Solar Phys (2010) 261: 321–335
DOI 10.1007/s11207-009-9483-x

Manifestations of the North – South Asymmetry in the Photosphere and in the Green Line Corona

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Received: 4 March 2009 / Accepted: 3 November 2009 / Published online: 16 December 2009

Abstract The north – south asymmetries (NSA) of three solar activity indices are derived and mutually compared over a period of more than five solar cycles (1945 – 2001). A catalogue of the hemispheric sunspot numbers, the data set of the coronal green line brightness developed by us, and the magnetic flux derived from the NSO/KP data (1975 – 2001) are treated separately within the discrete low- and mid-latitude zones (5° – 30°, 35° – 60°). The calculated autocorrelations, cross-correlations, and regressions between the long-term NSA data sets reveal regularities in the solar activity phenomenon. Namely, the appearance of a distinct quasi-biennial oscillation (QBO) is evident in all selected activity indices. Nevertheless, a smooth behavior of QBO is derived only when sufficient temporal averaging is performed over solar cycles. The variation in the significance and periodicity of QBO allows us to conclude that the QBO is not persistent over the whole solar cycle. A similarity in the photospheric and coronal manifestations of the NSA implies that their mutual relation will also show the QBO. A roughly two-year periodicity is actually obtained, but again only after significant averaging over solar cycles. The derived cross-correlations are in fact variable in degree of correlation as well as in changing periodicity. A clear and significant temporal shift of 1 – 2 months in the coronal manifestation of the magnetic flux asymmetry relative to the photospheric manifestation is revealed as a main property of their mutual correlation. This shift can be explained by the delayed large-scale coronal manifestation in responding to the emergence of the magnetic flux in the photosphere. The reliability of the derived results was confirmed by numerical tests performed by selecting different numerical values of the used parameters.

Keywords Magnetic fields, corona · Magnetic fields, photosphere · Solar cycle

1. Introduction

Until about the middle of the previous century the solar activity was investigated globally, viewing the Sun as a whole. It was commonly assumed that all the processes on the Sun run

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more or less similarly and simultaneously on its northern and southern hemispheres. Understandably, an occasional different level of activity on the solar hemispheres was noticed very early, even by the pioneer observers of the Sun. However, and unfortunately, for a long time the reality of the north – south asymmetry (NSA) was considered marginal, to be picked out explicitly within the regular records of solar activity. Consequently, under the assumption of practically identical behavior of the Sun's hemispheres, more recent and fundamental concepts on the generation of the solar activity have been developed (*e.g.*, interpretation of the solar differential rotation and the theory of solar dynamo). Anyway, already this "whole-Sun approach" allowed one to reveal a number of basic features in the solar activity behavior. Primarily, different short- and long-term cyclic changes were found in case of various indices characterizing activity within all the levels of the Sun's atmosphere from the photosphere up to the solar corona.

However, during the latest decades it became evident that the northern and southern solar hemispheres operate independently, to such a measure that this cannot be further completely neglected. Therefore, whenever possible, the NSA started to be explicitly observationally registered and even extracted from the past long-standing databases of solar activity. As for the NSA analysis in the sunspot appearance at least the studies of Newton and Milsom (1955), Roy (1977), Swinson, Koyama, and Saito (1986), Vizoso and Ballester (1990), Carbonell, Oliver, and Ballester (1993), Oliver and Ballester (1994), Pulkkinen *et al.* (1999), Li *et al.* (2002, 2009b), Vernova *et al.* (2002), Ballester, Oliver, and Carbonell (2005), and Li (2009), should be mentioned. The NSA in space-time distribution of solar flares was also analyzed extensively (*e.g.*, Yadav, Badruddin, and Kumar, 1980; Knoška, 1985; Verma, Pande, and Uddin, 1987; Verma, 1987; Garcia, 1990; Bai, 1990; Ataç and Özgüç 1996, 1998; Li, Schmieder, and Li, 1998; Temmer *et al.*, 2001; Li *et al.*, 2002; Joshi and Pant, 2005). The NSA of a number of other solar phenomena was investigated, as well – filaments, prominences, radio-bursts, gamma-rays, solar wind, solar magnetic field, coronal bright points, *etc.* (see, for example, Howard, 1974; Hansen and Hansen, 1975; Verma, 1987; Özgüç and Ücer, 1987; Tritakis, Mavromichalaki, and Petropoulos, 1988; Verma, 1993; Duchlev, 2001; Mariş, Popescu, and Mierla, 2002; Knaack, Stenflo, and Berdyugina 2004, 2005; Brajša *et al.*, 2005; Gigolashvili *et al.*, 2005; Li *et al.*, 2009a).

The NSA of solar rotation has also been investigated intensively using observations of sunspots (*e.g.*, Howard, Gilman, and Gilman, 1984; Balthasar, Vazquez, and Wöhl, 1986; Hathaway and Wilson, 1990; Brajša *et al.*, 2002a), photospheric magnetic fields (Antonucci, Hoeksema, and Scherrer, 1990), and also coronal tracers (*e.g.*, Hoeksema and Scherrer, 1987; Brajša *et al.*, 2002b; Badalyan, Obridko, and Sýkora, 2006; Sheeley, Nash, and Wang, 1987). Moreover, the NSA of the solar activity was also used for predicting solar activity, namely to derive strength of the solar cycle 24 providing considerably different results (*e.g.*, Javaraiah, 2007; Kane, 2007). The NSA can be used as a diagnostic tool for determination of nature of the solar activity, *i.e.*, to distinguish whether solar activity is purely stochastic or weakly chaotic (*e.g.*, Sokoloff and Nesme-Ribes, 1994; Charbonneau, 2005).

Some of our recent works were also devoted to a better understanding of the NSA properties and regularities, namely by analyzing the coronal green line brightness data, the data on numbers and areas of sunspots, and the photospheric magnetic field flux measurements (Badalyan *et al.* 2002, 2003, 2005; Temmer *et al.*, 2006; Badalyan, Obridko, and Sýkora 2005, 2008). Fairly original was our effort to express and understand the NSA as related to the arbitrarily chosen low-, mid-, and high-latitude solar zones and, when possible, to see the NSA behavior with decrement of 10° in solar latitude. Also relatively new in our approach was the analysis of our own extensive coronal database and the successive space-time comparisons of the coronal NSA manifestations with those in the solar photosphere. The spectral variation analysis (SVAN) and the wavelet method were primarily applied and (a) long-term ($\approx$12 years) and short-term NSA variations (1.5 – 3.0 years) were revealed; (b) the presence of the quasi-biennial oscillations (QBO) in the NSA of all the investigated activity indices was approved; (c) the QBO in the NSA of indices were found to be significantly better expressed in comparison with the QBO derived from the studied indices themselves; (d) the significance of the QBO in the NSA of the studied indices, particularly those in the coronal brightness and the sunspot parameters, appears to be in anti-phase with the magnitude of the NSA itself (this effect is reduced distinctly only close to the boundary between the low- and mid-latitude zone at 40° – 50°).

In addition to our previous studies, here we apply the well-known auto-correlation and cross-correlation methods to looking for the long-term course (almost six solar cycles) of the NSA variations and demonstrating the presence of the QBO in the NSA time changes of three solar activity indices: photospheric sunspot numbers and magnetic flux, and coronal green line brightness. The reliability of the results is checked by verifying the results using also an alternative definition of the NSA and a different combination of the applied numerical parameters.

2. Observational Data and Methods

Three different solar activity indices – the sunspot number (SN), the photospheric magnetic flux (MF), and the coronal green line brightness (CGLB) – are treated to demonstrate the long-term and large-scale variations in the asymmetry of solar activity as recorded at the northern and southern hemispheres of the Sun. Subsequently, mutual comparisons of the regularities found for the NSA of different indices are the principal topic throughout this paper.

It should be noted that the NSA was determined here by commonly used way as $A = (N - S)/(N + S)$, where N and S are understood as the values of the corresponding activity indices calculated for different hemispheres. Alternatively we have used also the asymmetry parameter calculated just as $A = N - S$ introduced and preferred by Ballester, Oliver, and Carbonell (2005).

The hemispheric sunspot number data sets are taken here from the catalogue prepared from sunspot drawings provided by the Kanzelhöhe Solar Observatory (KSO – Austria) and the Skalnaté Pleso Observatory (SPO – Slovak Republic) covering the time span 1945 – 2004 (Temmer *et al.*, 2006).[1] For KSO and SPO data together the coverage is 84% of days within the entire time span 1945 – 2004 including 38% of days where drawings from both observatories were available. For each available day the relative fraction of the northern and southern component normalized to the activity of the entire disk was calculated. The actual values of the hemispheric sunspot numbers were obtained multiplying the relative fractions with the total Sunspot Number R_i from SIDC,[2] for that day (SIDC-team; http://www.sidc.be/sunspot-data/). Dates without any observation are linearly interpolated.

The photospheric magnetic flux data set is based on the patrol measurements of the photospheric magnetic fields regularly obtained at Kitt Peak Observatory (National Solar Observatory, USA).[3] Data in the form of the Carrington rotation (CR) magnetic maps were

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[1] Data of this catalogue is freely available for users also at http://www.astro.sk/~choc/publications/trbvvoph_aa_2006/trbvvoph_aa_2006_public.html.

[2] Solar Influences Data Analysis Center – SIDC: http://sidc.oma.be/.

[3] Data archive is available at ftp://nsokp.nso.edu/kpvt/synoptic/mag/.

used covering the time interval from February 1975 until December 2001. These maps were created using magnetic measurements of regions near the central meridian in the individual daily magnetograms. Data were merged into a synoptic Carrington coordinate system with 180 bins in sine of latitude, each covering an equal projected (line of sight) area and with 360 longitude bins along a complete rotation of the Sun. Data have been reduced to provide the best estimate of the average magnetic flux density at each pixel of the Carrington map. Changes of the magnetographs and the spectral lines used to measure the surface magnetic fields and a projection effect were considered (Harvey *et al.*, 1980; de Toma, White, and Harvey, 2000).

The current long-lasting manifestations of activity in the solar corona are described here by our own data set compiled and homogenized using daily intensity measurements in the coronal green emission line Fe XIV 530.3 nm, as regularly performed by a world-wide network of coronal observatories. The exploited data set covers the period 1939 – 2001 in this paper. Our CGLB data set represents a matrix of the daily data recorded with steps of ≈13° and 5° in the solar longitude and latitude, respectively. All the data are related to the height of 60″ above the solar limb. In fact, this data set was extensively analyzed by us and the most instructive description of it could be found in Storini and Sýkora (1997) and Sýkora and Rybák (2005).

We should note that all the three data sets are treated here within two particular latitudinal zones (5° – 30° and 35° – 60°) in an effort to look for a specific chronological and/or spatial peculiarities in the course of NSA in these low- and/or mid-latitude zones symmetrically situated with respect to the solar equator. Understandably, only the low-latitude zone is pertinent for the presence of the sunspots. The magnetic flux data, unlimited in latitude, are regularly and reliably registered only since the year 1975. The monthly averages of the daily data were primarily used throughout this study.

Auto-correlation (AC), cross-correlation (CC), and regression methods were applied to compare the obtained NSA data sets. The following remarks should be added to clarify better the utilized procedures: Pearson's formula was used for the calculation of AC and CC both for the data sets of the whole length or for their parts; the edge effect and the global trend were removed before the calculation of CC in order to avoid the spurious signal in the derived results (Gömöry *et al.*, 2004). For a selection of the parts of the whole length data sets the temporal window of the 46.5-month length was used shifted step by step for one month. Correlations were calculated for the lag up to 31 months. Positions of the CC maxima were determined through a polynomial approximation of the particular CC lobe behavior in the vicinity of its maximum value with a sub-month precision.

3. Results

(1) Taking a glance, quite similar time variations of the NSA were identified in case of the three studied indices of solar activity, both in the low-latitude and mid-latitude zones over the short- as well as long-time scales (Figure 1). The corresponding correlations between the NSA curves of different indices are given in Table 1 (columns A and B). These coefficients demonstrate distinctly somewhat higher correlations (column A) of the moderately (five-monthly) smoothed curves in comparison with the correlations (column B) of the "raw" monthly data.

(2) The linear regressions calculated for the whole data periods show approximately doubled positive coincidence between the NSA of the SN and the low-latitude CGLB in comparison with, *e.g.*, that between the NSA of the mid-latitude MF and the low-latitude CGLB.

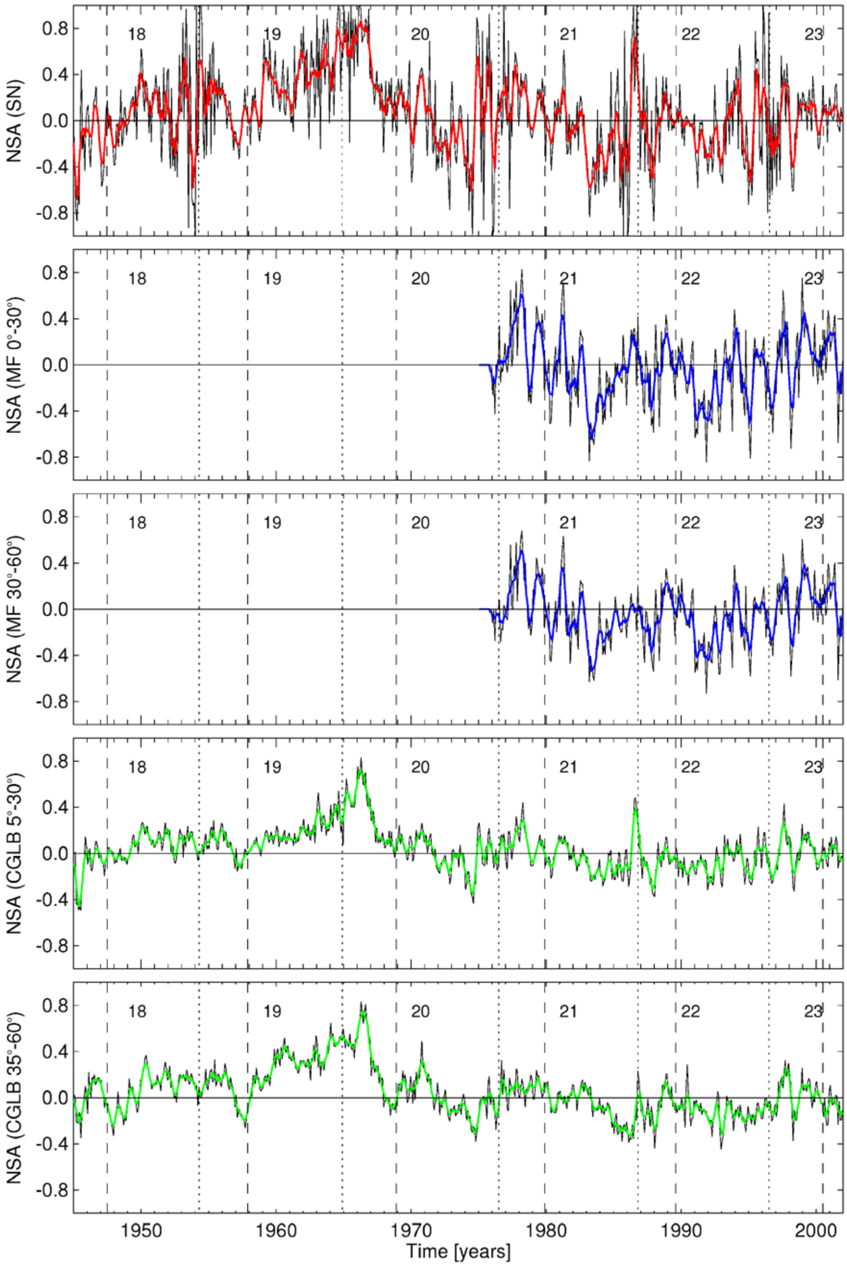


Figure 1 Time variations of the N – S asymmetry (NSA) for three indices of solar activity (from top to bottom: the sunspot number (SN), the photospheric magnetic flux (MF), and the coronal green line brightness (CGLB), drawn by red, blue and green colors, respectively. The NSA curves of the MF and those of the CGLB are drawn separately for the low- and mid-latitude zones, as indicated on vertical axis. In the case of all five panels the monthly averages of daily data were used to calculate the NSA of different indices (the black curves). Then, these curves were five-month-smoothed and the color curves of the NSA were obtained. Ordinary minima and maxima of the 18 to 23 solar cycles are demarcated by the dotted and dashed vertical lines, correspondingly.

Table 1 Correlation and regression parameters of the QBO of NSA: cross-correlation coefficients between the north – south asymmetries as derived from the five-month smoothed values (column A) and the "raw" one-month (column B); linear regression coefficients (*i.e.*, parameter characterizing the slope of the straight line obtained from the smoothed curves of NSA) in case of their "no shifting" (column C) and those coefficients after shifting the NSA curves to their best correlations (column D); periods (in months) of the quasi-biennial oscillations obtained from the smoothed cross-correlation curves (columns E and F). These periods are determined considering the real positions of the primary maxima.

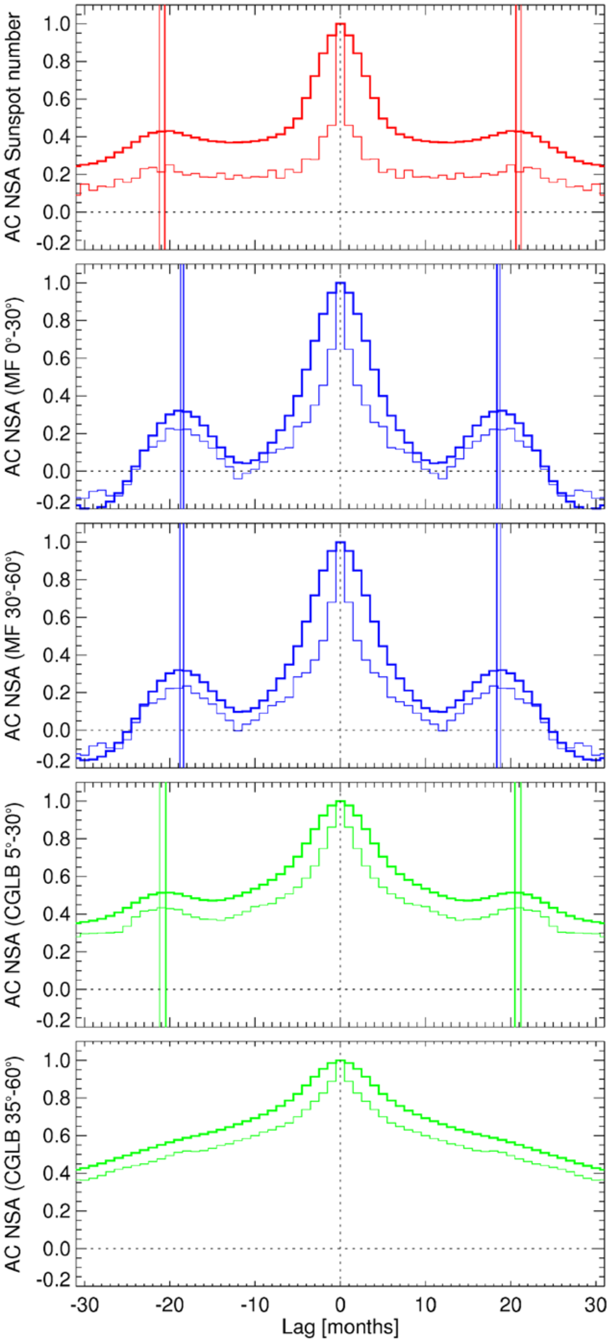
Pairs of the NSA curves	A	B	C	D	E	F
Sunspots vs. Low-lat. corona	0.87	0.65	0.50	0.51	−20.2	+20.0
Sunspots vs. Mid-lat. corona	0.54	0.52	0.48	0.51	none	+18.0
Low-lat. mag. flux vs. Low-lat. corona	0.81	0.62	0.38	0.41	−19.7	+19.8
Low-lat. mag. flux vs. Mid.-lat. corona	0.52	0.40	0.21	0.26	−19.6	+19.1
Mid-lat. mag. flux vs. Mid-lat. corona	0.56	0.44	0.29	0.33	−19.0	+19.3

A noticeably better positive coincidence is found between the NSA of the indices related to the same latitudinal zone than if the low- (mid-) zone of one index is compared with the mid- (low-) zone of another index. A more detailed analysis of the similar regressions (the corresponding figures are not presented here) carried out on the data sets shifted mutually for ≈1 – 3 months provide significantly higher regression coefficients in comparison with those where no mutual shift of the correlated curves was undertaken (compare columns C and D of Table 1). This really indicates a certain non-zero time delay of the global manifestations of the NSA phenomenon in the solar corona in relation to that in the photosphere.

(3) The presence of the quasi-biennial oscillations (QBO) in the NSA of the solar activity indices studied is indicated by the secondary maxima of the auto-correlation curves displayed in all the five panels of Figure 2. The QBO are most remarkable in the NSA of MF, while in the NSA of mid-latitude CGLB (outside of the sunspot activity belt) they are hardly noticeable. The QBO periods are found around 21 months for the NSA of SN and CGLB and they are close to 19 months in the case of MF (columns E and F in Table 1).

(4) An attempt to reveal the possible evolution of these auto-correlations throughout the individual solar cycle phases was made. Only two "time expansion" of the SN and CGLB (5° – 30°) auto-correlation curves from Figure 2 are presented here in Figure 3. These time-lag maps of the correlation constructed as described above show significant variability of the correlation in time. For example, during the onset of cycle 22 (1987 – 1989.5) the period of the QBO was nearly 27 months, while in the same phase of cycle 23 (1997 – 1999) it was only at about 20 months. Additionally, a significant change of the QBO period is taking place several times in the studied epoch especially after maxima of the solar cycles when it is shortened down to just at about 10 months. Moreover, the phenomenon of the QBO disappeared suddenly several times in the last 50 years when the secondary maxima were not present in the 2D maps of the time lag CC (*e.g.*, beginning of the year 1982). This allows us to conclude that the QBO of NSA is a phenomenon which is not persistent all over the solar cycle. Therefore, the NSA behavior of the photospheric as well as coronal manifestations of the magnetic flux is changing in time leading to the roughly two-year periodicity only after a statistically significant averaging.

Figure 2 The diagrams of auto-correlation coefficients as calculated from the whole sets of the NSA data (*i.e.*, from the curves presented in Figure 1). The thick and thin curves here are related to the smoothed and non-smoothed data, respectively. The vertical thick and thin full lines indicate the precise positions of the corresponding secondary maxima related to the QBO.



(5) The cross-correlations of the NSA data sets demonstrate repeatedly a generally high degree of correspondence between the NSA of the solar green-line corona and of the same phenomenon in both photospheric indices (Figure 4). The coefficients are close to 0.8 in

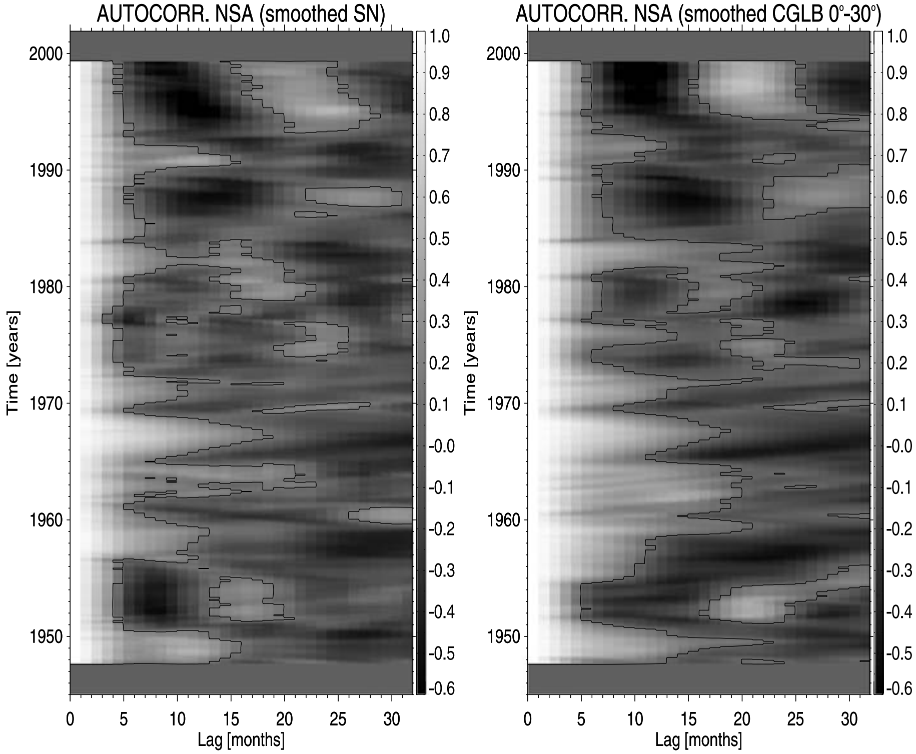


Figure 3 Examples of time evolution of the auto-correlation coefficient between the NSA curves of the five-month-smoothed sunspot numbers SN and the same of the CGLB (latitude zone 5° – 30°) during the whole period investigated. The scales of the correlation coefficient is given at the right vertical axes. The dark broken line stems from the CC value of 0.7.

the case of identical latitudinal zones and 0.5 in the case of the non-identical zones. The positions of the main maxima of CC, marked by vertical lines to the right from the vertical dotted line at the zero lag in Figure 4, prove that all the NSA maxima derived from the CGLB are reached later in relation to the NSA of the number of sunspots and magnetic flux. In the case of identical low-latitude zones the delays are from 1.0 – 1.5 months; for non-identical latitude zones these delays come up to 1.5 – 2.5 months, and for identical high-latitude zones it is 2.2 months.

(6) The secondary maxima clearly seen in the curves of the cross-correlation coefficients (Figure 4) are an unambiguous consequence of the presence of QBO in the NSA of the studied solar activity indices. The corresponding QBO periods (of course, related to the shifted primary maxima of the CC curves) are given in columns E and F of Table 1. Unequal heights of two secondary correlation maxima within the individual panels are recognized. The right secondary maximum is usually somewhat higher in comparison with the left one, indicating pronounced similarity of the NSA behavior of the coronal activity delaying after the magnetic flux in the photosphere. The only exception is the correlation of the magnetic flux and CGLB data for the low-latitude zone.

(7) Revealing the evolution of the NSA cross-correlations throughout the individual solar cycle phases was by the "time expansion" of the cross-correlation. Only two examples are presented here in Figures 5 and 6; *e.g.*, Figure 5 represents a certain time expansion of

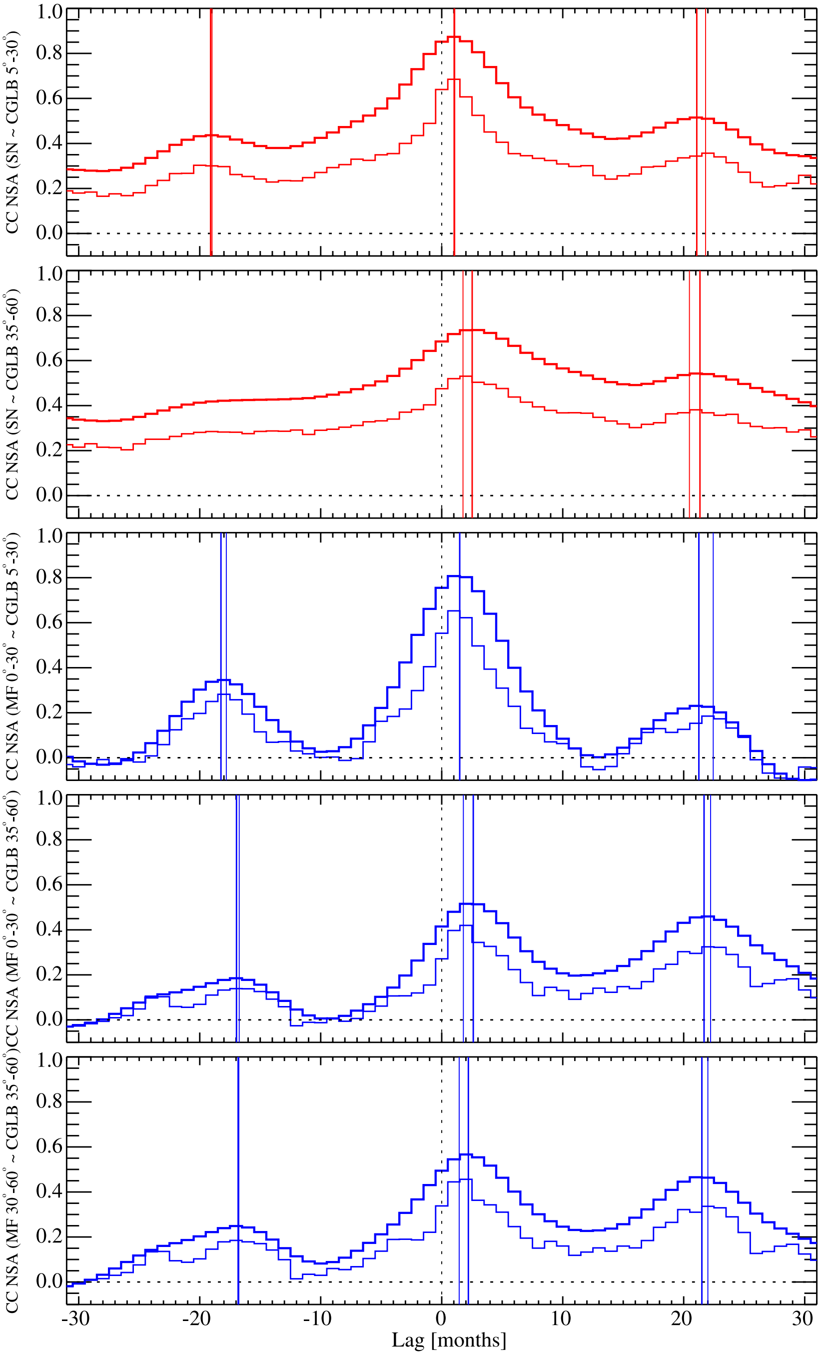


Figure 4 The diagrams of cross-correlation coefficients as calculated from the whole sets of the NSA data (*i.e.* from the curves presented in Figure 1). Again, the thick and thin broken-line curves are related to the five-month-smoothed and non-smoothed data, respectively. The vertical thick and thin full lines close to the center of panels indicate the time difference after which the best correlations of the NSA curves of two cross-correlated indices are reached.

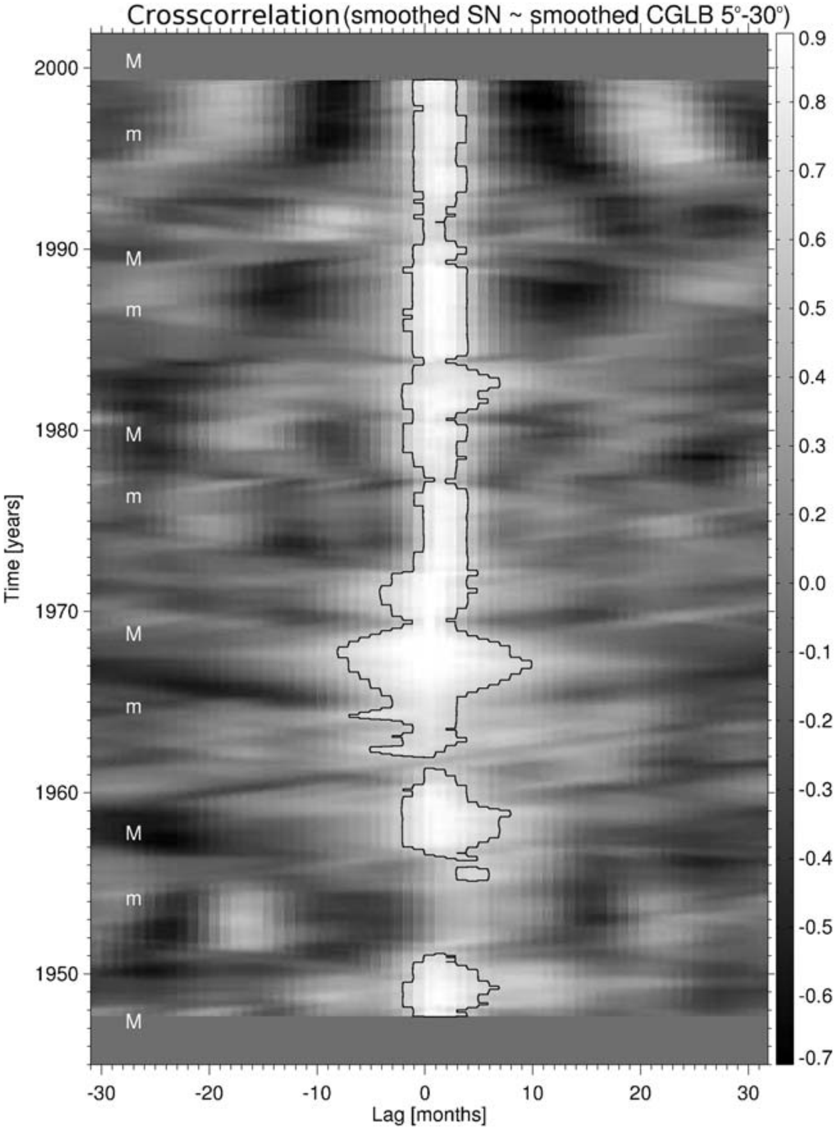


Figure 5 An example of time evolution of the cross-correlation coefficient between the NSA curves of the five-monthly smoothed sunspot numbers and the same of the CGLB (latitude zone $5° - 30°$) during the whole period investigated. The positions of the maxima and minima of individual solar cycles are denoted close to the left vertical axis by M and m, respectively. The scale of the degree of correlation is given at the right vertical axis.

information "compressed" within the uppermost curve of Figure 4. All the properties mentioned within the result (4) in this paper (relatively high correlations, shifts of the highest CC coefficients rightwards of the zero lag and the secondary correlation maxima, related to the QBO dispersed around the lag of ±20 months) are well visible also in the time expanded cross-correlations shown in Figures 5 and 6. One can notice a clear rightward deviation of the 0.7 CC isoline region (circumscribed by the dark broken-line) relatively to the zero lag.

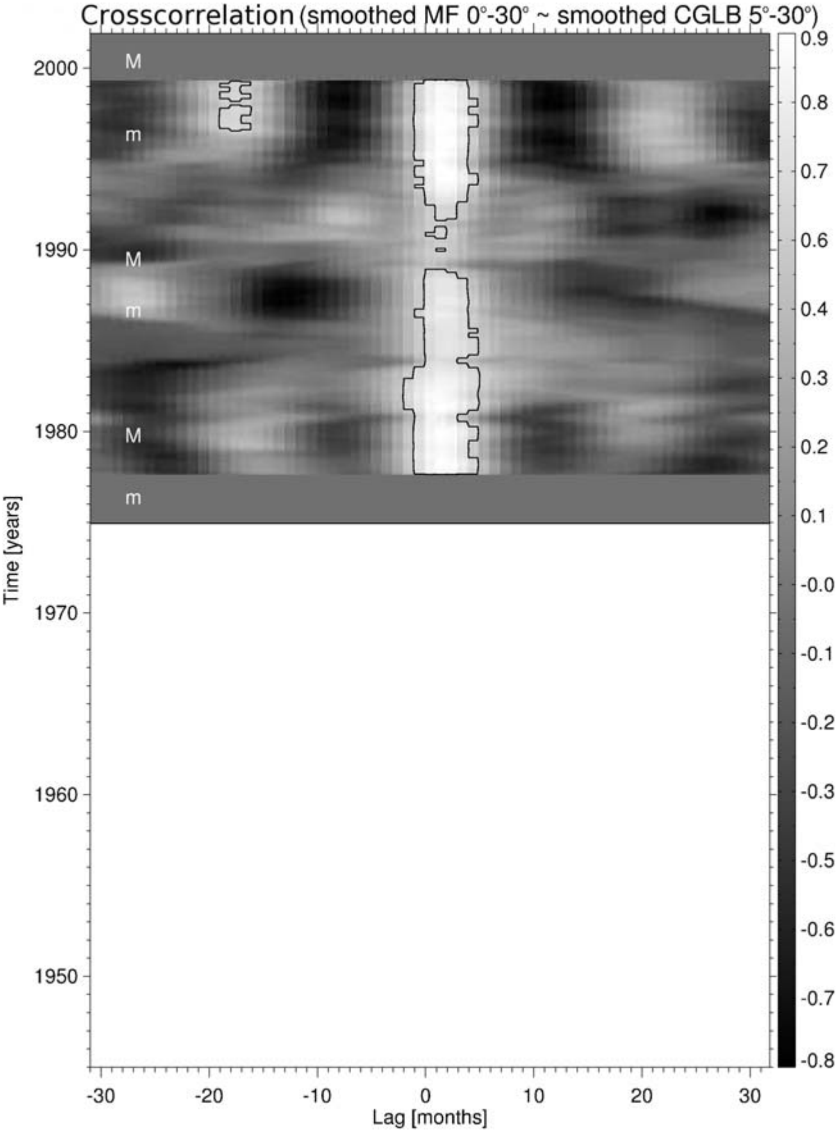


Figure 6 The same as in Figure 5 but now for the cross-correlation coefficient between the NSA curves for the MF and the CGLB (both related to the low-latitude zones 0° – 30° and 5° – 30°, respectively).

Notice also the regions of clear negative correlation around the ±10 month lags and clearly enhanced regions of positive correlations close to ±20 month lags. Time evolution of the CC coefficient between the NSA of the MF and CGLB indices (Figure 6) shows even more discrete and distinctive distribution than that in Figure 5 for the SN and CGLB. Apparently, no pronounced dependence of the cross-correlation coefficients on the cycle phase is generally noticed. Particular regularities were detected only for example in relation of the CGLB low-latitude zone and the SN data where a similar decrease of the time shift can be noticed for

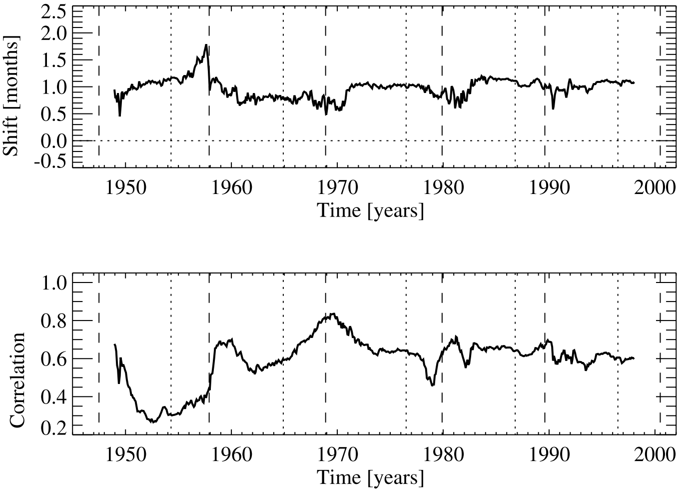


Figure 7 Mutual correlation of the SN and CGLB smoother data: maximum of the cross-correlation curve (bottom panel) and the corresponding temporal shift position (upper panel). Polynomial fitting of the central part of the CC curves was applied to derive the results with the sub-month precision. The positions of the maxima and minima of individual solar cycles are marked by the vertical dashed and dotted lines, respectively.

two of four studied solar cycle maxima (Figure 7). No clear relation between the correlation and the shift was derived either.

(8) Numerical tests performed have confirmed that the detected QBO periods are real and mutually comparable regardless of the chosen combination of the applied numerical parameters, *i.e.*, the lag length and/or window lengths of the partial data sets selected from the whole length data sets as illustrated in Figure 8.

(9) Qualitatively similar results were derived also for the north – south asymmetry defined by the alternative measure defined just as $A = N - S$ as it was introduced by Ballester, Oliver, and Carbonell (2005).

4. Discussion and Conclusions

The NSA behavior has been studied in detail in previous works using different data sets and different approaches. The most significant result, as was proved by several studies, is the phenomenon of the quasi-biennial oscillations (QBO) derived using different methods (Badalyan, Obridko, and Sýkora (2008) and references therein). In this paper we show convincingly that the very simple AC and CC approach can make manifest this QBO phenomenon clearly as well.

The general smooth behavior of the AC curves displays a clear QBO phenomenon with pronounced secondary correlation peaks when sufficient temporal averaging is performed over several solar cycles.

Time expanded AC time-lag maps reveal clearly and reliably that the period and/or power of the NSA behavior are significantly variable during the course of the solar activity cycles: a significant change of the QBO period is taking place several times in the studied epoch, especially after maxima of the solar cycles when it is shortened down to at about 10 months. Moreover, the QBO phenomenon is practically disappearing (suddenly) several times in the

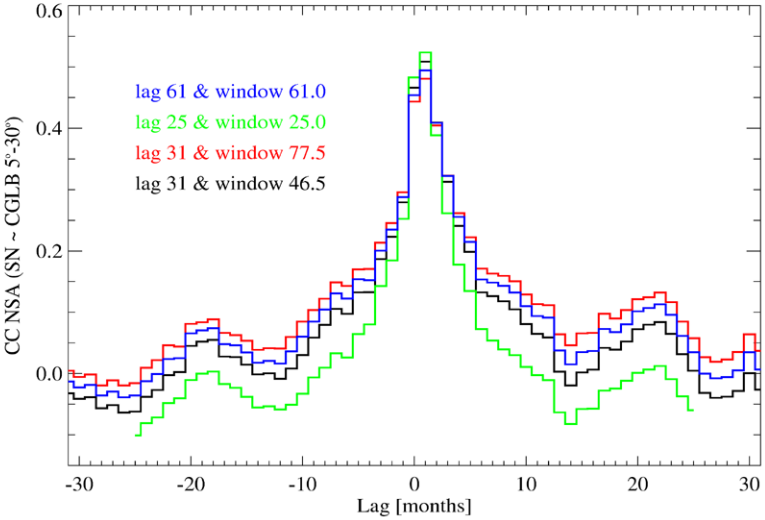


Figure 8 Reliability test of the detected QBO phenomenon. Using data sets of the SN and CGLB (latitudinal zone 5° – 30°) as an example, several values of the window length and lag interval were undertaken to calculate the cross-correlation over the whole time interval. The curves for four chosen combinations of the two parameters are presented in this figure. It is evident that neither the position of the CC maximum nor the positions of the secondary maxima on the CC curves are influenced by the chosen combination of lag and window. Therefore, there could hardly be speculations on some numerical artifact in the results of our present study.

previous 50 years when the cross-correlation lacks the secondary maxima in the CC time-lag maps. This indicates that the NSA QBO is a phenomenon which is not persistent during the whole solar cycle.

The similarity of the NSA behavior of the photospheric and coronal manifestations of the magnetic flux leads to the QBO phenomenon also for their mutual correlations.

Also here the general smooth behavior of the mutual correlation of the NSA data sets with clear QBO secondary maxima is just a consequence of the temporal averaging performed over several solar cycles. Time expanded CC time-lag maps of NSA themselves clearly show a variable degree of correlation as well as changing periodicity of these quasi oscillations.

The unequal heights of the two secondary CC maxima (Figures 4, 5, 6), when the right secondary maximum is usually somewhat higher in comparison with the left one, are natural, as the coronal response is a consequence of the newly emerging flux in the photosphere.

A clear and significant temporal shift of the coronal manifestations of the magnetic flux asymmetry relative to the photospheric manifestations for more than a month is revealed as a main property of their mutual correlation.

The derived shift of the NSA manifestations between the photospheric and coronal layers can be caused by at least the two following effects: (1) the SN data and also the MF data sets can diminish in time due to the disappearance of sunspots in white light for telescopic observations or due to decrease of observational signatures of the magnetic flux for magnetograph measurements while the coronal manifestation measured as the CGLB is still visible due to larger scale coronal emission present in the active region coronal loops. Alternatively, (2) filling of the newly created coronal loops with plasma of sufficient density and/or heating of plasma within these loops can be delayed relative to the first possible measurements of the sunspots or photospheric magnetic flux emergence in the photosphere. Both these reasons can consequently lead to the property that the asymmetry – a measure of difference between the activity on different hemispheres – is delayed for the coronal indices.

Nevertheless, the mutual correlation of the coronal and photospheric asymmetries is in fact quite changing both in the effectiveness and shift, and their actual relation may be quite different from the average correlation derived over several solar cycles of activity. This shift phenomenon between the coronal and photospheric asymmetries as well as its variability can be important for the investigation of the large-scale photosphere – corona coupling.

Acknowledgements The authors acknowledge discussion with O. Badalyan on the topic of this paper. This work was supported by the VEGA grant No. 2/0064/09 of the Slovak Academy of Sciences. The NSO/Kitt Peak data used here were jointly prepared by the NSF/NOAO, NASA/GSFC, and NOAA/SEL.

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