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North–South asymmetry of the sunspot indices and its quasi-biennial oscillations

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ABSTRACT

The space–time distribution of asymmetry in the area and total number of sunspot groups was considered over the time interval 1874–2009. The time behavior of the asymmetry in these indices of sunspot activity was shown to be similar on both small and large time scales. Spectral variation analysis (SVAN) was applied to study the spectral characteristics. Quasi–biennial oscillations (QBO) were revealed in the asymmetry of both indices under discussion. The SVAN diagrams for the asymmetry of the areas and numbers of sunspots in the range of QBO periods display pronounced similarity. In the activity indices *per se*, these effects are much weaker: the mutual correlation of the indices is lower, the QBO are less pronounced, and the similarity of the SVAN diagrams in the QBO range is absent. The effect of negative correlation between the QBO power and absolute value of the asymmetry over a long time interval was revealed: the increase in asymmetry is accompanied by a decrease in QBO amplitude regardless of which hemisphere is more active at the moment. This underlines the global nature of QBO and the relation of asymmetry to the quadrupole component of the solar large-scale magnetic field. The asymmetry is an independent fundamental characteristic of solar activity, which does not reduce to the classical characteristics of the 11-year cycle.

1. Introduction

Many studies have shown that the North–South asymmetry is a fundamental characteristic of solar activity, which obeys its own, independent laws and is not controlled directly by the solar periodicity. Recognition of the asymmetry as an independent phenomenon opens up new aspects in the problem of generation of solar activity and its originating factor – solar magnetic fields. On the one hand, it is well known that generation processes in both hemispheres are highly synchronized. At present, reliable observations of solar activity are available for as long as about 200 years. As seen from observations, the characteristic phases of periodic processes in the northern and southern hemispheres coincide all over this time interval. On the other hand, differences in the level of activity between the hemispheres are reliably identified. The time dependence of various activity indices in two hemispheres displays mismatch in phase and power lasting from months to years, i.e., the North–South asymmetry.

The N–S asymmetry was studied most comprehensively in the Wolf numbers and sunspot areas (e.g., see Newton and Milsom, 1955; Waldmeier, 1957; Waldmeier, 1971; Roy, 1977; Swinson et al., 1986; Vizoso and Ballester, 1990; Carbonell et al., 1993, 2007; Oliver and Ballester, 1994; Nagovitsyn, 1998; Li et al., 2001, 2002; Ballester et al., 2005). Many other indices of solar activity, such as solar flares, filaments, prominences, radio and gamma-bursts, solar wind, coronal emission, solar magnetic field, etc., were also analyzed by various authors. Publications dealing with N–S asymmetry in various indices are reviewed in Vizoso and Ballester (1990), Carbonell et al. (1993, 2007), Li et al. (2002), Mariş et al. (2002), and Sýkora and Rybák (2010).

In a number of papers, the N–S asymmetries, as found in various solar activity indices, were compared (e.g., Newton and Milsom, 1955; Waldmeier, 1971; Sýkora, 1980; Rušin, 1980). The results obtained suggest that the N–S asymmetry in different indices behaves similarly on different time and space scales. Badalyan et al. (2003, 2005, 2008) studied the N–S asymmetry A in four indices of solar activity: brightness of the coronal green line Fe XIV 530.3 nm, summarized area and total number of sunspots for the period 1939–2001, and total magnetic flux for 1975–2001. These indices refer to different layers of the solar atmosphere. In Badalyan et al. (2003, 2005, 2008) three principal features were revealed in the behavior of the asymmetry:

1. The typical time variations of A proved to be similar in all activity indices on both large and small time scales.
2. Quasi-biennial oscillations (QBO) were detected in the asymmetry of all four indices. It was shown that long-term enhancements and attenuations of QBO occurred synchronously in the asymmetry of the indices under examination.

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3. An interesting phenomenon of negative correlation was revealed between the asymmetry A and QBO power in the latter. This phenomenon manifested itself most clearly in a significant attenuation of QBO in the mid 1960-ies, which coincided with a particularly large increase in A.

However, the study in Badalyan et al. (2003, 2005, 2008) was limited in time by the length of the coronal green-line database (1939–2001). In that period, the asymmetry was mainly positive. The negative asymmetry appeared in the second half of the period and had a significantly smaller value. Thus, an important question is how general are the conclusions drawn by Badalyan et al. (2005, 2008). In particular, it seems interesting to use longer sets of data to check the regularities found in QBO behavior, e.g., the existence of negative correlation between the QBO power and N–S asymmetry. Besides, long data series allow us to study the asymmetry characteristics on large time scales. The longest set of observational data suitable for such analysis is that of daily sunspot observations.

In this work, we have considered the behavior of the asymmetry in two indices – the summarized area and total number of sunspot groups – over the time interval 1874–2009 (Greenwich – USAF/NOAA data). It is important to emphasize that we used the total number of sunspot groups rather that the traditional Wolf numbers. The indices under consideration are related with each other, but the parameters of this relation display distinct time dependence. In Sections 3 and 4, we consider the variation spectra of both original indices and their asymmetry. In particular, quasi-biennial oscillations are studied in detail in Section 4. In Section 5, the existence of anticorrelation between the asymmetry value and the power of the respective QBO is checked and corroborated using a long set of data (1874–2009), which comprises the intervals of large positive and large negative asymmetry.

2. Time variations of asymmetry in the sunspot area and total number

The summarized areas and total numbers of sunspot groups for the period 1874–2009 were calculated from Greenwich Observatory data available through the internet http://solar-science.msfc.nasa.gov/greenwch.shtml. The Greenwich data are up to 1976, and later data are compiled by US Air Force and NOAA. The database comprises the heliographic coordinates and area of each sunspot (sunspot group) observed on each day. We calculated the summarized area and total number of sunspot groups for each month separately for the northern and southern hemispheres. This means that the total area and number of all sunspots observed were calculated for each month, each sunspot being counted so many times so many days it was observed. This is how we obtained the values S_p in m.v.h. (millionths of the visible hemisphere) and Q used in all further calculations.

The values S_p and Q were used to obtain the monthly mean asymmetry of these indices A_{Sp} and A_Q. The asymmetry was determined, as usual, as $A = (N - S)/(N + S)$, where N and S denote respectively the indices for the northern and southern hemisphere. This is the so-called "normalized asymmetry". An example of the time dependence of the so determined asymmetry is illustrated in Fig. 1a in Carbonell et al. (1993). Later, we had to average the asymmetry over different time intervals. We mainly compared the asymmetry values on the time scales of the order of half a year and four years (smoothing over 7 months and 49 months, respectively).

Fig. 1 (upper panel) represents cyclic variations of the area S_p and total number Q of sunspots calculated for two hemispheres as a whole by smoothing over the window of 49 months. For convenience of representation along the Y axis in Fig. 1, the values S_p and Q were divided by 30, which corresponds to the daily mean values of these parameters in the given month. Though both values display the usual cyclic variation, one can see that the relationship between the total number of sunspots and their summarized area changes from cycle to cycle. This is because the relationship between S_p and Q is not unambiguous, and its parameters change with time.

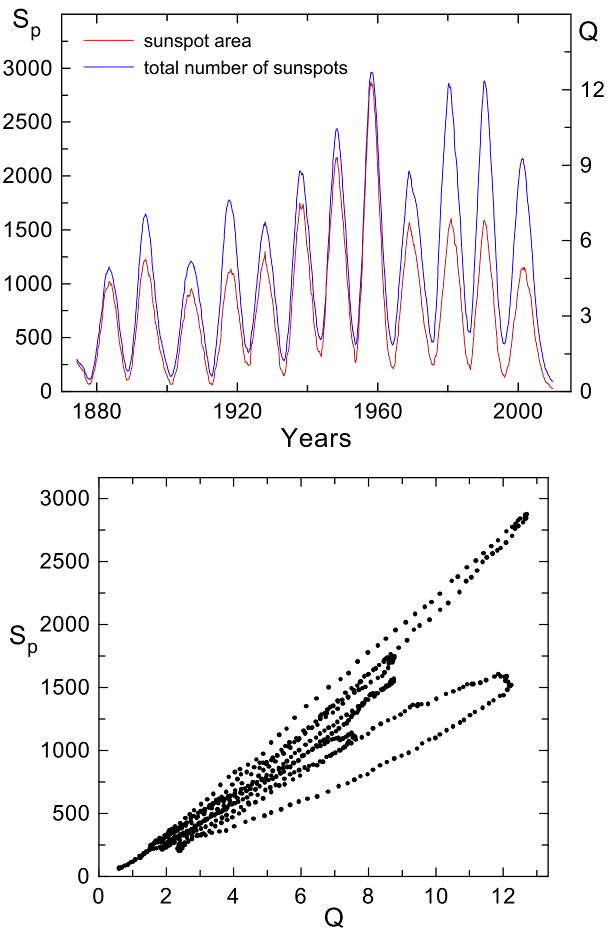


Fig. 1. Upper panel: cyclic curves of the sunspot activity indices (summarized sunspot area S_p in m.v.h. – left and total sunspot group number Q – right). Lower panel: relation between the number and summarized area of sunspot groups for the selected activity cycles. Data are averaged over the 49-month window.

The lower panel in Fig. 1 illustrates the relation between the numbers of sunspot groups and their summarized areas. We have chosen for illustration cycles 15, 17, 19, 20, and 21. One can see that the points inside each particular cycle do not display unambiguous relation with certain dispersion, but rather form a closed loop-like curve (hysteresis) where reliably different values of sunspot group numbers correspond to the same value of sunspot area in the rising and declining phases.

Fig. 2 illustrates the angular coefficient of linear relation between S_p and Q for different activity cycles, separately, for the northern and southern hemispheres. Here, we mean by the angular coefficient k the loop slope (i.e., the linear coefficient in the S_p vs Q regression equation). This relationship is seen to change systematically. The ratio of the maximum (in cycle 19) to the minimum (in cycle 22) angular coefficient is 1.93 in the northern and 1.78 in the southern hemisphere. The relation seems to be quasi-periodic with a period of about seven 11-year cycles. This is close to the 80-year activity cycle often mentioned in literature devoted to the analysis of variations of the activity indices. It is the well-known Gleissberg

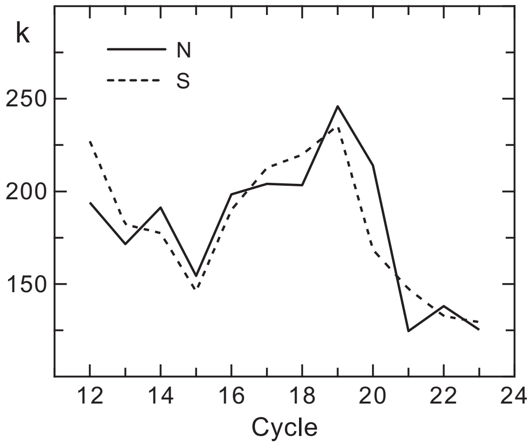


Fig. 2. The angular coefficient of linear relation between S_p and Q (i.e., the linear coefficient in the S_p vs Q regression equation) for different activity cycles, separately, for the northern and southern hemispheres.

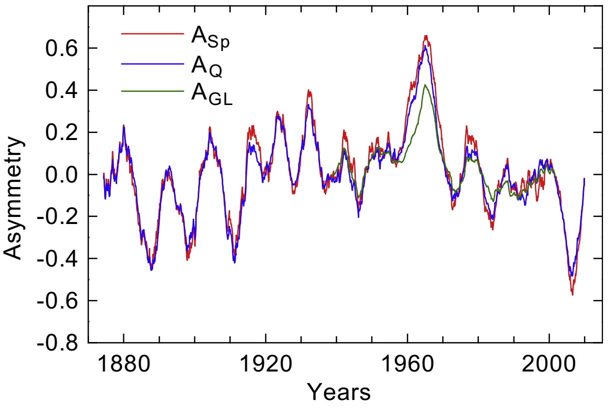
cycle demonstrated with the aid of the Morlet-type wavelet analysis in Ogurtsov et al. (2002), Faria et al. (2004), and Li et al. (2005).

Fig. 2 agrees (on the whole and in detail) with Fig. 5 in Fligge and Solanki (1997). It should be noted, however, that there is no complete coincidence, since we used somewhat different indices. Fligge and Solanki (1997) analyzed the time variation in the ratio of sunspot area to Zürich sunspot relative number. In our work, we are using the slope of the regression function between the mean area of sunspot groups and their number (rather than the Wolf number). However, these quantities are closely related physically, which explains the general likeness of the curves.

Thus, the relationship between the initial indices S_p and Q changes noticeably both within a cycle (loop-like dependence) and from cycle to cycle (changing general slope of the loop). The discrepancy between the statistical properties of the summarized areas and total numbers of sunspot groups follows directly from the concept of the primary sunspot formation indices proposed by Kopecký (1958, 1967), developed in his subsequent publications, and presented in the monograph (Vitinskii et al., 1986). These primary indices are the number or occurrence rate of the features f_0 and their mean lifetime T_0 characterizing their mean power. According to the concept by Vitinskii et al. (1986), the commonly used indices, such as the sunspot area and total number and the Wolf numbers, depend on the primary sunspot formation indices in quite different ways; therefore, their statistical properties may differ significantly. The character of the cyclic curves in Fig. 1 (upper panel) suggests that either the dependence of S_p and Q on the primary indices or the primary indices *per se* are different in different phases of the cycle and in different cycles.

Thus, though the indices S_p and Q used in our work are related to each other, they reflect different aspects of the sunspot activity of the Sun. So, we may regard them as quasi-independent indices and study their asymmetry values A_{Sp} and A_Q separately.

Let us turn now to the North–South asymmetry of the indices S_p and Q. The relations similar to those illustrated in Fig. 1 are shown in Fig. 3 for the asymmetry. The upper panel represents the variation of asymmetry in the sunspot areas A_{Sp} (red line) and sunspot group numbers A_Q (blue line), both calculated by averaging over 49 months. It is seen that the asymmetry in sunspot group numbers virtually coincides with the asymmetry in sunspot areas. Long time intervals are readily seen when one or another hemisphere is dominating. A large negative asymmetry (domination of the south hemisphere) can be noticed at the end of XIX and beginning of XX centuries. In the mid 60-ies last century, the north hemisphere was dominant – one can see a significant increase of the positive asymmetry. At the end of the XX and the beginning of the XXI century, the asymmetry becomes negative again. Fig. 3 shows also, for comparison, the asymmetry of brightness of the coronal green line A_{GL} in the sunspot formation zone 0°–30° for 1939–2001 calculated from the database compiled by Sýkora and Rybák (2005). The green curve in Fig. 3 displays the same behavior as the asymmetry of the sunspot activity indices in the same time interval. The asymmetry of the total photospheric magnetic flux for 1975–2001 in the sunspot formation region is also similar to the curves in Fig. 3 (see Badalyan et al., 2005).



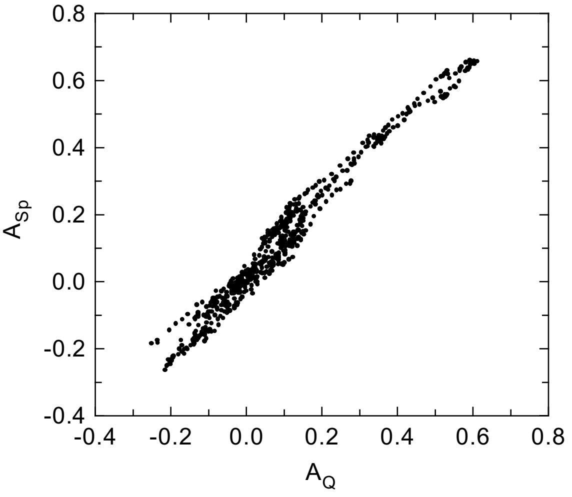


Fig. 3. Time variation of asymmetries in the summarized areas and numbers of sunspot groups and in the coronal green-line brightness – upper panel; relationship between these asymmetry values for the selected activity cycles – lower panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Note that the asymmetry curves for S_p and Q are very similar all over the period under discussion (1874–2009). The correlation between them increases as we pass to greater time scales. The monthly means A_{Sp} and A_Q correlate with the coefficient 0.853 ± 0.007. Averaging over a moving window (i.e., passing to the greater time scales) increases the correlation coefficient, which is 0.933 ± 0.03 for the 7-month window and 0.978 ± 0.001 for the 49-month window.

The lower panel of Fig. 3 represents the relationship between the asymmetry in the sunspot group numbers A_Q and areas A_{Sp}. Here, unlike the lower panel of Fig. 1, the character of the relationship between A_Q and A_{Sp} does not virtually change with time, and the mean angular coefficient is close to unity.

Fig. 4 represents the asymmetry of sunspot areas over still longer time interval. Here, we have combined data from the catalogues of Pulkovo (dashed part of the curve for 1821–1874) and

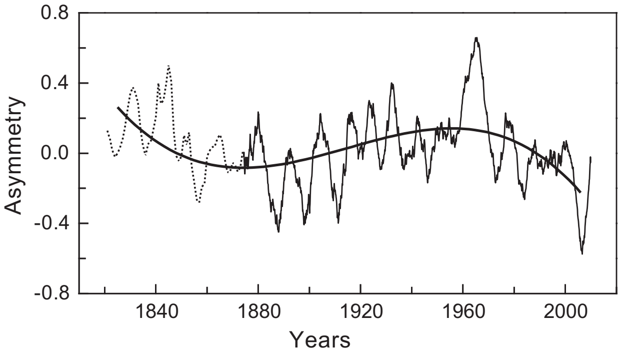


Fig. 4. North–South asymmetry of sunspot areas for 1821–2009. The dashed and solid parts of the curve are based on the data from the Pulkovo and Greenwich catalogs, respectively. The heavy curve represents the third-order polynomial (secular trend).

Greenwich (solid part of the curve). The Pulkovo data (http://www.gao.spb.ru/database/esai/) are compiled of the series of annual mean sunspot areas in the northern and southern hemispheres (see Nagovitsyn et al., 2004). We have additionally averaged these data over a 3-year window to match the averaging used in our work.

The third-order polynomial (thick curve) illustrates the long-term variation of the asymmetry. This is a sinusoid with a period more than 100 years. Oliver and Ballester (1994) obtained a similar polynomial for the period 1874–1993. The secular variation of asymmetry in the numbers of sunspot groups close to ours was obtained by Li et al. (2002). Fig. 4 confirms the quasi-periodic nature of the N–S asymmetry. Considerable positive asymmetry was observed approximately at the middle of the XIX and XX centuries, while at the end of both centuries, it was changed by large negative values.

Thus, the analysis of long data series corroborates our earlier conclusion (Badalyan et al., 2003, 2005, 2008) that the time variation of asymmetry in different indices of solar activity has similar typical details. It is also evident from Figs. 1 and 3 that the behavior of the asymmetry in two indices under discussion displays more similarity than the behavior of the initial indices themselves. Quantitatively, this is reflected in the fact that the relative error of the free term in the linear regression equation is 0.37 for the indices and 0.07 for the asymmetry. The relative error of the angular coupling coefficient is 0.011 for the indices and 0.0053 for the asymmetry.

The statistical significance of the asymmetry values can be estimated taking into account two sources of error: (a) the accuracy of sorting *n* objects into two groups or, in other words, the accuracy of assigning sunspots to the northern or southern hemisphere and (b) the accuracy of determining the sunspot areas. The first problem was considered in detail by Carbonell et al. (1993). The authors have shown that the division of sunspot groups into two hemispheres when combining the data for one Carrington rotation is statistically significant in 96% of the cases.

Here, we shall estimate the accuracy of calculation of the normalized asymmetry. The data from the Greenwich Catalogue for the period 1987–1976 are given with an accuracy of 1 m.v.h. From 1977, the sunspot areas according to US Air Force and NOAA are given with an accuracy of 5–10 m.v.h. Let us assume that the sunspot area is determined with a mean accuracy of 5 m.v.h. so that, actually, the asymmetry calculation error is overestimated. The accuracy of calculation of the monthly mean asymmetry ΔA can be expressed as

$$\Delta_A = \frac{\Delta((N+S)+|N-S|)}{(N+S)^2}, \qquad (1)$$

where Δ is the general error of determining the summarized sunspot area $N+S$ for the given month, equal to the product of the assumed value 5 m.v.h. by the total number of sunspot groups in this month. The calculations show that the mean value Δ_A for 1874–2009 is 0.094. It is clear that inaccuracy increases significantly at the minimum of the cycle and is small (about 0.002), at the maximum. Of interest is the signal-to-noise (i.e., the asymmetry to error) ratio, which ranges from 0 to 50. This ratio is less than unity at 112 points, which makes 7% of the total length of realization equal to 1628 points. The number of points at which the signal-to-noise ratio is smaller than 2 amounts to 15%. It should be noted that the asymmetry being a quasi-periodic function with a quasi-period other than 11 years (see Sections 3), this ratio sometimes happens to be less than unity even in the vicinity of the cycle maximum (e.g., in February 2001). Since the aforementioned 7% of the points at which the signal-to-noise ratio is less than unity are distributed randomly over the time interval under discussion, we can suggest that they have little effect on our results.

3. Spectra of the summarized area and total sunspot group number and their asymmetry

Various mathematical methods were used earlier to study the asymmetry characteristics. Vizoso and Ballester (1990) analyzed the asymmetry of sunspot areas for the period 1874–1976 and discovered a significant 3.27-year peak in the Blackman–Tukey power spectrum. Carbonell et al. (1993) used for the same purpose the statistical modeling of the asymmetry (Monte Carlo method, "chi-squared" test, and deterministic chaos methods). They revealed three components: the long-period cubical trend, the sine wave with a period of 12.1 years, and the dominating random component. Nagovitsyn (1998) studied the asymmetry in three different indices (sunspot areas, mean latitudes of sunspots, and the number of polar faculae) as a nonlinear process using the wavelet method. He revealed the periods of 12 and 10 years for the low and high latitudes, respectively, and a long-periodic wave of 30–40 years (see also Knaack et al., 2004, Ballester et al., 2005). The statistical significance of the North–South asymmetry and the choice of the appropriate investigation method were considered by Carbonell et al. (2007).

We considered the Fourier spectra of the indices and asymmetry over the entire time interval under examination. The conventional procedure of Discrete Fourier Transform (DFT) was used. This procedure was supplemented with normalization to the standard (division by the standard deviation). As a result of this procedure, all oscillations in a given spectrum were reduced to a single scale, and the sum of squares of all amplitudes was equal to unity. This allowed us to compare the spectra of such dissimilar, differing in their absolute value indices as oscillations of the sunspot areas and numbers and their asymmetries.

The asymmetry spectra and the spectra of the corresponding indices turn out to differ significantly. Fig. 5 represents the Fourier spectra of the summarized sunspot areas and their asymmetry (upper and lower panels, respectively). The corresponding spectra for the total number of sunspot groups are virtually the same. The Fourier spectrum of the summarized areas, naturally, displays a distinct 11-year cycle, while the other harmonics are much (by an order of magnitude) lower. No preferable period can be isolated in the range of 1–4 years. The asymmetry spectrum does not display noticeable periodicity, but it has a maximum at 12 years. Besides, the asymmetry spectrum reveals high frequency oscillations with periods less than 6 years and the amplitude only slightly lower than the amplitude of the main maximum. The reliability of this period was considered in Ballester et al. (2005). We discuss this question again below, in Conclusion.

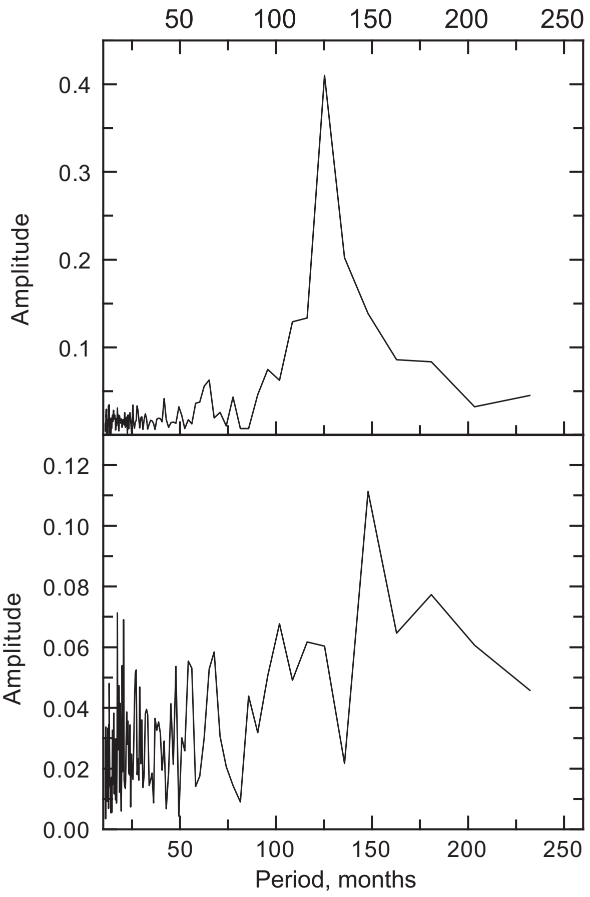


Fig. 5. Fourier spectra of summarized sunspot areas (top) and their asymmetry (bottom).

To study the difference between the spectra of the asymmetry and the corresponding initial indices in more detail, we calculated the sums of squares of the oscillation amplitudes in several ranges of the periods for the overall bulk of data (1628 monthly values). The sum of squares of the oscillation amplitudes in a certain range of frequencies (or periods) will be, henceforth, referred to as "power". The results are presented in Table 1.

In Table 1, the general spectrum of oscillations with the periods from 2 to 181 months is divided into three ranges. The first one covers the periods from 2 months to a year. The power of asymmetry oscillations in this region is rather high. This range, apparently, corresponds to the local sunspot activity manifested as individual sunspots and small sunspot groups with the lifetimes from 6 days to a few months (Obridko, 1985).These groups are numerous, but their appearance is rather chaotic and nonsynchronous in the northern and southern hemispheres. The lack of synchronism explains why the oscillation power of the asymmetry in this range increases much stronger than the oscillation power of the initial indices.

Table 1
Sums of squares of the oscillation amplitudes in different ranges.

Range	1	2a	2b	3
Summarized sunspot area, S_p				
Period (months)	2.1–13.1	13.0–19	19–39	102–181
Asymmetry	0.3069	0.0305	0.0397	0.0375
Index	0.0888	0.0141	0.0135	0.2809
Total number of sunspot groups, Q				
Period (months)	2.1–13.1	13.0–19	19–39	102–181
Asymmetry	0.2583	0.0320	0.0415	0.0518
Index	0.0336	0.0049	0.0077	0.3281

The range of the periods of 8.5–15 years (or 102–181 months) is easily understood. It corresponds to the 11-year cycle, which, naturally, makes the primary contribution to oscillations of the sunspot group numbers and areas. On the other hand, the asymmetry oscillation power in this range is much lower than in the first one. This is due to the fact that the 11-year cycle occurs rather synchronously in both hemispheres with the dates of maxima (or minima) not differing in time by more than 1–1.5 years. Therefore, the oscillation power in the asymmetry is also relatively small.

The range of 13–39 months in Table 1 is divided into two subranges – quasi-annual (2a) and quasi-biennial (2b) oscillations. In these ranges, the oscillation power of the indices Q and S_p is low, while the oscillation power of the asymmetry is a factor of 2–6 higher.

This is, probably, due to the fact that high frequency oscillations in subrange 2a are noise-like, and synchronization of activity in the northern and southern hemispheres is absent. Large phase shifts between the oscillations in two hemispheres result in the increase of oscillation intensity in the given range. Our results agree fairly well with the results by Li et al. (2009), Zolotova and Ponyavin (2006). In subrange 2b, the phase shift between oscillations becomes more stationary (less noise-like), and stable time intervals of both synchronization and anti-synchronization are possible.

The subrange of 19–39 months corresponds to the so-called quasi-biennial oscillations (QBO), which we discuss separately in the next Section.

4. Quasi-biennial oscillations in the asymmetry and in initial indices

Among the periodic oscillations of solar active events, the quasi-biennial oscillations (QBO) revealed in various indices are of particular interest. This phenomenon was dealt with a many publications (see, e.g., the references in Obridko and Shelting (2001)). However, there are relatively few papers devoted to QBO in the asymmetry. In Obridko and Gaziev (1992), it is shown that QBO can be clearly identified in the asymmetry of the magnetic fields reconstructed from Hα data. Knaack et al. (2004), Knaack et al. (2005) also revealed oscillations in this range of periods in the asymmetry of solar magnetic fields and sunspot areas. Ballester et al. (2005) showed that a significant peak in the range of 1.44 years in the Fourier spectrum of the asymmetry (for $N - S$ value) of sunspot areas was only slightly smaller than the peaks with the periods over 10 years. Badalyan et al. (2005, 2008) revealed and discussed quasi-biennial oscillations in the N–S asymmetry of various activity indices. Note also an interesting paper by Sýkora and Rybák (2010), where the existence of QBO in asymmetry was confirmed by autocorrelation analysis.

We have applied the spectral variation analysis (SVAN) to study the behavior of quasi-biennial oscillations in the asymmetry with time. In our SVAN program, unlike the widely-used ones described in the literature (see Dziewoński et al., 1969; Thomson, 1982), we have introduced normalization to the standard (division by r.m.s. deviation). For more detail see Badalyan et al. (2008).

The spectral variation analysis consists in the successive Fourier expansion in a moving time window. This means that the time interval under investigation (1628 months) is treated with a window of chosen length. In each window, we calculate the amplitudes and phases of the Fourier components. Then, the window is shifted in time by a certain interval, and the procedure is repeated. The expansions obtained in such a way are used to plot the general map of the oscillation amplitudes (SVAN diagram) in the time–oscillation period reference frame. The length of the moving window was taken equal to 132 months, and the shift was 12 months. Inside each window, normalization to the standard was performed. Though the relative power of oscillation is characterized by its squared amplitude, it was sometimes more convenient to plot and analyze just the amplitudes. Below, we shall specify in each case what precisely (the amplitude or its square) is given in the figures and tables. The methods used to estimate the reliability of the SVAN diagrams are described in Badalyan et al. (2008).

Fig. 6 shows the SVAN diagrams for the asymmetry of two indices under consideration. The range of the periods is 15–35 months, which corresponds approximately to quasi-biennial oscillations. The entire range of amplitudes is represented with four shades of tone from white to black, the darker tone corresponding to larger amplitudes. One can see quasi-biennial oscillations (about 25 months) clearly pronounced in certain time intervals in the asymmetry of both the summarized sunspot areas A_{Sp} (upper panel) and total sunspot group numbers A_Q (lower panel). The oscillations intensify and decay regularly, but their general variation pattern is similar for both indices. The correlation coefficient for two maps in Fig. 6 calculated for the set of 444 pairs of points coinciding in space is 0.77 ± 0.02. No relationship was revealed between the times of enhancement and decay of QBO and the 11-year cycle. One can notice that the periods of oscillations with the maximum amplitudes in the asymmetry of summarized sunspot areas change gradually from 32 months at the end of the XIX and the beginning of the XX century to 20 months by 2000. Weak oscillations can also be revealed in the range of the periods of 12–16 months.

Fig. 7 represents analogous SVAN diagrams for the initial indices under consideration. These diagrams are seen to differ significantly in their general characteristics from the corresponding diagrams for the N–S asymmetry of these indices. First of all, the QBO amplitudes for the initial indices are much lower as is readily seen from the amplitude scales in Figs. 6 and 7 (the full range of amplitude variations in Fig. 6 is about twice as large as that in Fig. 7). This means that using in Fig. 7 the same scale as in Fig. 6 would make QBO in the initial indices virtually indiscernible. Second, there are neither stable frequency–time features no distinct correspondence between the SVAN diagrams for the sunspot group areas and numbers (upper and lower panels in Fig. 7). E.g., the oscillation amplitudes of the sunspot areas display some increase in 1915–1925, while the corresponding increase for the sunspot group numbers is much weaker. On the whole, the correlation coefficient for the maps in Fig. 7 is 0.57 ± 0.03.

Fig. 8 illustrates the time variation of the sum of squared amplitudes for oscillations in the initial indices S_p and Q (lower panel) and in their asymmetry (upper panel). The squared amplitudes of six harmonics in the QBO range (14.67, 16.50, 18.86, 22.00, 26.40, and 33.00 months) were summed up. With the expansion window 132 months long, these are the periods of harmonics 9 to 4, respectively. Fig. 8 shows much more similarity between the curves for A_{Sp} and A_Q on the upper panel than on the lower one for S_p and Q. The corresponding correlation coefficients are 0.86 ± 0.02 and 0.58 ± 0.06. As follows from comparison of the upper and lower panels of Fig. 8, the sums of the squared oscillation amplitudes in the QBO range are significantly larger for the asymmetry than for the initial indices.

As the oscillation period increases, the noise character of oscillations typical of subrange 2a decreases, and the oscillations become more deterministic. Long periods of stable anti-phase oscillations can be revealed in the range of 19–39 months (subrange 2b), see Fig. 12 in Li et al. (2009). One can see that the highest peaks in QBO enhancement are close to the points of time when the phase shift between the northern- and southern-hemisphere oscillations in subrange 2b reaches $\pm\pi$. Thus, we can speak of a strong desynchronization of oscillations (even anti-phase oscillations) in the northern and southern hemispheres.

Thus, we arrive at the conclusion that the spectral–time characteristics of asymmetry of the two indices under discussion in the QBO range are closer to each other than the characteristics of the initial indices. This is, probably, due to the typical fluctuation times of solar activity. The fluctuation time in the Wolf numbers was estimated by Vitinskii (see Vitinskii et al., 1986). It is associated with the appearance of large complexes of activity and ranges from a few months to a year. This time is small compared with the periods of the order of 11 years, but it makes a significant part of QBO

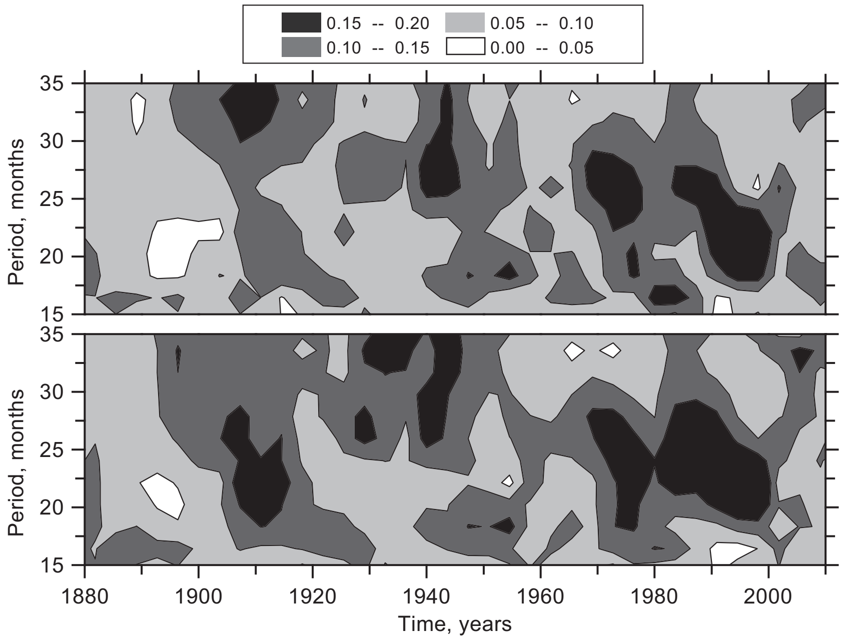


Fig. 6. SVAN diagrams for the asymmetry in the areas and total numbers of sunspot groups in the QBO range (upper and lower panels, respectively).

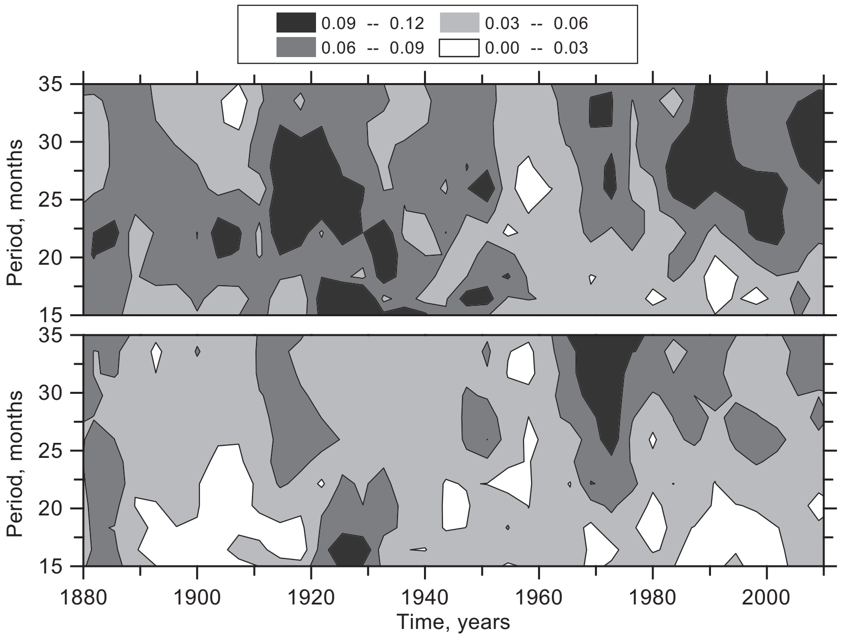


Fig. 7. SVAN diagrams for the areas and total numbers of sunspot groups (upper and lower panels, respectively).

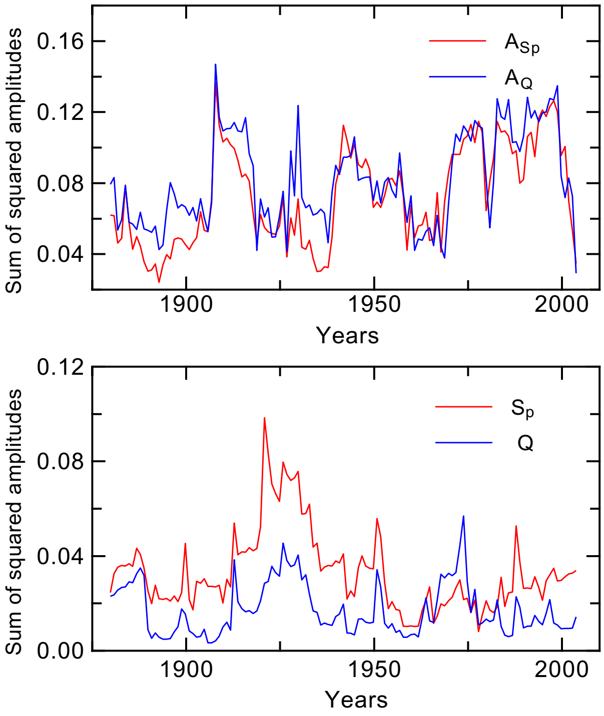


Fig. 8. The power of quasi-biennial oscillations in the initial indices of sunspot activity (bottom) and in their asymmetry (top).

period. Hence, the initial indices are well synchronized in the range of large periods (e.g., 11 years). The phase shift between them makes but a small part of the oscillation period and, therefore, they are suppressed when calculating the asymmetry. Quasi-biennial oscillations are present in both hemispheres. However, even a small phase shift is significant compared to the QBO period; therefore, the QBO are not suppressed when calculating the asymmetry, and their relative value increases.

5. Relation between the magnitude of the N–S asymmetry and the amplitude of its QBO

Badalyan et al. (2003, 2005, 2008) revealed an interesting phenomenon of the relationship between the power (amplitude) of quasi-biennial oscillations and the magnitude of asymmetry itself. Comparing the maps of space–time distribution of the asymmetry and sums of amplitudes in the QBO range, the authors suggested the existence of a general large-scale anti-correlation between these parameters.

Particular attention was paid in Badalyan et al. (2003, 2005, 2008) to a detailed study of the asymmetry in the brightness of the coronal green line. Since this line is observed at all heliographic latitudes, the latitudinal dependence of the found relationship could be analyzed. It turned out that the negative correlation between the magnitude of the asymmetry and the QBO power in it was present at all latitudes with the correlation coefficients reaching the highest negative values in the latitude bands of 10°–20° and 60°–70°. Between them, there is a narrow zone of 40°–50° where the correlation is low. In this zone, the green-line asymmetry reaches its greatest value in the period 1965–1968 and the high frequency oscillations virtually cease. This is also where the separation boundary between the low-latitude and polar magnetic fields lies.

In Badalyan et al. (2005, 2008), the anti-correlation between the asymmetry and QBO power was considered for three different indices of solar activity: asymmetry of brightness of the coronal green line 530.3 nm, summarized sunspot areas, and total sunspot group numbers. The data series used in the study were relatively short covering the past 5.5 cycles (1939–2001). The fourth index – the integral magnetic flux for about three cycles (since 1975) was analyzed in Badalyan et al. (2005). The indices under examination refer to different layers in the solar atmosphere, and all of them reveal the phenomenon of anti-correlation. However, the asymmetry of the activity indices in the analyzed period was mainly positive. In the intervals of negative asymmetry during 1939–2001 its values were small. Here we have used long data series to corroborate the anti-correlation effect. As mentioned above, significant negative asymmetry was observed at the frontiers of the XIX and XX centuries. The use of long data series allowed us to verify and generalize the conclusions obtained in Badalyan et al. (2003, 2005, 2008).

Fig. 9 illustrates the relationship between the QBO power (sum of the squared amplitudes) and the mean asymmetry of the sunspot areas A_{Sp} (upper panel) and numbers A_Q (lower power) in an expansion window. It should be noted that the largest correlation coefficients are obtained when using the moving SVAN window of 150 months, which is approximately equal to the asymmetry quasi-period (12 years). The results of calculations with such a window are represented in Fig. 9 and Table 2.

The squared amplitudes of the asymmetry oscillations were summed up in the range of 16.7–37.5 months (six frequencies). The negative correlation coefficients for the QBO power and the absolute values of A_{Sp} and A_Q are given in Table 2 separately for the positive and negative asymmetry ranges. Since the asymmetry is an alternating-sign quantity and the oscillation amplitudes are positive, the negative correlation must be interpreted as the increase of the asymmetry absolute value at the decreasing initial indices.

Thus, extending the time scale of our analysis compared to Badalyan et al. (2003, 2005, 2008), we have shown that anti-correlation between the asymmetry and QBO power is conserved in the intervals of negative asymmetry. This means that the QBO power decreases with the increase of the asymmetry absolute value no matter in which hemisphere the enhancement of activity occurs. Let us give also the general correlation coefficient for the absolute value of the asymmetry (without taking into account the sign) and QBO power. For the sunspot areas, it is −0.55 ± 0.06, and for the sunspot group numbers, −0.61 ± 0.06.

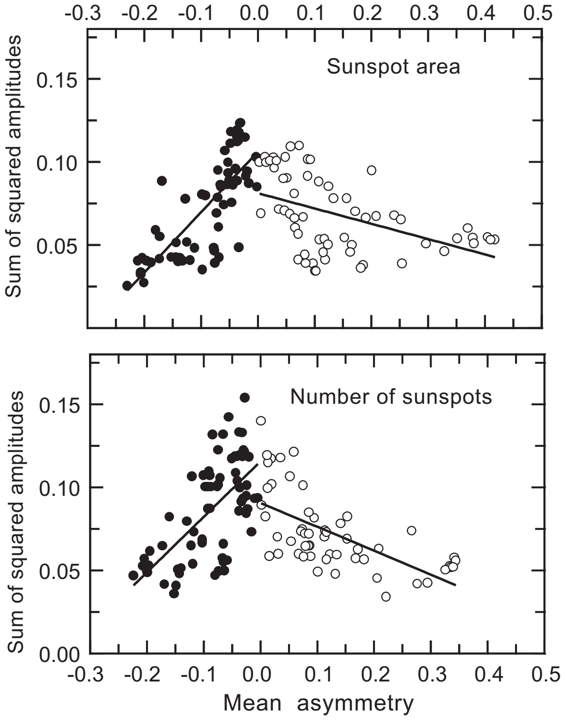


Fig. 9. Relationship between quasi-biennial oscillations and asymmetry (sunspot areas – top; sunspot group numbers – bottom). The open and filled circles denote, respectively, the positive and negative asymmetry.

Table 2
Correlation r between the QBO power and absolute value of the asymmetry.

Range	r
$A_{Sp} > 0$	−0.46 ± 0,09
$A_{Sp} < 0$	−0.78 ± 0,05
$A_Q > 0$	−0.63 ± 0,08
$A_Q < 0$	−0.65 ± 0.07

In is interesting to note that the sum of the squared amplitudes of QBO in the asymmetry of sunspot group areas and numbers has a marked period of 40 years, which is distinctly identified from the curves on the upper panel of Fig. 8. Recall that the quasi-period of about 40 years can be also isolated in the asymmetry itself with the aid of a simple Fourier analysis. Note that in accordance with the anti-correlation law, the time intervals of decreased QBO power coincide with those of increased absolute value of the asymmetry.

For the present, the effect of anti-correlation between the asymmetry and QBO is difficult to interpret adequately. Probably, it is associated with the global nature of QBO. As shown by Obridko and Shelting (2001), the QBO are mainly manifested in the low-order (global) spatial harmonics of the large-scale magnetic field. Then, the increase in the QBO power might result in the decrease of the asymmetry.

6. Conclusion

We have analyzed the North–South asymmetry of two sunspot activity indices – summarized area and total number of sunspot groups for a long time interval 1874–2009. The analysis allowed us to corroborate and develop further some results obtained earlier in Badalyan et al. (2005, 2008).

It is shown that the characteristic time variations in the asymmetry of the sunspot group areas and total numbers are similar both on relatively small and on large time scales. On the other hand, the initial indices *per se*, in spite of their close physical relation, behave more distinctly. The conclusion of similar behavior of the asymmetry in four different activity indices related to different layers in the solar atmosphere and controlled by different mechanisms was obtained in our earlier work based on shorter data series. The spectral characteristics of the asymmetry and the corresponding activity indices differ essentially. The spectra of the indices display a pronounced 11-year period, while the other harmonics are much weaker. In the asymmetry spectrum, there is no distinct periodicity. One can see the principal maximum in the vicinity of 12, a long-period wave of about 40 years, and a secular trend. The same periods were noted earlier in a number of publications (e.g., see Ballester et al., 2005).

The meaning of this period was discussed in detail by Ballester et al. (2005). In that work, the authors arrive at a conclusion that the peak in the power spectrum around the solar cycle is spurious. They believe that the presence of this peak is due to the use of the normalized asymmetry, which is the circular convolution DFT of the functions $N - S$ and $1/(N + S)$. However, it seems to us that the period of 12 years is reliable. Its origin is not entirely clear. Note that it is clearly revealed on a long realization of 189 annual mean asymmetry values from 1821 to 2009. This problem needs special consideration, which will be the subject of a separate work.

To study the time behavior of the spectral characteristics of the asymmetry and the initial indices, we have used a special version of the spectral-variation analysis (SVAN) including normalization to the standard. Such normalization allowed us to compare the spectra of very dissimilar and differing in their absolute value characteristics. The analysis has revealed quasi-biennial oscillations in the asymmetry of both indices under consideration. This finding complements and develops the conclusions drawn earlier (Badalyan et al., 2005, 2008). Periodically, quasi-biennial oscillations in the asymmetry increase in amplitude and become particularly well pronounced during long time intervals. This periodicity is close to 40 years. The SVAN diagrams for the asymmetry of sunspot group areas and numbers in the QBO range display similar features. The QBO in the initial activity indices are much weaker, and the similarity between the corresponding SVAN diagrams is lacking. We should mention here the work by Sýkora and Rybák (2010) who used the autocorrelation analysis to reveal and study QBO in the asymmetry of some indices. The authors plotted auto- and cross-correlation curves, which demonstrate the appearance of secondary maxima in the QBO range. Thus, the method used by Sýkora and Rybák (2010) confirm the existence of QBO in the asymmetry of the solar activity indices.

An interesting effect of anti-correlation between the QBO power in the asymmetry and the magnitude of the latter has been investigated. It is shown that the power of quasi-biennial oscillations decreases with the increase of the absolute value of the asymmetry. This conclusion was obtained in our earlier work (Badalyan et al., 2005, 2008) for the past 5.5 activity cycles. However, in the time interval analyzed in that work the North–South asymmetry was mainly positive. In this paper, the same conclusion was drawn from the analysis of longer data series covering the periods of significant negative asymmetry. Thus, the increase of asymmetry is accompanied by the decrease of QBO power no matter in which hemisphere the activity enhancement occurs.

The results obtained emphasize the importance of the asymmetry indices. It can be argued that the asymmetry, which characterizes the processes odd with respect to the equator, is an independent parameter of solar activity not coinciding in its properties with the even processes.

The revealed differences in the behavior of the asymmetry and its parent indices strongly suggest that the asymmetry cannot be reduced to a mere interaction of the 11-year activity cycle and some other slowly changing cycle as believed, for example, by Waldmeier (1957). The analysis of the asymmetry reveals some particular features of solar activity, which escape our attention when we analyze the integral indices. It seems that the N–S asymmetry is a fundamental characteristic of solar activity, which obeys its inherent laws and is not controlled directly by the activity cycle.

As a matter of fact, the origin of the asymmetry in the solar indices is not clear. It might be the result of the action of the slowly changing relic magnetic field. The existence of such field is an important item in some modern dynamo theories (see Mordvinov and Kitchatinov, 2004). However, our results rather testify against this explanation, since they indicate to a relatively fast variation of the asymmetry. It seems more reasonable to suggest the relation of the asymmetry to the fields of quadrupole type. These fields were reliably identified in some work on large-scale fields (Obridko and Shelting, 1992, 2003; Rivin et al., 1999) and were used in Zhao et al. (2005), Obridko and Shelting (2008) to explain variations in the heliospheric structure. In general, different cyclic and dynamic behavior of the even and odd (relative to the equator) harmonics (respectively, the dipole- and quadrupole-type magnetic features taking into account the field sign) was mentioned by various authors (see, e.g., Obridko and Gaziev, 1992).

An impression arises that solar activity is generated, to a great extent, independently in two hemispheres and is controlled by the laws of differential rotation and meridional flows in each of them. However, since the cyclic variations of activity in both hemispheres have similar temporal and energetic characteristics, there must exist some (still unknown) mechanism, which would make them agree. This must be a kind of independent, super-generation mechanism. The North–South asymmetry is, at all appearance, the quantitative measure, which reflects the properties of such mechanism.

The results of our analysis show that the asymmetry is a meaningful and informative parameter of solar activity. This phenomenon seems to provide a specific, very promising tool for the study of solar activity variations. Further investigation of the North–South asymmetry is an important task, which will improve our understanding of the asymmetry origin, as well as the origin and variation of the solar magnetic field.

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