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Distribution of solar energetic particle events over an 11-year solar cycle

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Abstract. Solar energetic particle (SEP) events are powerful signatures of solar activity. In general, the rate of SEP events changes in phase with the 11-year solar cycle, as it is seen, for instance, in the sunspot number. However, it is known that the rate of major SEP events suffers a reduction around solar activity maximum (Gnevyshev Gap). Other depressions in the SEP event rate also occur in the course of a solar activity cycle. Such a behaviour is a common feature of many solar activity parameters. A suggestion was put forward that these depressions are a consequence of the superposition of 11-year and quasibiennial oscillations of solar activity. Based on the different appearance of these phenomena on the Sun and in the interplanetary space, an attempt is undertaken to get some information on the SEP origin.

1 Introduction

There are some distinctive features in the temporal evolution of an 11-year solar cycle that can be used for a better understanding of solar activity and its relation to heliospheric and terrestrial conditions. Among them the Gnevyshev Gap (GG) effect was defined as an occurrence of a double/multi-peaked structure in the maximum phase of an 11-year solar activity cycle (Storini and Felici, 1994; Storini, 1995; Storini and Pase, 1995). It is a common feature of solar activity parameters relevant to both the rather slow and rapid processes, e.g., sunspot area formation and X-ray bursts (Feminella and Storini, 1997). It was found (Bazilevskaya et al., 2000) that in the solar activity cycles 21 and 22 GGs appear even more pronounced if considered separately for the Northern and Southern solar hemisphere. Furthermore, it was found that a similar peak and gap structure occurs in the ascending and descending phase of a solar cycle although it is masked there by the rapid change of solar activity. Subtraction of a smoothed 11-year trend from the monthly averaged series of several solar activity indices (sunspot area, H-alpha flare number, energy index of solar magnetic field at the photosphere) separated into Northern and Southern hemispheres revealed a quasibiennial oscillation (QBO) with an amplitude modulated in the course of the 11-year cycle. The maximum amplitudes were observed in the maximum phase of solar activity giving rise to the Gnevyshev Gaps. The QBOs in the opposite solar hemispheres have a similar time-scale but they may (or may not) be shifted in time. Since interplanetary space parameter response depends on the whole solar disk activity, their corresponding variations differ to some extent from that of solar activity.

Solar energetic particle events (SEP events) refer to the most powerful signatures of solar activity. It is now widely accepted that majority of SEPs is accelerated by shock waves driven by coronal mass ejections (CMEs) through the corona and interplanetary space (e.g. Reames, 1999). However, many SEP events, including ground level enhancements (GLEs), are reliably associated with solar flares not rejecting the contribution from CMEs. An effect of SEP event rate reduction close to the solar maximum was reported by M.N. Gnevyshev (Gnevyshev, 1963, 1967, 1977) and later repeatedly confirmed.

This paper is focused on the comparison of temporal variation in the SEP event rate during the 11-year solar cycle with the QBOs observed on the Sun and in the interplanetary space. The purpose is to clarify the role of solar flares and CME driven shocks in the SEP occurrence. The solar parameters allowing separation into Northern and Southern hemispheres are correlated to the SEP events reliably associated with flares. Then all SEP events without any selection with respect to the flare association are related

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to the solar activity summarized over the disk and to the rate of storm sudden commencements (SSC) which are taken as proxies for interplanetary disturbances.

Only brief results of our analysis are presented here because of space lack. Details will be published later.

2 Data selection and processing

2.1 Solar energetic particle events

The period from 1955 to 2000 was considered. Information on SEP events with >10 MeV solar proton intensity in the maximum of the intensity time profile J_{10}= J(E ≥10 MeV) ≥10 cm^{-2} s^{-1} sr^{-1} was compiled by Shea and Smart (1990) and in the GOES data sets (http://spidr.ngdc.noaa.gov). Search for the solar flares associated with a given SEP event was performed by a team including cosmic ray and solar physicists while compiling the SEP event Catalogues (Akiniyan et al., 1983, Bazilevskaya et al., 1990, Sladkova et al., 1998), where the association procedure is described in detail. Information on reliability of the SEP-solar flare association is available for a series of SEP events with J_{10} (E ≥10 MeV) ≥1 cm^{-2} s^{-1} sr^{-1}. Only events reliably associated to flares were selected for further processing. They make around 70% of the total number of SEP events with J_{10}= J(E≥10 MeV) ≥ 1 cm^{-2} s^{-1} sr^{-1}. These data cover 21 and 22 solar cycles. The GLE series (1956-2000) were obtained at WDC-B.

2.2 SEP related parameters

The data for the grouped H-alpha flares and X-ray bursts were taken from (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES). These data are available only beginning from solar cycle 21. It was shown by Bazilevskaya et al. (2000) that QBOs in the solar flare rates are in phase with QBO in other solar indices, e.g., sunspot area (SSA) when considered separately for each solar hemisphere. Therefore, we used SSA data from Pulkovo (Solar Data, 1955-1995) and USAF/NOAA data for 1996-2000 (http://science.msfc.nasa.gov/ssl/pad/solar/greenwch.html) as proxies for the flare activity. The information about SSC is from (gopher.ngdc.noaa.gov)

2.3 Data processing

The monthly means for all analysed data series were constructed: all SEP event rates for 1955-2000 (hereafter SEP (*J >10)* series); SEP events related to flares in the Northern and Southern solar hemispheres for 1975-1995 (*FlassN, FlassS* series); monthly mean series for SSA for each solar hemisphere. Concerning the QBOs the SSA series were taken as proxies for the flare activity. Monthly means of SSC rate served as a robust signature for CME rate.

A procedure revealing QBO proposed by Bazilevskaya et al. (2000) is applied here to the SEP, SSA, and SSC data series. It consists of a 7-month and 25-month running averaging and subtraction of the 25-month smoothed values from the 7-month smoothed ones. A validation of the procedure will be proved elsewhere.

3 Results

Figure 1 shows the time history of SEP (*J >10*) events and GLEs just to demonstrate the peak and gap structure during more than 4 solar cycles. The GG in the GLEs is not seen in cycle 22 because it lasted less than 1 year. Periods of solar maxima are denoted by horizontal bars.

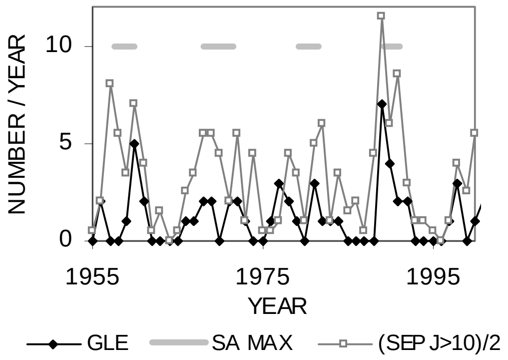

Fig. 1 Annual means of GLE number and SEP (*J >10*) event number (divided by 2).

In Figure 2 we present the QBOs in SSA and H-alpha solar flare rate to demonstrate a very close correlation between these two data series in each solar hemisphere for solar cycles 21-23. The flare rate is normalized to SSA values by linear regression method. The GLEs are shown by vertical bars and periods of solar maxima by horizontal bars. The QBOs amplitude reaches maximum in the solar maximum periods.

The SEP (*J >10*) events cannot be always referred to a definite solar hemisphere. Hence, we used the total data set without hemispheric division, i.e., the SEP (*J >10*) QBOs were correlated to the total disk SSA and SSC series. The results are given in Figure 3. It is seen that the QBO amplitude of SSC number is not so low in the minima of solar activity as that of SEP (*J >10*), especially in 1987-1988 and 1994-1996. Nevertheless, the correlation coefficient between the QBOs in SEP (*J >10*) and those in SSC is R_{ssc} = 0.57 ± 0.03, whereas, the correlation coefficient between the QBOs in SEP (*J >10*) and those in SSA is R_{ssa} = 0.32 ± 0.04. A significant value of R_{ssc} confirms a major role of interplanetary disturbances in the SEP event occurrence.

This result is corroborated by the superposed epoch analysis. The months of the minimum values of QBO in the

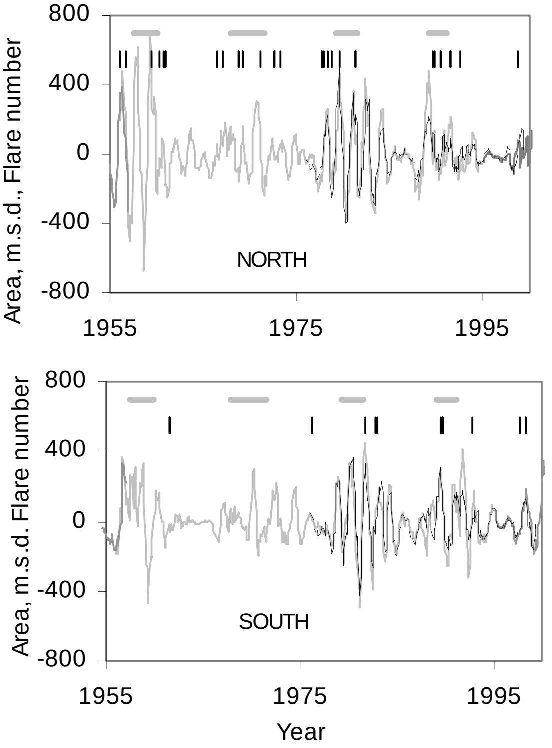

Fig. 2 QBOs in sunspot area and flare number.

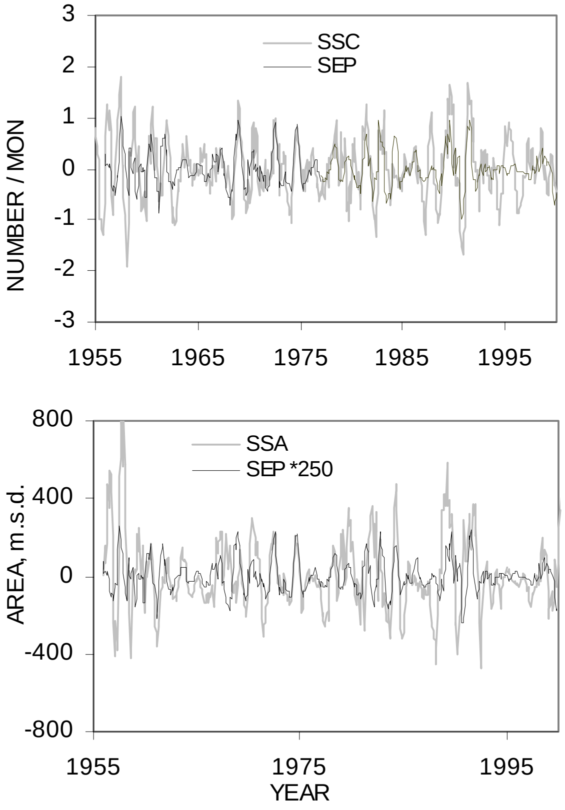

Fig. 3 QBOs in SEP($J > 10$) series in comparison with SSC (top) and SSA (bottom) series

SSC and in the whole disk SSA were taken as the zero months. The SEP ($J > 10$) monthly rate distribution relative to the zero months during 1955-2000 is shown in Figure 4. The SEP ($J > 10$) event occurrence is less probable in the SSC QBO minimum phase, but this is not the case in the SSA QBO minimum. The SEP events with reliable flare association compiled series *FlassN, FlassS* according to connection with Northern and Southern flares, respectively.

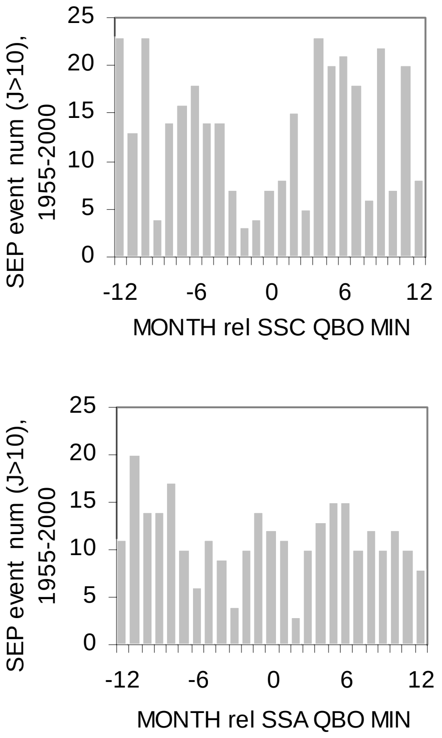

Fig. 4 Number of SEP (J >10) events relative to QBO minimum phase in SSC (top) and SSA number (bottom).

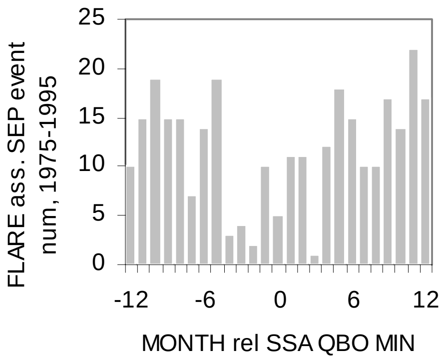

Fig. 5 Number of the flare associated SEP events relative to QBO minimum phase in SSA taken separately in each solar hemisphere.

The superposed epoch procedure was fulfilled choosing the zero months at the QBO minimum phase for SSA separately in the Northern and Southern solar hemispheres. The result is plotted in Figure 5.

There is a clear reduction around the zero month. Therefore, reliably flare associated SEP events certainly follow the QBOs in SSA. The results of similar analysis with SSC QBO minimum phase as the zero months (not shown) evidence that the flare associated SEP events are also influenced by the SSC variation.

Even more clearly this dual influence is seen in the GLE behaviour. Being the most powerful SEP events GLEs are always accompanied by powerful solar flares, with exception of events associated with active regions behind the limb. The GLE rate distribution relative to the QBO minimum phase in SSA (taken separately in each hemisphere) and in SSC is presented in Figure 6. GLEs are more numerous before and after QBO minima both for SSA and SSC. It is most probable that both solar flares and CMEs contribute into generation of powerful SEP events.

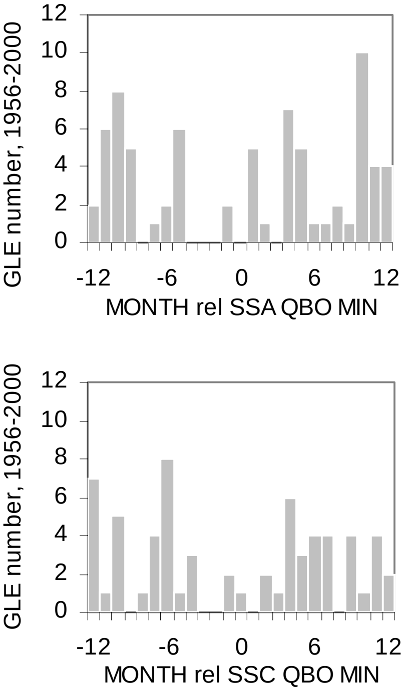

Fig. 6 Number of GLEs relative to QBO minimum phase in SSA taken separately in each solar hemisphere (top) and relative to SSC QBO minimum phase (bottom).

4 Conclusion

The quasibiennial oscillations exhibited by solar activity indices and translated into the interplanetary space were used to trace the solar energetic particle origin. Although SEP event rate for majority of events correlates better with QBOs in the SSC number (taken as a signature of interplanetary space disturbances), the rate of SEP events which can be reliably associated with solar flares is equally correlated with both QBOs on the Sun and in the interplanetary space.

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