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Prediction of Amplitude of Solar Cycle 24 Based on Polar Magnetic Field of the Sun at Cycle Minimum

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Abstract. We have quantitatively investigated the correlation between the relative sunspot number and magnitude of Sun's polar magnetic field in solar cycles 21–23 from May 1976 to November 2009. Sunspot number is in anti-correlation with average magnitude of polar field ($r = -0.62$, $P < 0.001$). Maximal positive correlation between the parameters was calculated when average magnitude of polar magnetic field was time-shifted forward on about 5.2 years ($r = 0.84$, $P < 0.001$). Magnitude of polar field of the Sun in the minimum of solar activity between solar cycles 23 and 24 was used as precursor to forecast maximal amplitude of sunspot number in solar cycle 24. It was found that solar cycle 24 is expected to be relatively weak cycle with maximal strength of 67□8 in units of monthly smoothed sunspot numbers.

Keywords: Sun, solar activity, solar cycles, 24rd solar cycle, Polar Magnetic Field

Introduction

The 11-year sunspot cycle is the most famous and most used characteristic of the solar activity. The solar activity variations cause some changes in the interplanetary space and, in particular, in the Earth's magnetosphere. The last, in turn, affect the operation of such space-borne and ground-based technological systems as manned space flights, space navigation and aero-navigation, radars, ground power lines, high-frequency radio communication, etc. The solar activity variations have also some influence on the climate and living organisms on the Earth including people. This is why knowledge of the solar activity level in advance is interesting and sometimes very important.

Now, at November of 2009, the solar activity is very low, it is in deep minimum between solar cycles 23 and 24, although the first bipolar active region and sunspots with magnetic polarity of solar cycle 24 appeared as early as in the middle of December 2007 and in the beginning of January 2008 respectively (see, e.g., data at http://www.solarmonitor.org for corresponding days). At the present time it is very hard to say when maximum of solar cycle 24 will occur and what maximal amplitude of sunspot number will be achieved. Many predictions for solar cycle 24 exist at the present time. The most extensive set of predictions was collected and published by Pesnell [1], some published predictions are also collected, for example, in [2]. More than 45 published predictions are gathered at the Janssens's panel (http://users.telenet.be/j.janssens/SC24.html). Maximal amplitude of sunspot number in solar cycle 24 is predicted to be in a wide range from 42 [3] to about 190 [4].

Many methods for the prediction of solar activity have been suggested up to date (see, e.g., Ref. [1], [5]–[8] and references therein). One of them is the precursor method, which uses some indexes or values as leading indicators of solar activity. Polar magnetic field of the Sun is one of such precursors. It is in addition physically-based precursor [9]. Predictions for solar cycle 24 based on the Sun's polar magnetic field were done by Schatten [10] and Svalgaard et al. [11] where values 80□30 and 75□8 respectively were obtained for predicted amplitude in units of monthly smoothed sunspot numbers. These predictions were based on polar field data of 2004, more than 4 years before the minimum between solar cycles 23 and 24.

In the present paper to forecast maximal amplitude of solar cycle 24 we use data on polar field of the Sun right up to November 2009 and different procedure than in papers [10] and [11]. At first we quantitatively analyze correlation between relative sunspot number and strength of Sun's polar magnetic field.

Sunspot number and polar field of the Sun

Fig. 1 shows time evolution of relative sunspot number, heliospheric current sheet (HCS) tilt and strength of Sun's polar magnetic field in solar cycles 21–23. Monthly sunspot numbers were taken from the Solar Influences Data analysis Center (SIDC, http://sidc.oma.be), HCS tilts and magnitudes of polar fields were taken from the Wilcox Solar Observatory (WSO, http://wso.stanford.edu). Smoothed values, obtained using 13-point running average, are shown by bold lines. Vertical solid and dashed lines indicate times of magnetic reversals at northern and southern poles respectively according to Pishkalo et al. [12]. Horizontal dashed line at the middle panel corresponds to the latitude of 550.

Relative sunspot number (or the Wolf number) characterizes the number of sunspots on the visible solar surface. Polar magnetic fields of the Sun are determined every 10 days as 30-day average strength of magnetic field in the near-polar regions measured with 3□-aperture, from about 550 to the poles. It should be noted that values of polar field strength observed at WSO and used in this paper is not strength of magnetic field at the poles directly. It represents an integrated magnetic flux from about ±550 latitude to the poles. In the following part of the paper we will call absolute value of strength of polar field measured from about ±550 latitude to the poles as magnitude of polar field. It should be also mentioned that observed strength of polar field reverses its sign near maximum of sunspot number and 1-2 years before magnetic reversals at the poles. The HCS tilts are determined using coronal synoptic maps computed in the potential approach as maximal latitudes of magnetic neutral line at the source surface in the northern and southern hemispheres during specific rotations and are limited in high latitudes at the range of about ±750. Here radial and classic tilts were calculated in radial and classic approach with radius of the source surface to be 3.25 and 2.5 solar radii respectively. The HCS position reflects the position of the magnetic neutral line of the global solar magnetic field at the "source surface", which, in turn, mainly defines structure of the whole heliospheric magnetic field and, in particular, the sector structure of the interplanetary magnetic field near the Earth's orbit. In other words, the HCS is a manifestation of solar magnetic equator. HCS tilts characterize the angle between the solar equator and the solar magnetic equator. The HCS divides the interplanetary space into two parts with oppositely directed open magnetic field lines and is a framework of the heliosphere.

One can see form Fig. 1 that sunspot number variations are in good agreement with variations of the HCS tilts and that polarity (or direction) of polar magnetic field in the Sun's northern hemisphere is opposite to polarity of the field in the southern hemisphere, and polar magnetic field reversals occur near the times of the sunspot activity maxima. Sunspot maxima consist of two peaks. Moreover, magnetic reversals at northern and southern poles occur at different time; sometimes (as in solar cycle 22) the time difference is slightly greater than one year. A pair of even and odd 11-year cycles forms one 22-year magnetic solar cycle (the Hale cycle). Time evolution of the HCS tilts and polar fields may be described in an idealized manner by the model of Starkova and Solov'ev [13]. High correlation between sunspot numbers and HCS tilts allows calculating HCS tilts before 1976 [14].

Magnitude of the Sun's polar magnetic field decreases from solar cycle 21 to 23. Maximal sunspot in each cycle also decreases from solar cycle 21 to 23. Time evolution of the HCS tilts in solar cycle 23 is very different from one in solar cycles 21 and 22. In solar cycle 23 we can see flat section in the "time - HCS tilt" dependence during about three years at the descending phase of activity.

Average magnitude of polar magnetic field of the Sun is in anti-correlation with sunspot number. It is easily seen at the upper panel of Fig. 2. Maxima of polar fields' strength occur at minima of solar activity and vice versa. To be more correct maximal values of magnitude of polar field are observed some time before solar minima. The correlation coefficient between smoothed sunspot number and magnitude of polar field (without any time shift) is equal to -0.62 (P < 0.001).

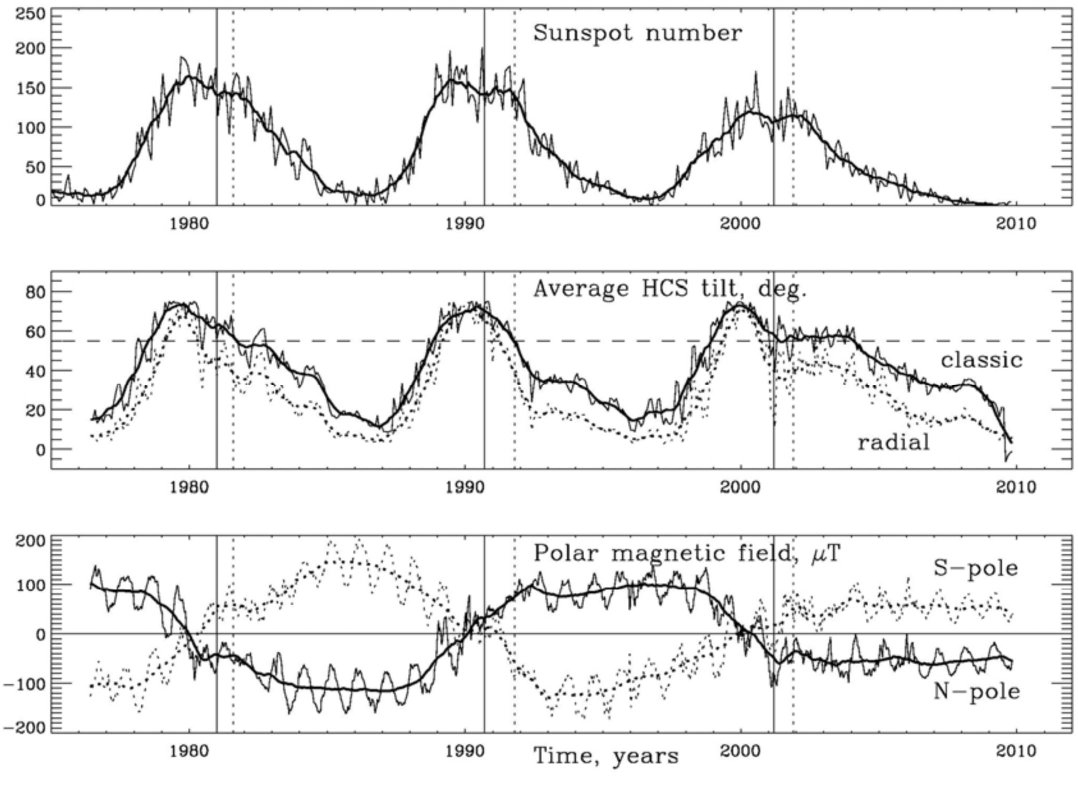

Fig. 1. Relative sunspot number (the top panel), average classical (solid line) and radial (dashed line) tilt of the heliospheric current sheet (the middle panel) and strength of Sun's polar magnetic field (the bottom panel) at the northern pole (solid line) and the southern pole (dashed line) in solar cycles 21–23. Smoothed values are shown by bold lines. Vertical solid and dashed lines present times of magnetic reversals at northern and southern poles, respectively. Dashed horizontal line at the middle panel corresponds to the latitude of 55^0.

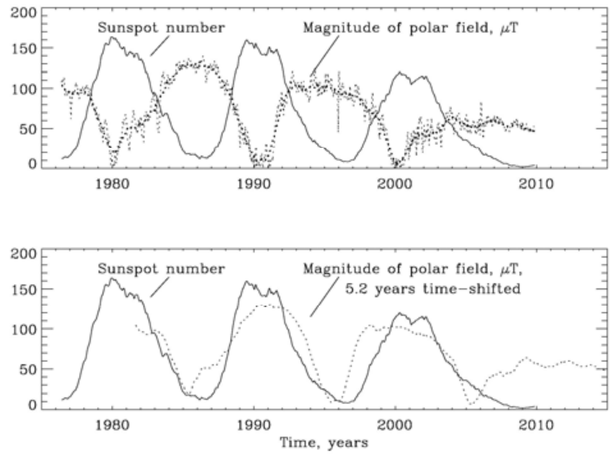

Fig. 2. Smoothed sunspot numbers and average magnitudes of Sun's polar magnetic field without any time shift (the upper panel) and with the time shift of 1920 days corresponding to about 5.2 years (the bottom panel). Unsmoothed average magnitudes of polar field are shown at the upper panel by thin dashed line.

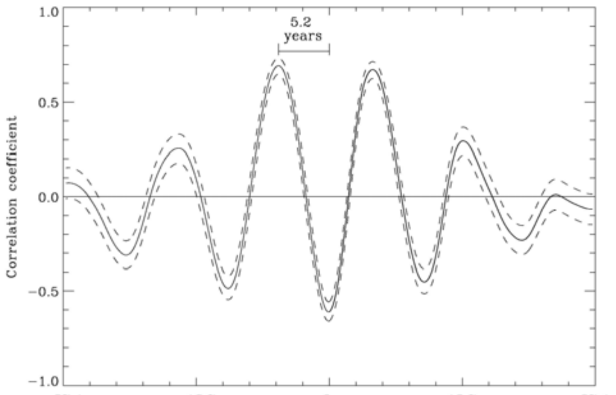

Fig. 3. Cross-correlation between smoothed sunspot numbers and magnitudes of polar magnetic fields of the Sun. The 99% confidence limits estimated by means of the standard Fisher r to z transformation are shown by dashed lines.

Cross-correlation analysis of smoothed sunspot numbers and magnitudes of polar field is presented at Fig. 3. Here the 99% confidence limits are plotted by dashed lines. They were estimated by means of the standard Fisher *r* to *z* transformation [15]. The first left and right secondary maxima at Fig. 3 are equal to 0.69 ($P < 0.001$) and 0.67 ($P < 0.001$) correspondingly and tally with the time lag about 5.2 and 4.5 years.

Each solar cycle is unique. Its characteristics are determined by a number of parameters concerning some different physical processes in the solar interior. One can see from Figs. 1 and 2 that time lag between maximum of polar field magnitude and following sunspot number maximum is not constant for all cycles as well as between corresponding sunspot number minima and maxima. Maxima of polar field magnitude occur close to sunspot number minima. The curves describing time evolution of polar field magnitude and sunspot number are not very similar. As a time shift between maxima of polar field magnitude and sunspot number we use the time lag when cross-correlation between the parameters is maximal (5.2 years).

Time lag between maximum of polar field magnitude and following sunspot number maximum is a measure of deep meridional flow towards the equator according to dynamo models. This deep meridional circulation manifests itself at the solar surface by the migration of the sunspot formation belts towards the equator. Hathaway et al. [16] examined the drift of the centroid of the sunspot area toward the equator in each solar hemisphere from 1874 to 2002 and found that the drift rate at sunspot maximum was significantly correlated with the amplitude of the following cycle and anti-correlated with cycle period (hemispheres with faster drift rates had shorter periods).

Shown at the bottom panel of Fig. 2 are sunspot numbers in solar cycles 21-23 and magnitudes of polar magnetic field time-shifted forward on about 5.2 years corresponding to the first left secondary maximum at the upper panel of Fig. 3. The correlation coefficient between these values (time shift is 5.2 years) is equal to 0.83 ($P < 0.001$).

It should be noted that ratio of maximal sunspot number amplitude in solar cycles 22 to corresponding time-shifted maximal magnitude of polar magnetic field is close to the same ratio in solar cycle 23 (1.23 and 1.14 respectively). From proportionality of smoothed maximal sunspot numbers and magnitudes of polar fields at the bottom panel of Fig. 2 one can conclude that solar cycle 24 will be relatively weak cycle.

Prediction of amplitude of solar cycle 24

Schatten et al. [9] pioneered the use of the Sun's polar magnetic field as a precursor to predict the amplitude of solar cycle 21. They predicted yearly mean sunspot number at solar maximum of 140□20. Observed values of smoothed yearly and monthly sunspot number in solar cycle 21 were 155.4 and 164.5, respectively. The use of solar polar field as physical precursor in itself is based on the dynamo theory developed by Babcock [17] and Leighton [18]. According to the dynamo theory solar polar fields near solar minimum are wrapped up by differential rotation to form the toroidal fields which float to the Sun's surface to form active regions (and sunspots) during solar maximum. Toroidal magnetic field of the Sun in the solar activity maximum is determined by poloidal magnetic field in the previous minimum. Sunspots (therefore sunspot number as well) are representations of toroidal magnetic field. Strength of polar magnetic field characterizes poloidal field. So, magnitude of polar magnetic field of the Sun in the minimum between solar cycles 23 and 24 can inform us about maximal amplitude of sunspot numbers in maximum of the forthcoming solar cycle 24.

To estimate numerically amplitude of smoothed sunspot number in solar cycle 24 and its uncertainties we have only data for solar cycles 22 and 23. Therefore we should make an excerpt from the data. When we, in accordance with the use of polar field as physical precursor, select only the sunspot number points that are from sunspot maximum to the end of the polar magnetic reversals (which is close to the second maxima in solar cycles 21-23, see, Fig. 1) and corresponding 5.2-year-time-shifted magnitudes of polar magnetic field, then the following equation for linear fit can be found (see, Fig. 4, r = 0.89, P < 0.01, 1-sigma uncertainty)

$$y = 9.1(\pm 5.3) + 1.09(\pm 0.05)x.$$

This equation can be used to calculate sunspot number in activity maximum when magnitude of polar magnetic field at the previous minimum is known. We have analyzed the current sunspot number data and found that minimum between solar cycles 23 and 24 was most likely observed in January 2009 and $R_{\min}$ was equal to about 1.8. Mean smoothed magnitude of polar magnetic field for the minimum epoch is about $53\mu T$. Using this value and the above obtained equation one can easily find that the amplitude of solar cycle 24 will be mounted to 67±8. So, solar polar field indicates that solar cycle 24 will be weak one. Solar cycle 24 is expected to be only slightly higher than a half of solar cycle 23. Observed smoothed sunspot numbers in solar cycles 21–23 and predicted values for solar cycle 24 based on magnitude of polar magnetic field are shown in Fig. 5.

It can be seen from Fig. 2 that smoothed magnitude of polar field at the descending phase of solar cycle 23 was nearly constant during about 5 years from 2003-2004 to 2009. Due to this phenomenon predictions based on polar fields observed in 2004 (papers [10] and [11]) and 2008-2009 (the current study) are closely approached.

It is very hard to tell at the present time when the maximum of solar cycle 24 will occur. From average parameters of solar cycle (see, e.g., equation (3) from paper [2]) it can be concluded that the maximum of solar cycle 24 is expected to be in the beginning of 2014. Subsequently, the next solar minimum is expected to be at the first half of 2020.

The result obtained here is close to the results by Schatten [10] and Svalgaard *et al.* [11] that were also obtained using the Sun's polar field as precursor. Their predictions for maximal amplitude of monthly smoothed sunspot number in solar cycle 24 are equal to 80±30 and 75±8 respectively. Svalgaard *et al.* [11] have used time variation of the solar magnetic axial dipole moment expressed as the difference between the polar fields in the north and in the south hemispheres for the epochs of minima since 1970. Prediction by Schatten [10] is based on the SODA method which uses a combination of polar and toroidal fields.

Prediction by de Jager and Duhau ($R_{\max}$ = 68±17 [19]) is especially close to our result presented here. That was obtained using physical-statistical method for forecasting solar activity on the basis of aa-index values at solar minimum. Some other predictions (see, e.g., the Pesnell's panel [1]) are also close to our result, while the majority of predictions are higher.

Two predictions of solar cycle 24 were made using some theoretical parameters of dynamo theory. Dikpati *et al.* [20] found that the peak amplitude of cycle 24 will be 30–50% above that of cycle 23 (R_{max}= 155-180). Choudhuri *et al.* [21] predicted that cycle 24 will be about 35% weaker than cycle 23 (R_{max}= 80). Such difference seems to tell us that modern dynamo theories are still needed to be improved. In paper [22] it was found that the difference was caused by different dynamo models: Dikpati et al. [20] used an advection-dominated model and Choudhuri et al. [21] used a diffusion-dominated model. Prediction in paper [21] is somewhat similar in spirit to the precursor method used in the current study and in papers [10] and [11].

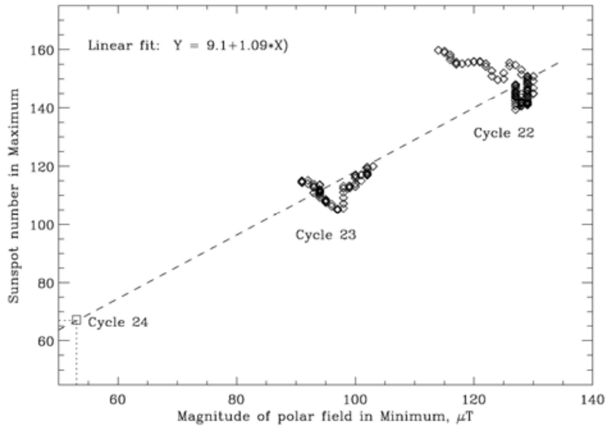

Fig. 4. Smoothed monthly sunspot number near cycle maximum depending on average magnitude of polar field time-shifted forward on 5.2 years, for solar cycles 22 and 23. Straight dashed line represents linear fit. Extrapolation indicates low amplitude of solar cycle 24.

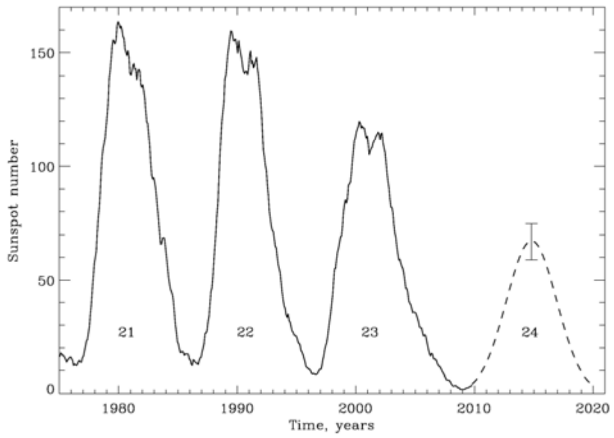

Fig. 5. Observed smoothed sunspot number in solar cycle 21-23 and predicted value for solar cycle 24.

In paper [22] extensive dynamo simulations were also made, using two contrasting regimes, one dominated by diffusive magnetic flux transport in the solar convection zone, the other dominated by advective flux transport by meridional circulation. Two main conclusion were made: 1) diffusion play an important role in flux transport, even when the solar cycle period is governed by the meridional flow speed and 2) observed solar cycle amplitude-period relationship arises more naturally in the diffusion-dominated regime, thereby supporting those dynamo models in which diffusive flux transport plays a dominant role in the solar convection zone.

Our previous preliminary prediction based on the correlation between cycle parameters [2] indicates that maximal amplitude of monthly sunspot number is expected to be about 110±33. In the paper [2] we have used preliminary sunspot number data for activity minimum epoch in solar cycle 24. But when we use current minimal value for smoothed sunspot number in solar cycle 24 (about 1.8 early in 2009) and equation (1) from [2] then we can conclude that maximal amplitude of solar cycle 24 is expected to be 88±17. Hence, statistical relations between cycle parameters also indicate that solar cycle 24 will be relatively weak one.

The result obtained here is very close to the prediction by Abdusamatov [23] based on analysis of solar radius and solar constant measurements (R_{max}= 70±10). Abdusamatov [23] have also concluded that next solar cycles will be weak similar to a new Maunder minimum. Recently Obridko and Shelting [24] pointed out some anomalies of the evolution of global and large-scale solar magnetic fields in the last solar cycles and concluded that several next solar cycles will be low. It is evident that only future observations of the Sun in next decades may confirm or disprove such forecast.

Conclusions

According to the dynamo theory, parameters of polar magnetic field of the Sun can be used as precursors to forecast strength of solar activity in the maximum of solar cycle. We have used average magnitude of polar magnetic field in the minimum of solar activity between solar cycles 23 and 24, measured at the WSO, as the precursor to forecast maximal amplitude of sunspot number in solar cycle 24. Monthly international relative sunspot numbers from the SIDC were also used. The correlation between the sunspot number and magnitude of Sun's polar magnetic field in solar cycles 21–23 was numerically investigated. Sunspot number is in anti-correlation with average magnitude of polar field ($r = -0.62$, $P < 0.001$). Maximal positive correlation between the parameters ($r = 0.83$, $P < 0.001$) was calculated when average magnitude of polar magnetic field was time-shifted forward on about 5.2 years. It was found that solar cycle 24 is expected to be relatively weak cycle with maximal strength of 67□8 in units of monthly sunspot numbers that is only about 1/2 of the strength of solar cycle 23. Maximum of solar cycle 24 is expected to be in the beginning of 2014.

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References

[1] Pesnell W.D. "Predictions of solar cycle 24", Solar Phys. Vol. 252, 2008, pp. 209-220. doi:10.1007/s11207-008-9252-2.

[2] Pishkalo M.I. "Preliminary prediction of solar cycles 24 and 25 based on the correlation between cycle parameters", Kinematics and Physics of Celestial Bodies Vol. 24, 2008, pp. 242-247. doi:10.3103/S0884591308050036.

[3] Clilverd M.A., Clarke E., Ulich T., Rishbeth H. and Jarvis M.J. "Predicting solar cycle 24 and beyond", Space Weather Vol. 4, 2006, S09005. doi:10.1029/2005SW000207.

[4] Li K.-J., Gao P.-X. and Su T.-W. "Estimating the size and timing of the maximum amplitude of solar cycle 24", Chin. J. Astron. Astrophys. Vol. 5, 2005, pp. 539-545. doi:10.1088/1009-9271/5/5/011.

[5] Thompson R.J. "A technique for predicting the amplitude of the solar cycle", Solar Phys. Vol. 148, 1993, pp. 383-388.

[6] Lantos P. and Richard O. "On the prediction of maximum amplitude for solar cycles using geomagnetic precursors", Solar Phys. Vol. 182, 1998, pp. 231-246.

[7] Schatten K. "Solar activity prediction: Timing predictors and cycle 24", J. Geophys. Res. Vol. 107, 2002, SSH 15-1, ID 1377. doi:10.1029/2002JA009404.

[8] Obridko V.N. and Shelting B.D. "On prediction of the strength of the 11-year solar cycle No. 24", Solar Phys. Vol. 248, 2008, pp. 191-202. doi:10.1007/s11207-008-9138-3.

[9] Schatten K.H., Scherrer P.H., Svalgaard L., Wilcox J.M. "Using dynamo theory to predict the sunspot number during solar cycle 21", Geophys. Res. Lett. Vol. 5, 1978, pp. 411-414.

[10] Schatten K. "Fair space weather for solar cycle 24", Geophys. Res. Lett. Vol. 32, 2005, L21106. doi:10.1029/2005GL024363.

[11] Svalgaard L., Cliver E.W., Kamide Y. "Sunspot cycle 24: Smallest cycle in 100 years?", Geophys. Res. Lett. Vol. 32, 2005, L01104. doi:10.1029/2004GL021664.

[12] Pishkalo M.I., Babij V.P. and Ivanchuk V.G. "North-south asymmetry of solar activity and Sun's global magnetic field reversals during 21, 22 and 23 cycles of activity", Visnyk Kyiv University. Astronomy Iss. 41-42, 2005, pp. 86-90 (in Ukrainian).

[13] Starkova L.I. and Solov'ev L.S. "On the precession of the solar magnetic axis", Astron. Lett. Vol. 23, 1997, pp. 207-211.

[14] Pishkalo M.I. "Reconstruction of the heliospheric current sheet tilts using sunspot numbers", Solar Phys. Vol. 233, 2006, pp. 277-290. doi:10.1007/s11207-006-1981-5.

[15] Mitropolsky A.K. Technique of statistical computing, Science, Moscow, 1971, (in Russian).

[16] Hathaway D.H., Nandy D., Wilson R.M. and Reichmann E.J. "Evidence that a deep meridional flow sets the sunspot cycle period", Astrophys. J. Vol. 589, 2003, pp. 665-670.

[17] Babcock H.W. "The topology of the Sun's magnetic field and the 22-year cycle", Astrophys. J. Vol. 133, 1961, pp. 572-587.

[18] Leighton R.B. "A magneto-kinematic model of the solar cycle", Astrophys. J. Vol. 156, 1969, pp. 1-26.

[19] De Jager C. and Duhau S. "Forecasting the parameters of sunspot cycle 24 and beyond", J. Atmos. Solar-Terr. Phys. Vol. 71, 2009, pp. 239-245. doi:10.1016/j.jastp.2008.11.006.

[20] Dikpati M., de Toma G. and Gilman P.A. "Predicting the strength of solar cycle 24 using a flux-transport dynamo-based tool", Geophys. Res. Lett. Vol. 33, 2006, L05102. doi:10.1029/2005GL025221.

[21] Choudhuri A.R; Chatterjee P. and Jiang J."Predicting solar cycle 24 with a solar dynamo model", Phys. Rev. Lett. Vol. 98, 2007, ID 131103. doi:10.11103/PhysRevLett.98.131103

[22] Yeates A.R., Nandy D. and Mackay D.H. "Exploring the physical basis of solar cycle predictions: flux transport dynamics and persistence of memory in advection- versus diffusion-dominated solar convection zones", Astrophys. J. Vol. 673, 2008, pp. 544-556.

[23] Abdusamatov Kh.I. "Optimal prediction of the peak of the next 11-year activity cycle and of the peaks of several succeeding cycles on the basis of long-term variations in the solar radius or solar constant", Kinematics and Physics of Celestial Bodies Vol. 23, 2007, pp. 97-100. doi:10.3103/S0884591307030026.

[24] Obridko V.N. and Shelting B.D. "Anomalies in the evolution of global and large-scale solar magnetic fields as the precursors of several upcoming low solar cycles", Astron. Lett. Vol. 35, 2009, pp. 247-252. doi:10.1134/S1063773709040045.