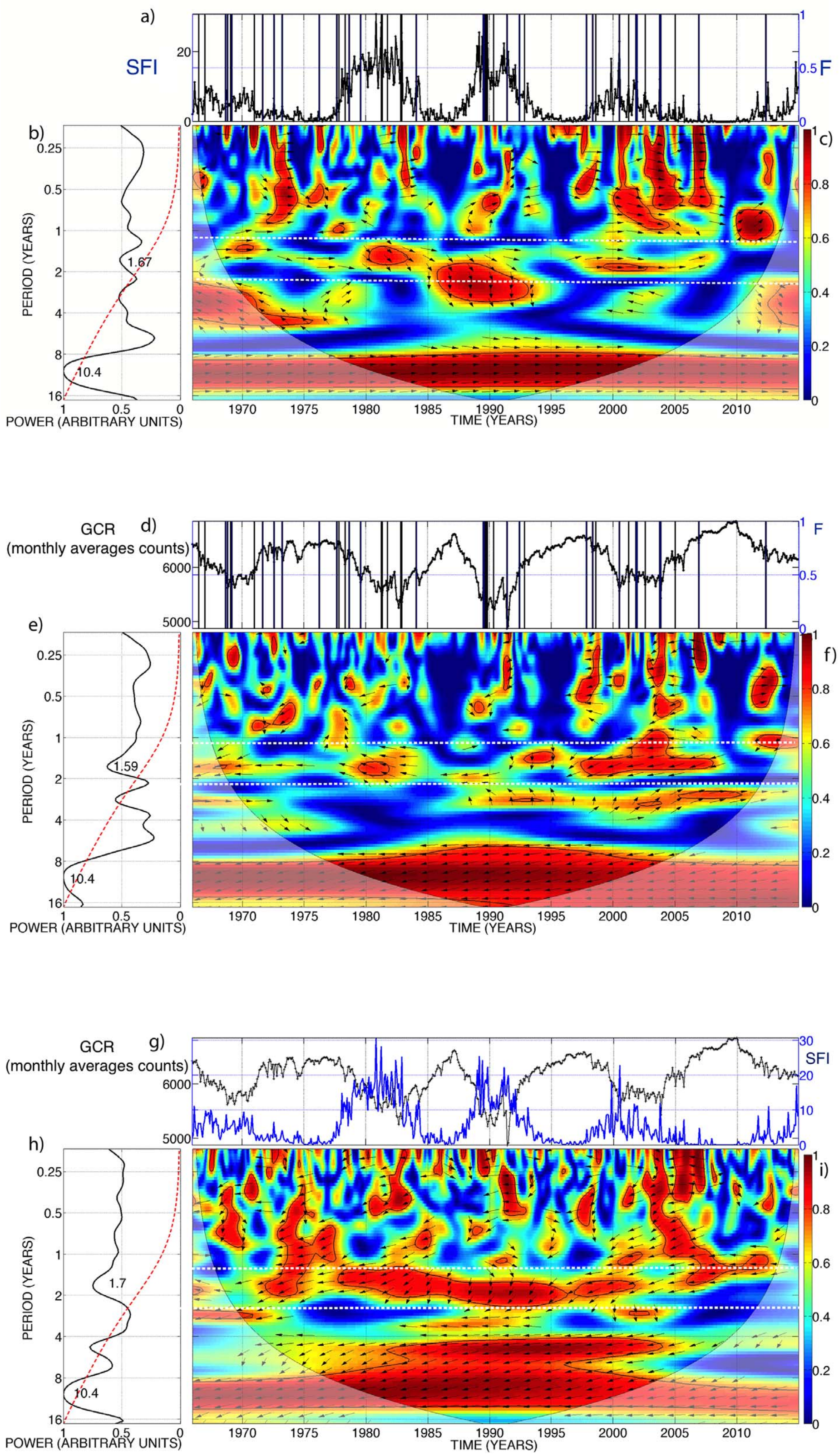

Fig. 2. Results of the wavelet coherence (WTC) analysis for the solar flare index and ground level enhancement (black line and black bars respectively in a), galactic cosmic rays and ground level enhancement (black line and black bars respectively in d), and solar flare index and galactic cosmic rays (blue line and black line respectively in Fig. 2g) time series from 1966 to 2014. The left panels (Fig. 2b, 2e, and 2h) shows the global spectrum of the wavelet coherence power. The red dotted line represents the significance level of the global spectrum and refers to the power of red noise level at the 95% confidence interval, as described in Fig. 1. The center panels show the wavelet coherence power (c, f, and i). The color bar scale shows the wavelet coherence power. The orientation of the arrows shows relative phasing of the two time series at each timescale; arrows at 0° (pointing to the right) indicate that both time series are perfectly positively correlated (in phase) and arrows at 180° (pointing to the left) indicate that they are perfectly negatively correlated (180° out of phase), both of these two perfect cases implying a linear relationship between the considered phenomena; non- horizontal arrows indicate an out of phase situation and a more complex non-linear relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

periodicity that divides the ground level enhancement in 5 intervals: 1966–1974, 1976–1985, 1988–1995, 1997–2006 and 2010–2014.

Fig. 2g and i presents the wavelet coherence spectrum between the solar flare index and galactic cosmic rays (blue line and black line, respectively). Here, the common periodicities are 10.4, 4.79, 3.19 1.76 1.13, 0.76, 0.3 and 0.23 years. Again, these two phenomena are anticorrelated. All these periodicities have confidence levels greater than 95%, with the exception of the periodicity of 2.89 years. In Table 2, we present the main periodicities detected with their uncertainties from the pairwise wavelet coherence calculations among the three time series records: solar flare index, ground level enhancement and galactic cosmic rays statistics.

Table 1
Main periodicities (in years) that contribute to solar flare index, ground level enhancement and galactic cosmic rays.

Periodicities	Solar flare index	ground level enhancement	Galactic cosmic rays
Short (≤1 years)	0.72 ± 0.3	0.86 ± 0.2	0.77 ± 0.2
	0.40 ± 0.2	0.61 ± 0.3	
	0.21 ± 0.01	0.40 ± 0.1	
		0.24 ± 0.1	
Mid-term periodicities (1–2 years)	2.45 ± 0.5	2.9 ± 0.5	1.73 ± 0.6
	1.73 ± 0.5	1.73 ± 0.6	1.22 ± 0.5
			2.75 ± 0.5
3 years cycle (Quasi-triennial)	3.3 ± 0.7	4.12 ± 0.7	3.09 ± 0.8
5 years cycle (Quasi- quinquennial)	5.2 ± 1.1	6.55 ± 0.9	5.20 ± 1.4
Decadal	10.4 ± 2.3	10.4 ± 2.1	10.4 ± 1.9

Table 2
Main common periodicities (in years) in the pairwise wavelet coherence between solar flare index, ground level enhancement and galactic cosmic rays.

Periodicities	Galactic cosmic rays	Ground level enhancement
Solar flare index	10.40 ± 2.1	10.4 ± 2.3
	4.79 ± 1.3	4.74 ± 1.1
	3.19 ± 0.5	3.04 ± 0.7
	1.76 ± 0.3	1.67 ± 0.3
	1.13 ± 0.2	0.90 ± 0.1
	0.76 ± 0.1	0.59 ± 0.1
	0.30 ± 0.03	
	0.23 ± 0.01	
ground level enhancement	10.40 ± 2.3	
	4.52 ± 1.2	
	2.89 ± 0.5	
	1.59 ± 0.2	
	0.70 ± 0.1	
	0.44 ± 0.03	

The quasi-biennial oscillation of 1.7 years divides all ground level enhancement events into five intervals, and is one of the most prominent periodicities in the wavelet coherence. This empirical observation permits the assumption that there is a connection between this oscillation and the occurrence of the ground level enhancement events. To identify the relationships between ground level enhancement and quasi-biennial oscillation of 1.7 year as a function of time, we apply the inverse wavelet transform in wavelet spectrum of the ground level enhancement events (Torrence and Compo, 1998; Velasco Herrera et al., 2017).

Fig. 3 shows the time variation of the 1.7 years oscillation (obtained with inverse wavelet transform) and the discrete ground level enhancement events (dotted red line and black bars, respectively) analyzed from 1966 to 2014 (see Table 3 for all recorded ground level enhancement events). In addition, the sunspots (gray shaded area) are shown to describe the solar cycles. It can be observed that of the 57 ground level enhancement events analyzed, none of the events occurred during solar minima of Cycles 20 to 23. In the solar Cycle 20, the ground level enhancement-no. 15 to ground level enhancement-no. 26 events were registered, in the solar Cycle 21 the ground level enhancement-no. 27 to ground level enhancement-no. 39 events occurred, during the Cycle 22 of the ground level enhancement-no. 40 to ground level enhancement-no. 54 events occurred, in the solar Cycle 23 of ground level enhancement-no. 55 to ground level enhancement-no. 70 events were recorded. During the solar Cycle 24 only the ground level enhancement-no. 71 event is reported around May 17, 2012.

It is often assumed that ground level enhancement events are random phenomena. However, it can be deduced from the 57 ground level enhancement events analyzed that they occur preferentially in the

Table 3
57 Ground level enhancement events from 1966 through 2014.

Event	Event date			Event	Event date		
15	7	July	1966	44	22	October	1989
16	28	January	1967	45	24	October	1989
17	28	January	1967	46	15	November	1989
18	29	September	1968	47	21	May	1990
19	18	November	1968	48	24	May	1990
20	25	February	1969	49	26	May	1990
21	30	March	1969	50	28	May	1990
22	24	January	1971	51	11	June	1991
23	1	September	1971	52	15	June	1991
24	4	August	1972	53	25	June	1992
25	7	August	1972	54	2	November	1992
26	29	April	1973	55	6	November	1997
27	30	April	1976	56	2	May	1998
28	19	September	1977	57	6	May	1998
29	24	September	1977	58	24	August	1998
30	22	November	1977	59	14	July	2000
31	7	May	1978	60	15	April	2001
32	23	September	1978	61	18	April	2001
33	21	August	1979	62	4	November	2001
34	10	April	1981	63	26	December	2001
35	10	May	1981	64	24	August	2002
36	12	October	1981	65	28	October	2003
37	26	November	1982	66	29	October	2003
38	7	December	1982	67	2	November	2003
39	16	February	1984	68	17	January	2005
40	25	July	1989	69	20	January	2005
41	16	August	1989	70	13	December	2006
42	29	September	1989	71	17	May	2012
43	19	October	1989				

positive phase of the oscillation of 1.7 years. This could possibly mean that the ground level enhancement events, apparently not quite a random process, but that they appear in packages in the positive phase of this periodicity, most likely when there are certain favorable conditions in the solar chromosphere. This result is surprising, since solar phenomena have almost always been considered to be quasi-continuous events. These ground level enhancement events show that there is apparently another type of solar manifestation, i.e., the "solar packets" that, occur only in a selected phase of a very particular persistent oscillation.

The fact that the ground level enhancement events, can occur at any time of the positive phase of the quasi-biennial oscillation of 1.7 years, has indeed been suggested that these events are a consequence of random processes. However, from the point of view of solar packets, the ground level enhancement events may ultimately not a random process at all. The occurrence of these events are very well determined in the positive phase of the quasi-biennial oscillation of 1.7 years. We admit, that within this phase, there is an indeterminacy of when ground level enhancement events can or will occur. But, we have managed to limit in time, the occurrence of these relativistic sporadic wave-packet-like events. The periodicity of 1.7 years has been reported in different quasi-continuous solar indices (see for example Bazilevskaya et al., 2014; 2016; Mendoza et al., 2006; Valdés-Galicia and Velasco, 2008 and the cited references). What is surprising about the ground level enhancement events is that it is a discrete time series but that it also has this periodicity.

5. Conclusions

We have applied wavelet transform to study the time-frequency characteristics of ground level enhancement events and we found quasi-regular periodicities of 10.4, 6.55, 4.12, 2.9, 1.73, 0.86, 0.61, 0.4 and 0.24 years.

It can be noted that the quasi-biennial oscillation of 1.7 years divides the ground level enhancement events into five intervals, each of which are well defined within solar Cycles 20–24.

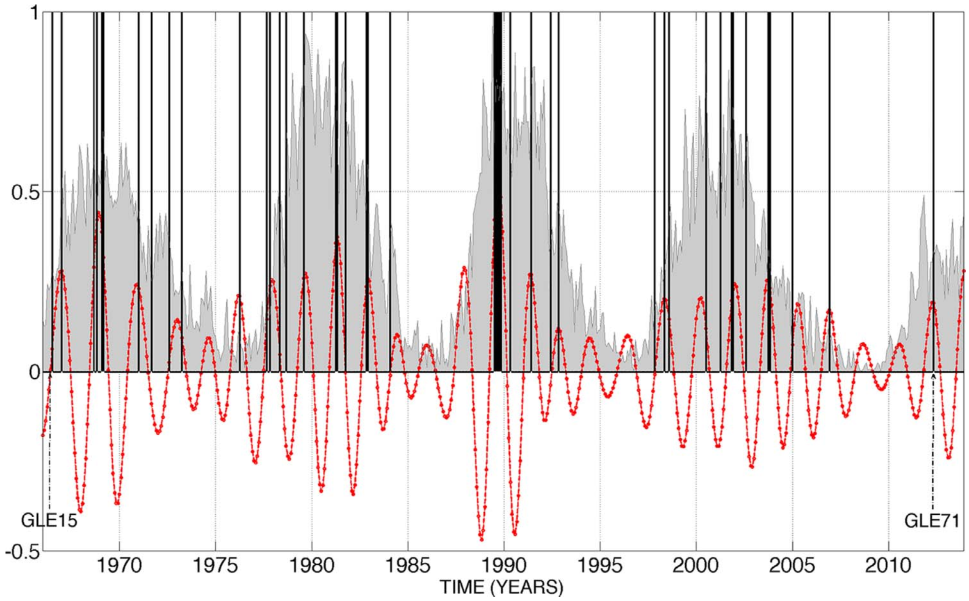

Fig. 3. The distribution of discrete ground level enhancement events (black bars marking events 15 to 71) in solar Schwabe Cycles 20–24 (gray shaded area). These events occur preferentially in the positive phase of the quasi-biennial oscillation of 1.7 years (dotted red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The ground level enhancement sporadic events are typically assumed to be of a random nature. However, we find that the last 57 ground level enhancement events reported from 1966 to 2012 occur preferentially in the positive phase of the quasi-biennial oscillation of 1.7 years. This empirical result suggests that the ground level enhancement events may not simply be of chance occurrences after all.

In order to understand the physical relationship among solar activity, galactic cosmic rays and ground level enhancement, we have performed a wavelet coherence analysis of three inter-related phenomena involved: galactic cosmic rays, ground level enhancement and the source itself of ground level enhancement, that is, solar flare index. As it can be expected galactic cosmic rays are in anti-correlation with phenomena of solar activity, specifically in our case, with solar flare index and ground level enhancement. In contrast, the relationship between ground level enhancement and the solar flare index is positively related and roughly linear in its correlation.

The changes in galactic cosmic rays provide information about the occurrence when ground level enhancement can be related to the synchronization of some periodicities of galactic cosmic rays with those developed in solar flare index and ground level enhancement during the gestation of an ground level enhancement event. Thus, the empirical relation deduced here may ultimately be used as a predictor of ground level enhancement occurrences.

In Table 1, we summarize the most prominent periodicities for each of the studied phenomena. It can be appreciated that in spite of slight differences, these periods can be grouped in five categories.

In Table 2 we show the common periodicities between the studied phenomena. It can be observed that they are quite close, within the limits of the detection uncertainty: among the most prominent periodicities involved in the coupling of these three phenomena are the 1.7 year periodicity (1.67, 1.76 and 1.59 years) as well as the 4.7 years (4.74, 4.79 and 4.52) which likely played a prominent role for the synchronization between solar flare index , ground level enhancement and galactic cosmic rays. Our independent analyses confirm the mid-term flare periodicities previously reported by Kilcik et al. (2010). Finally, the physical reality (rather than a mere statistical chance or even artefact) of the mid-term 1.7 years periodicity can find independent confirmation from a recent result on the study of a young Sun analog, HD 30495 (Egeland et al., 2015).

Acknowledgments

Pérez-Peraza thanks the support of UNAM, DGAPA-PAPIIT by means of grant IN106214. Velasco Herrera V.M. acknowledges the support from CONACyT-180148 and PAPIIT IN107618 grants. Willie Soon's work was partially supported by the SAO grant with proposal ID: 000000000003010-V101. We express our sincere gratitude to T. Ataç and A. Özgüç from Bogazici University Kandilli Observatory, Istanbul, Turkey for providing us with the flare index data used in this study.

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