North–South Asymmetry in Solar Activity and Solar Cycle Prediction, V: Prediction for the North–South Asymmetry in the Amplitude of Solar Cycle 25

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Abstract There exists a small but statistically significant north–south asymmetry in most of the solar activity indices and it has important implications on the solar dynamo mechanism. Here we analyzed the daily sunspot-group data reported by the Greenwich Photoheliographic Results (GPR) during the period 1874–1976, Debrecen Photoheliographic Data (DPD) during the period 1977–2017, and the revised Version-2 of international sunspot number (ISSN) during the period 1874–2017. We determined the amplitudes (the largest 13-month smoothed monthly ISSN) of Solar Cycles 12–24 and the 13-month smoothed monthly mean corrected areas of the sunspot groups in the Sun’s whole-sphere (WSGA), northern hemisphere (NSGA), and southern hemisphere (SSGA) at the epochs of the maxima of Solar Cycles 12–24. Using all these we obtained the relations similar to that found in our earlier analyzes—i.e. the existence of a high correlation between the sum of the areas of sunspot groups in the southern-hemisphere near-equatorial band during a small (7–9 months) interval just after a maximum epoch of a solar cycle and the amplitude of next solar cycle—separately for the Sun’s whole-sphere and northern- and southern-hemispheres. By using these relations we predict ≈701 msh (millionth of solar hemisphere), ≈429 msh, and ≈366 msh for the values of WSGA, NSGA, and SSGA, respectively, at the maximum epoch of Solar Cycle 25. We predict 86 ± 18 for the amplitude of Solar Cycle 25. The 13-month smoothed monthly mean sunspot-group area highly correlate with that of ISSN. Using this relation and the predicted values of WSGA, NSGA, and SSGA we obtain 68 ± 11 for the amplitude of Solar Cycle 25, which is slightly lower than the aforementioned predicted value, and 39 ± 4 and 31 ± 6 for the values of northern- and southern-hemispheres’ sunspot numbers at the maximum epoch of Solar Cycle 25. The difference between the predicted NSGA and SSGA and also that between northern- and southern-hemispheres’ sunspot numbers at the maximum epoch of Cycle 25 are considerably small. Overall, our results suggest that the amplitude of Cycle 25 would be 25%–40% smaller, and the corresponding north–south asymmetry would be much smaller, than those of Cycle 24.

Keywords Sun: Dynamo – Sun: surface magnetism – Sun: activity – Sun: sunspots – (Sun:) space weather – (Sun:) solar–terrestrial relations

1 Introduction

Prediction of the strength of a solar cycle well in advance is important in view of the effects of solar activity on the terrestrial atmosphere and the space environment. There exists a small but statistically significant north–south asymmetry in most of the solar activity indices, such as sunspots, solar flares, prominence eruptions, coronal mass ejections, etc. (see Norton et al. [2014] [Hathaway [2015]. During the late Maunder minimum the north–south asymmetry was very large [Sokoloff and Nesme-Ribes [1994]. Asymmetric polar field reversals may be a consequence of the asymmetry of solar activity [Svalgaard and Kamide [2013]. North–south asymmetry in solar activity is also known to vary on many time scales [Vizoso and Ballester [1990] Carbonell et al. [1993] Verma [1993] Duchlev and Dermendjiev [1996] Javaraiah and Gokhale [1997] Knaack et al. [2004] Chowdhury et al. [2013] Ravindra and Javaraiah [2015] Chowdhury et al. [2016] Mandal and Banerjee [2016] Deng et al. [2016] Javaraiah [2019]. There is also a suggestion on some systematic phase shift in the activity cycle between the hemispheres (e.g. Zolotova et al.
We have used here the same dataset of sunspot-groups that was used in Javaraiah (2019). That is, we have analyzed the combined Greenwich and DPD sunspot-group daily data during the period April 1874–June 2017 that were downloaded from fenyi.solarobs.unideb.hu/pub/DPD/. These data contain the values of the date and the time of observation, corrected whole-spot area ($A$ in msh: millionth of solar hemisphere), heliographic latitude ($\lambda$) and longitude ($L$), central meridian distance ($CMD$), etc. of sunspot groups (for details see Györi et al. 2010, Barányi et al. 2016, Györi et al. 2017). In Javaraiah (2019) besides determining the actual amplitudes of WSGA-, NSGA-, and SSGA-Cycles 12–24, we have also determined the values of WSGA, NSGA, and SSGA at the epochs of the maxima (maximum values of the 13-month smoothed monthly mean ISSN, i.e. the values of $R_M$) of the Sunspot Cycles 12–24. Hereafter the values of WSGA, NSGA, and SSGA at the epoch of $R_M$ of a sunspot cycle are denoted as $A_W$, $A_N$, and $A_S$, respectively. In that earlier article the values of $R_M$ and the corresponding epoch of each of the Sunspot Cycles 12–24 were determined by using the updated time series of the 13-month smoothed monthly mean Version-1 ISSN during the period 1874–2015. It was downloaded from www.sidc.be/silso/datafiles. Here we have used the corresponding Version-2 SN time series during the period October 1874–June 2017 (used the file SN_ms_total.v2.0.txt). We have also used the Version-2 SN time series of northern- and southern-hemispheres during the period July 1992–June 2017 (used the file SN_ms_hem.V2.0.txt). All these are also downloaded from www.sidc.be/silso/datafiles. The details of changes and corrections in Version-2 SN are given in Clette and Lefèvre (2016). Using the Version-2 SN time series we determined the values of $R_M$ and the
determined the correlations of the values of
lar Cycles 24 and 25 (Javaraiah 2007, 2008, 2015). We
cycles (Javaraiah 2019).
cases of only a few cycles the values of
values of WSGA at the maximum epochs of Cycles 12 – 24 (which
accurate and unreliable. In fact, even in the case of the
predictions based on the polar fields at minimum of cycle
could more uncertain and fail if the polar fields were
early before the start of the cycle. Therefore, we
have found the exact interval through partitioning the
datasets until a maximum correlation is found. The
sunspot-group data near the maximum of a solar
cycle is well measured and the sizes of the intervals that
yielded the maximum correlations are still sufficiently
large (7 months and above). In addition, these intervals
may have some physical significance because they
comprised the epochs of polarities change in the Sun’s
global magnetic fields.

For the sake of the readers convenience we listed below
the meanings of all the abbreviations that are used here,
because they are large.

- SN - 13-month smoothed monthly mean Version-2
ISSN during the period October 1874 – June 2017,
- SN - 13-month smoothed monthly mean Version-2
ISSN in northern hemisphere during the period July
1992 - June 2017,
- SN - 13-month smoothed monthly mean Version-2
ISSN in southern hemisphere during the period July
1992 – June 2017,
- § - Waldmeier solar cycle number,
- TM - maximum epoch of a solar cycle,
- RM - value of SN at TM,
- σRM - error in RM,
- AW - the value of the 13-month smoothed monthly
mean area of the sunspot groups in whole sphere
(WSGA) at TM,
- AS - the value of the 13-month smoothed monthly
mean area of the sunspot groups in northern hemi-
sphere (NSGA) at TM,
- AS - the value of the 13-month smoothed monthly
mean area of the sunspot groups in southern hemi-
sphere (SSGA) at TM,
- AN - the value of the 13-month smoothed monthly
mean area of the sunspot groups in northern hemi-
sphere during the different time intervals that
are close to the maximum epochs of Cycles 12 – 23. We
choose the time intervals in which the sum of the area
has a maximum correlation with AW and then we ob-
tained the linear best-fit of the area-sum and AW. By
using the obtained linear relationship and the area-sum
in the time interval that is close to the maximum epoch
of Cycle 24, we predicted the value of AW of Cycle 25.
Similarly, we predicted the values of AN and AS, i.e.
the values of NSGA and SSGA at the maximum epoch
of Solar Cycle 25. It should be noted that the values of
the amplitudes and their epochs of some of the cy-
cles are different from the corresponding values that
were taken from www.ngdc.noaa.gov and were used in
our earlier analyzes (Javaraiah 2007, 2008, 2015). We
have already predicted the amplitude (RM) of Cy-
cle 25 (Javaraiah 2013, 2017). However, since we have
used here a different set of the maximum values and
the corresponding epochs of Solar Cycles 12 – 24, hence,
here we have also predicted the RM of Sunspot Cy-
cle 25. For the sake of reducing the uncertainty in the
determined sums of the areas of sunspot groups due
to the foreshortening effect (if any) in the measured
areas of sunspot groups, we have not used the sunspot-
group data correspond to the [CMD] > 75°. By us-
ing the predicted values of AN and AS of Cycle 25, we
determined the corresponding north–south asymmetry,
AN - AS. In the next section we described the results.

Here it may be worth to mention that the (linear)
fits that correspond to the poorer correlations are less
accurate. Hence, obviously, the predictions are less ac-
curate and unreliable. In fact, even in the case of the

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our earlier articles for predicting the amplitudes of So-
lar Cycles 24 and 25 (Javaraiah 2007, 2008, 2015). We
determined the correlations of the values of AW, i.e.
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cles 13 – 24 with the sums of the areas of the sunspot
groups in 0° – 10° latitude interval of the Sun’s southern
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\* \* A\* \* N - the sum of the areas of sunspot groups in 0°–10° latitude interval of the southern hemisphere during T\* \* N of Cycle n, which has maximum correlation with A\* \* N of Cycle n + 1,

\* \* A\* \* S - the sum of the areas of sunspot groups in 0°–10° latitude interval of the southern hemisphere during T\* \* S of Cycle n, which has maximum correlation with A\* \* S of Cycle n + 1,

\* \* T\* \* m - the preceding minimum epoch of a cycle,

\* \* T\* \* n - the time interval around T\* \* m of a cycle, and

\* \* a\* \* R of Cycle n - the sum of the areas of sunspot groups in 0°–10° latitude interval of the northern hemisphere during T\* \* m of Cycle n, which has maximum correlation with R\* \* M of Cycle n + 1.

3 Results

Fig. 1 shows the cycle-to-cycle variations in A\* \* W, A\* \* N, A\* \* S, and R\* \* M. As can be seen in this figure, there exists a considerable difference between the variations in A\* \* N and A\* \* S. The correlation between A\* \* N and A\* \* S is found considerably weak (correlation coefficient r = 0.45). However, the correlation (r = 0.85) between A\* \* N and A\* \* W, and that (r = 0.86) between A\* \* S and A\* \* W, are found to be almost the same. In Table 4 we have given the values of A\* \* R, A\* \* W, A\* \* N, and A\* \* S, \* viz., the sums of the areas of the sunspot groups in 0°–10° latitude interval of the southern hemisphere during the intervals T\* \* M, T\* \* W, T\* \* N, and T\* \* S, respectively, just after T\* \* M of a solar cycle when each of the aforementioned sums of the areas of the sunspot groups in a Cycle n well correlate with the corresponding R\* \* M, A\* \* W, A\* \* N, and A\* \* S of Cycle n + 1. The intervals T\* \* M, T\* \* W, T\* \* N, and T\* \* S started from the years 1.15, 0.95, 0.95, and 0.75, respectively, and ended at the years 1.75, 1.6, 1.75, and 1.65, respectively, from T\* \* M of a cycle (T\* \* S started and also ended slightly earlier than T\* \* N). It should be noted that, as already mentioned above, the values of R\* \* M, and those of T\* \* M of some of the solar cycles, that are used here differ with those were used in the earlier analyses Javaraiah (2007, 2008, 2015, 2017). Therefore, the intervals T\* \* M, T\* \* W, T\* \* N, and T\* \* S of the present analysis differ with the corresponding earlier ones. However, each of these intervals of the present analysis comprised the corresponding earlier ones in large extent. The results have been specifically optimized to produce the maximum correlation. In Figure 11 of Article III, we have shown that how sensitive the results are at small variations in the exact start and stop times of the intervals over which the sums of the areas of sunspot-groups are made. There is a considerable consistence in the data sampling. That is, the intervals T\* \* M, T\* \* W, T\* \* N, and T\* \* S are sufficiently long. Hence, small changes in the start and stop times of these intervals have no significant change in the results.

Fig. 1 Cycle-to-cycle variations in A\* \* W (Continuous curve), A\* \* N (□ - □ curve), and A\* \* S (□ - □ curve), \* viz., the 13-month smoothed monthly mean areas of the sunspot groups in the Sun’s whole sphere, northern-, and southern-hemispheres, respectively, at the epoch of R\* \* M, i.e. at the largest 13-month smoothed monthly mean ISSN of a solar cycle. The ○ - ○ curve represents the variation in R\* \* M. The corresponding mean values of all these quantities are shown with horizontal lines. The errors in R\* \* M are also shown. The errors in the areas of sunspot groups are not available.

In Figs. 3(a), 5(a), 7(a), and 9(a) we have compared the variations in A\* \* R, A\* \* W, A\* \* N, and A\* \* S with the variations in R\* \* M, A\* \* W, A\* \* N, and A\* \* S, respectively, during Solar Cycles 12–24. As can be seen in these figures each of the former parameters leads the corresponding one of the latter parameters by about one-cycle period. Figs. 3(b), 5(b), 7(b), and 9(b) show the correlations of A\* \* R, A\* \* W, A\* \* N, and A\* \* S of Cycle n with R\* \* M, A\* \* W, A\* \* N, and A\* \* S, respectively, of Cycle n + 1. The values 0.94, 0.97, 0.89 and 0.85 of the corresponding correlation coefficients are also shown. All of these correlations are significant on >99.9% confidence level (P < 0.001). (The corresponding Student’s t values are 8.5, 12, 6, and 5.1 respectively. In the case of eleven degrees of freedom t = 4.44 for P = 0.001.) We obtained the following linear relationships.

\[ R_{M(n+1)} = (1.98 \pm 0.12)A_{R}^*(n) + 74 \pm 7, \]  

\[ A_{W(n+1)} = (30.2 \pm 2.5)A_{W}^*(n) + 404 \pm 136, \]  

\[ A_{N(n+1)} = (9.9 \pm 1.6)A_{N}^*(n) + 308 \pm 120, \] and

\[ A_{S(n+1)} = (13.0 \pm 2.5)A_{S}^*(n) + 57 \pm 192. \]
Table 1 \( R_M \) represents the maximum (the largest 13-month smoothed monthly mean ISSN) and \( T_M \) is the corresponding epoch (year) of a Solar Cycle \( n \). \( A_W \), \( A_N \), and \( A_S \) represent the 13-month smoothed monthly mean areas (msh) of the sunspot groups in the Sun’s whole-sphere, northern hemisphere, and southern hemisphere, respectively, at \( T_M \) of a solar cycle. \( \sigma_R \), \( \sigma_M \), \( \sigma_N \), and \( \sigma_S \) represent the sums of the areas (msh) of the sunspot groups (normalized by 1000) in \( 0^\circ - 10^\circ \) latitude intervals of the southern hemisphere during the time intervals \( T_M \), \( T_W \), \( T_S \), and \( T_N \), respectively, just after \( T_M \) of a solar cycle. \( \sigma_R \) represents the error in \( R_M \). Errors in the areas of sunspot groups are not available.

| \( n \) | \( T_M \) (Year) | \( R_M \) (msh) | \( \sigma_R \) (msh) | \( A_W \) (msh) | \( A_N \) (msh) | \( A_S \) (msh) |
|------|-----------------|----------------|----------------|---------------|---------------|---------------|
| 12   | 1883.958        | 124.4          | 12.5           | 599.73        | 138.79        | 358.22        |
| 13   | 1894.042        | 146.5          | 10.8           | 671.98        | 152.88        | 319.10        |
| 14   | 1906.123        | 161.6          | 9.2            | 715.04        | 152.93        | 328.11        |
| 15   | 1917.623        | 175.7          | 11.8           | 758.17        | 155.96        | 342.21        |
| 16   | 1928.290        | 193.2          | 12.6           | 801.22        | 160.06        | 355.16        |
| 17   | 1937.288        | 218.7          | 10.3           | 852.32        | 165.12        | 367.18        |
| 18   | 1947.371        | 251.9          | 11.3           | 903.42        | 170.23        | 379.20        |
| 19   | 1958.204        | 285.0          | 11.3           | 954.53        | 175.34        | 391.22        |
| 20   | 1968.874        | 328.2          | 12.6           | 1005.64       | 180.45        | 403.24        |
| 21   | 1979.958        | 366.0          | 10.2           | 1056.76       | 185.56        | 415.26        |
| 22   | 1990.874        | 400.2          | 10.8           | 1107.88       | 190.67        | 427.28        |
| 23   | 2001.874        | 434.4          | 10.2           | 1158.99       | 195.78        | 439.30        |
| 24   | 2012.874        | 468.6          | 10.8           | 1209.11       | 200.89        | 451.32        |

Fig. 2 (a) Plot of the amplitude \( (R_M) \), i.e. the largest 13-month smoothed monthly mean ISSN of a solar cycle \( (\bigcirc – \bigcirc \ curve) \) and \( A_R \), i.e. the sum of the areas of the sunspot groups in \( 0^\circ - 10^\circ \) latitude interval of the Sun’s southern hemisphere during the interval \( T_M \) just after the maximum epoch \( T_M \) of a solar cycle \( (\bigcirc – \bigcirc \ curve) \) versus the solar cycle number. (b) The scatter plot of \( A_R \) of a Solar Cycle \( n \) versus \( R_M \) of Solar Cycle \( n+1 \). The continuous line represents the corresponding linear best-fit and the dotted lines are drawn at one-rmsd (root-mean-square deviation) level. The values of the correlation coefficient \( (r) \) is also shown. The ■ represents the predicted value 86 ± 18 for \( R_M \) of Cycle 25.

The fit of each of these equations to the corresponding data is reasonably good. The slopes of (1), (2), (3), and (4) are about 16, 12, 6, and 5 times larger than the corresponding uncertainties, respectively. In each of these cases, except one or two data points, all of the remaining data points are inside or close to the one-rmsd (root-mean-square deviation) level (see Figs. 2-5). Since errors \( (\sigma_R) \) in the values of \( R_M \) are available (see Table 1), hence, they are taken into account in the fit of (1). That is, the least-square fit is weighted with \( weight = \frac{1}{\sigma_R^2} \). Errors in the areas of sunspot groups are not available. Using (1)–(4) and the values of \( A_R \), \( A_W \), \( A_N \), and \( A_S \) of Cycle 24 that are given in Table 1, we obtained 86 ± 18, 701 ± 156 msh, 429 ± 157 msh, and 366 ± 202 msh for \( R_M \), \( A_W \), \( A_N \), and \( A_S \), respectively, of Cycle 25. The rmsd values look to be substantially large for the predicted values, because the ranges of
Fig. 3 (a) Plot of $A_W$, i.e. the 13-month smoothed monthly mean area of the sunspot groups in the Sun’s whole-sphere at the maximum epoch of the solar cycle (●—○ curve)– and $A'_W$, i.e. the sum of the areas of the sunspot groups in $0^\circ$ – $10^\circ$ latitude interval of the southern hemisphere during the interval $T'_W$ just after $T_M$ of a solar cycle (○···○ curve)–versus the solar cycle number. (b) The scatter plot of $A'_W$ of a Solar Cycle $n$ versus $A_W$ of Solar Cycle $n+1$. The continuous line represents the corresponding linear best-fit and the dotted lines are drawn at one-rmsd level. The values of the correlation coefficient ($r$) is also given. The ■ represents the predicted value $701 \pm 156$ for $A_W$ of Cycle 25.

$A_W$, $A_N$, and $A_S$ values are large and the corresponding predicted values are close to the lower limits of the ranges. In Figs. 2(b), 3(b), 4(b), and 5(b) we have also shown the predicted values. These predicted values of $R_M$, $A_W$, and $A_S$ are about ≈25%, ≈56%, and ≈69%, respectively, smaller than the corresponding observed values of Cycle 24, whereas the predicted value of $A_N$ of Cycle 25 is almost equal to the corresponding observed value of Cycle 24. These predicted values of $A_N$ and $A_S$ are almost equal. Thus, the corresponding north–south asymmetry is predicted to be only 0.08. That is, there will be no significant north–south asymmetry in $A_W$ of the upcoming Solar Cycle 25. The sum, ≈795 msh, of the predicted values of $A_N$ and $A_S$ is slightly larger than the predicted value of $A_W$, but the difference between this sum and the predicted value of $A_W$ is within one-rmsd level of the latter. The predicted values, particularly, in the cases of $A_N$ and $A_S$, have a very large uncertainties (the values of rmsd are large). However, the corresponding linear best-fits are reasonably good because the corresponding slopes are about 5–6 times larger than their respective standard deviations. The corresponding north–south asymmetry is reasonably accurate because the uncertainty in the ratio of two parameters is much smaller than the corresponding uncertainties of the individual parameters (see Javaraiah and Gokhale 1997).

The values of $A'_W$, $A'_N$, and $A'_S$ of Cycle 24 are substantially (a factor of three times) smaller than the corresponding values of all the previous cycles (see Table[1]). This is consistent with that Cycle 24 is a small cycle and moreover, in the decline phase of this cycle the southern hemisphere’s activity is decreased more steeply than in the corresponding phases of other cycles (see Figure 1 in Javaraiah 2020, also see Figure[10] below). As already mentioned above, the epochs $T'_W$, $T'_N$, and $T'_S$ are close to the time of change in polar-
Fig. 5  (a) Plot of $A_S$, i.e. the 13-month smoothed monthly mean area of the sunspot groups in the southern hemisphere at the maximum epoch of the solar cycle (○—○ curve) and $A_S^*$, i.e. the sum of the areas of the sunspot groups in $0^\circ - 10^\circ$ latitude interval of the southern hemisphere during the interval $T^*_S$ just after $T_M$ of a solar cycle (○·○ curve) versus the solar cycle number. (b) The scatter plot of $A_S^*$ of a Solar Cycle $n$ versus $A_S$ of Solar Cycle $n+1$. The continuous line represents the corresponding linear best-fit and the dotted lines are drawn at one-rmsd level. The values of the correlation coefficient ($r$) is also given. The ■ represents the predicted value $366 \pm 202$ for $A_S$ of Cycle 25.

Fig. 6  (a) Plot of $A_W$, i.e. the 13-month smoothed monthly mean area of the sunspot groups in the whole sphere at the maximum epoch of a solar cycle (○⋯○ curve) and the amplitude ($R_M$) of the solar cycle (●—● curve) versus the solar cycle number. (b) The scatter plot of $A_W$ versus $R_M$. The continuous line represents the corresponding linear best-fit and the dotted lines are drawn at one-rmsd level. The values of the correlation coefficient ($r$) is also shown. The ■ represents the corresponding predicted value $81 \pm 19$ for $R_M$ of Cycle 25.

The amplitudes of global magnetic fields. In our earlier articles, [Javaraiah 2008, 2012], we have suggested equatorial crossing of magnetic flux/down flows could be a possible physical process behind all the relationships, similar to (1) above, found there. During Cycle 24 meridional motions of sunspot groups were found to be large and mostly equatorward and poleward directions in the northern- and southern-hemispheres, respectively (see Figure 1 in Javaraiah 2018). In the text of the earlier article Javaraiah (2018) the directions of the meridional motions were incorrectly mentioned as equatorward in both the hemispheres, we regret for that mistake. The meridional motions of sunspot groups may depict some extent the meridional plasma flows in the solar convection zone. Therefore, we suggest that due to the aforementioned south-bound meridional flows there might be equatorial crossing of a large northern-hemisphere magnetic flux and a large cancellation of southern-hemisphere magnetic flux. This might contributed to Cycle 24 being weaker than previous cycles and the values of $A_W$, $A_N^*$, and $A_S^*$ being smaller in Cycle 24 than in previous cycles. However, sustained cross-equatorial meridional flows are ruled out by dynamical and symmetry considerations (Norton et al. 2014). Therefore, the physical reason behind the small values of the aforementioned parameters in Cycle 24 yet to be found.

We also determined the correlation between $R_M$ and $A_W$. It is shown in Fig. 6. We found $r = 0.92$ (the corresponding Student’s $t = 7.8$) and obtained the following linear relationship:

$$R_M = (0.077 \pm 0.005)A_W + 27.5 \pm 9.3.$$  \hspace{1cm} (5)

The fit of this equation to the data is very good (in this fit error in $R_M$ is taken into account). The slope is 15 times larger than the corresponding standard deviation. By using the value 701 msh predicted for $A_W$ of Cycle 25 above, we have obtained $81 \pm 19$ for $R_M$ of this cycle, which is almost same as the value predicted by using (1) above. Thus, overall, there is a sugges-
Fig. 7 The scatter plots of (a) $A_W$ versus $A_N$ and (b) $A_W$ versus $A_S$. The continuous line represents the corresponding linear best-fit and the dotted lines are drawn at one-rmsd level. The values of the correlation coefficient ($r$) is also shown. The ■ represents the corresponding predicted value $334 \pm 190$ for $A_N$ and $467 \pm 190$ for $A_S$ of Cycle 25.

As already mentioned above, both $A_N$ and $A_S$ reasonably well correlate with $A_W$. By using these relationships that are shown in Fig. 7 and the value 701 msh of $A_W$ of Cycle 25 which is predicted above, we obtained the values $334 \pm 190$ msh and $467 \pm 190$ msh for $A_N$ and $A_S$, respectively, of Cycle 25. From these values also we get north–south asymmetry in $A_W$ of Cycle 25 is small ($-0.05$), but it is a small negative value (indicates a slight more activity in south).

In our earlier analyzes, Javaraiah [2007, 2008], we have also found that the sum (here namely $a_R^*$) of the areas of the sunspot groups in $0^\circ - 10^\circ$ latitude interval of the northern hemisphere–and in the time interval (namely $T_m^*$) $-1.35$ year to $+2.15$ year from the time of preceding minimum ($T_m$)–of Cycle $n$ well-correlate with the $R_M$ of Cycle $n + 1$. Although by using this relationship also we have found $R_M$ of Cycle 24 is slightly smaller than that of Cycle 23, but it is found to be considerably higher than the observed $R_M$ of Cycle 24. That is, this relationship in general yields a considerable over estimate for the amplitude of a cycle. From this method here we got slightly different values for $T_m^*$. We obtained $107 \pm 25$ for $R_M$ of Cycle 25, and the values $2223 \pm 233$ msh, $619 \pm 144$ msh, and $608 \pm 231$ msh for $A_W$, $A_N$, and $A_S$ of Cycle 25, respectively. The corresponding correlations are considerably smaller than those of (1)–(4) above. These values of $A_N$ and $A_S$ are also almost equal. That is, from this method also we obtain a negligibly small value (0.009) for the north–south asymmetry in $A_W$ of Cycle 25. We would like to mention that the value of $R_M$ of Cycle 24 predicted by us Javaraiah [2007] using the method that correspond to (1) is found about 10% smaller than the observed $R_M$. However, in that earlier analysis we have used Solar Optical Observing Network (SOON) sunspot group data for Cycle 21–23, in which the areas of sunspot groups seem to be some extent under estimated even after increased by a factor of 1.4 (Hathaway and Choudhary 2008). There is no such problem in the DPD data. Hence, the values predicted here for the parameters of Cycle 25 by using (1)–(4) above, may be not under estimated, i.e. may not be
about 10% smaller than the respective observed ones. Nevertheless, our predictions indicate that Cycle 25 will be at least few percent weaker than Cycle 24.

Here we would like to point out that as already mentioned above $R_M$ of Cycle 21 is slightly larger than that of Cycle 22, whereas the behavior of $A_W$ seems opposite to this (see Fig. 1). However, still a reasonably high correlation exits between $R_M$ and $A_W$ (cf., Fig. 6). We have also determined the correlation between the 13-month smoothed monthly mean sunspot-group area and ISSN in whole sphere (/total), northern hemisphere, and southern hemisphere, i.e. the correlations between WSGA and SN, NSGA and $SN_N$, and SSGA and $SN_S$, respectively. The whole sphere has 1713 SN-values during October 1874–June 2017, whereas the northern and southern hemispheres have 300 SN$_N$- and SN$_S$-values during July 1992–June 2017. Figs. 8, 9, and 10 show the corresponding relations in the whole sphere, northern hemisphere, and southern hemisphere, respectively. In these figures the corresponding values of the correlation coefficient ($r$) are also shown. Each of these values of $r$ is vary high (also see Hathaway et al. 2002) and obviously, the corresponding linear best-fit is very good. We obtained the following relations:

$$SN = (0.089 \pm 0.0002)\text{WSGA} + 5.74 \pm 0.15,$$  \hspace{1cm} (6)

$$SN_N = (0.084 \pm 0.0008)\text{NSGA} + 2.72 \pm 0.19,$$  \hspace{1cm} (7)

and

$$SN_S = (0.08 \pm 0.0007)\text{SSGA} + 2.08 \pm 0.18.$$  \hspace{1cm} (8)

In the fit of each of these equations the errors in the values of ISSN are taken into account. Using (6), (7), and (8) and the values of $A_W$, $A_N$, and $A_S$ that are predicted from (2)–(4) above (i.e. the values of WSGA, NSGA, and SSAG at the epoch of $R_M$ of Cycle 25), we obtained $68 \pm 11$ for $R_M$ of Cycle 25 and $39 \pm 4$ and
Table 2 The values predicted for various parameters of Solar Cycle 25.

| Equation | Relation between                  | Predicted       |
|----------|-----------------------------------|-----------------|
| 1        | \( A'_R \) (n) and \( R_M \) (n+1) | \( R_M = 86 \pm 18 \) |
| 2        | \( A'_W \) (n) and \( A_W \) (n+1) | \( A_W \approx 701 \) |
| 3        | \( A'_S \) (n) and \( A_N \) (n+1) | \( A_N \approx 429 \) |
| 4        | \( A'_S \) (n) and \( A_S \) (n+1) | \( A_S \approx 366 \) |
| 5        | \( A_W \) and \( R_M \)            | \( R_M = 84 \pm 19 \) |
|          | \( A_W \) and \( A_N \)            | \( A_N \approx 334 \) |
|          | \( A_W \) and \( A_S \)            | \( A_S \approx 467 \) |
| 6        | WSGA and SN                        | \( R_M = 68 \pm 11 \) |
| 7        | NSGA and \( S_N \)                | \( S_N = 39 \pm 4 \) |
| 8        | SSGA and \( S_S \)                | \( S_S = 31 \pm 6 \) |

31 ± 6 for the values of \( S_N \) and \( S_S \) at the epoch of \( R_M \) of Cycle 25. It may be noted here these predicted values of \( S_N \) and \( S_S \) may or may not represent the values of northern- and southern-hemispheres’ sunspot peaks of Cycle 25. This predicted value of \( R_M \) of Cycle 25 is some extent smaller than that predicted by using (1) above, and about 40% smaller than that of Cycle 24. This predicted value of \( R_M \) of Cycle 25 may be more accurate than that predicted from (1) because the corresponding correlation for (2) is higher than that of (1). That is, the value of \( A_W \) of Cycle 25 used in (3) is more accurately predicted from (2) than that of \( R_M \) of Cycle 25 predicted from (1). However, as can be seen in Figs. 8(a), 9(a), and 10(a) the variations in ISSN and sunspot-group area seem to be matching much better around the minimum period than around the maximum period of a cycle and it should also be noted that Waldmeier effect is not present in the cycles of sunspot-group area (Dikpati et al. 2008; Javaraiah 2013). The predicted value of \( S_N \) is about 20% larger than that of \( S_S \). However, still there is a suggestion that the corresponding north–south asymmetry (0.11) of \( R_M \) of Solar Cycle 25 will be much smaller than the absolute value of the north–south asymmetry (−0.38) of \( R_M \) of Solar Cycle 24. Note that at the epoch of \( R_M \) of Cycle 24 the observed values of \( S_N \) and \( S_S \) are 36.0, and 80.4, respectively.

In Table 2 we have given the values predicted for various parameters of Solar Cycle 25. Fig. 11 shows the cycle-to-cycle variation in the corresponding north–south asymmetry of \( A_W \), i.e., in \( \frac{A_S - A_N}{A_S + A_N} \) and of \( A'_W \), i.e., in \( \frac{A'_S - A'_N}{A'_S + A'_N} \) during Cycles 12–24. In this figure we have also shown the cycle-to-cycle variation in \( R_M \). In addition, the predicted values of \( R_M \) and the corresponding north–south asymmetry of \( A_W \) of Cycle 25 were also shown. There exist no significant correlations between \( R_M \) and the corresponding north–south asymmetry of either \( A_W \) or \( A'_W \). In addition, as can be seen in Fig. 11 the corresponding asymmetry of \( A_W \) of each of Cycles 13, 17, and 20 has a considerable positive value and that of each of Cycles 12, 13, and 24 has a considerable negative value. There is a suggestion that the amplitude of Cycle 25 will have a positive or a negative very small (/negligible) north–south asymmetry similar as that correspond to the average Cycle 15 or the small Cycle 16 (see Fig. 11). Overall, there is a suggestion that there will be no significant north–south asymmetry correspond to the amplitude of Cycle 25.

Note: we have repeated all the above calculations by using Version-1 of ISSN-series and obtained the relations similar as (1–4), but their corresponding correlations are found better than those of (1–4). We found 51 ± 12 for \( R_M \) (Version-1) of Cycle 25, which is about 38% less than that (81.9) of Cycle 24 and the corresponding north–south asymmetry is also found negligible.

As mentioned in Section 1, in some cycles the northern- and southern-hemispheres typically peaks at different times, i.e. they are out of phase. At least one of the hemispheric maxima frequently doesn’t coincide with the overall maximum. In some cycles northern-
hemisphere’s peak is strong and in some other cycles southern-hemisphere’s peak is strong. The strong peak is always do not occur first in the same hemisphere. In Figure 1 of our recent paper, Jiang et al. (2019), the properties such as dominant hemisphere, phase difference between the northern- and southern-hemispheres, etc. of Solar Cycles 12–24 can be seen clearly. Regarding the relationships (1–4), we would like to point out that in the case of Cycle 24 its second SN-peak (coincided with the strong southern-hemisphere’s peak) is taken into account because it is substantially larger than its first peak (coincided with the weak northern-hemisphere’s peak), whereas in the case of most of the previous cycles the respective first peak is taken into account because it is larger than the corresponding second peak. Here we predicted the levels of activity in the northern- and southern-hemispheres at the epoch of the peak ($R_m$) of whole-sphere activity of Cycle 25. However, the hemispheres may be somewhat independent (e.g. Dikpati and Gilman 2001; Belucz and Dikpati 2013). Therefore, it may be necessary to make a prediction for each hemisphere’s maximum independently.

4 Conclusions and Discussion

We have analyzed the daily sunspot-group data reported by GPR during the period 1874–1976, DPD during the period 1977–2017, and the revised Version-2 of ISSN during the period 1874–2017. We determined the amplitudes and corresponding epochs of Solar Cycles 12–24, and the 13-month smoothed monthly mean corrected areas of the sunspot groups in the Sun’s whole-sphere ($A_W$), northern hemisphere ($A_N$), and southern hemisphere ($A_S$) at the epochs of the maxima of Solar Cycles 12–24. By using all these we obtained the relations—that are similar to the one found and used for predicting the amplitudes of Solar Cycles 24 and 25 in our earlier analyzes (Javaraiah 2007, 2008, 2013)–separately for the Sun’s whole sphere and northern- and southern-hemispheres. Using these relations we predict the values $\approx$701 msh, $\approx$429 msh, and $\approx$366 msh for $A_W$, $A_N$, and $A_S$, respectively, at the maximum epochs of the upcoming Solar Cycle 25. We predict $86 \pm 18$ for $R_M$ of Solar Cycle 25. The 13-month smoothed monthly mean WSGA, NSGA, and SSGA highly correlate with SN, SN$_N$, and SN$_S$, i.e. the corresponding total, northern-, and southern-hemispheres’ sunspot numbers, respectively. Using these relations and the predicted values of $A_W$, $A_N$, and $A_S$ we obtain $68 \pm 11$ for $R_M$ of Solar Cycle 25, which is slightly lower than the aforementioned predicted value, and $39 \pm 4$ and $31 \pm 6$ for the values of $SN_N$ and $SN_S$ at the maximum of epoch of Solar Cycle 25. The aforementioned predicted values of $R_M$ of Solar Cycle 25 are 20%–40% smaller than the corresponding observed values of Solar Cycle 24. The predicted values of $A_W$, $A_N$, and $A_S$ of Solar Cycle 25 are significantly smaller than the corresponding observed values of Solar Cycle 24, whereas the predicted values of $A_N$ and $SN_N$ of Solar Cycle 25 are almost equal to the corresponding observed values of Solar Cycle 24. The difference between the predicted $SN_N$ and $SN_S$ and also between the predicted $A_N$ and $A_S$ at the maximum epoch of Solar Cycle 25 are considerably small, i.e. the corresponding values of the north–south asymmetry are very small (0.08–0.11).

In addition, $A_W$ is found to be well correlated to both $A_N$ and $A_S$. From this relationship also we get a small value (~0.05) for the corresponding north–south asymmetry in $A_W$ of Solar Cycle 25. That is, there is a suggestion that there will be no significant north–south asymmetry in the amplitude of the upcoming Solar Cycle 25. Overall, our results suggest that the amplitude of Solar Cycle 25 would be 25%–40% smaller, and the corresponding north–south asymmetry would be much smaller, than those of Solar Cycle 24.

A number of authors have provided several explanations for the north–south asymmetry in the solar activity on both the observational and theoretical grounds (for a detail review see Norton et al. 2014). Recent numerical simulations from a flux transport dynamo model show the meridional circulation works differently in the northern- and southern-hemispheres in producing differing solar cycles in the northern- and southern-hemispheres (Belucz and Dikpati 2013). The flux-transport-dynamo process is the physical mechanism behind our earlier (Javaraiah 2007, 2008, 2013, 2019) and the present predictions. All our predictions are consistent with the kind of flux transport models in which a long magnetic memory is an important criteria (e.g. Dikpati and Gilman 2006). As suggested in our earlier articles, here also we suggest that the magnetic flux-transport by the solar meridional flows and down-flows at active regions is the main physical process behind our all predictions.

According to a kind of flux transport dynamo models the strength of the polar field at the minimum of a cycle would decide the strength of the same cycle. There exists a good correlation between the polar field at minimum epoch of cycle and the amplitude of the cycle (Jiang et al. 2007). Hence, the high correlation between the sum of the sunspot-group area in the southern-hemisphere near-equatorial band during the small interval just after maximum of Cycle $n$ and the maximum of Cycle $n + 1$, implies a high correlation
between the former and the strength of the polar field at the following minimum (i.e. at the preceding minimum of Cycle \( n + 1 \)). As pointed by one of the referees, the values of \( A_W \), \( A_N \), and \( A_S \) are all related to the same area on the Sun, but are so different (see Table 1) even though differences in the time intervals are very small. If the correlation actually indicates some kind of physical link, this would suggest that a very few active regions in this one narrow latitude band in the southern hemisphere over a relatively short time period are very important indicators of strength of the following cycle over many cycles. An interesting follow-up study would be to look in more detail at the cause of the differences.

As already mentioned in the previous section, it might be worth thinking about cross-equatorial flux flows as well, which would be related to polar flux strength at the following minimum (Cameron et al. 2014).

Earlier, a cosine-fit of the amplitudes of Sunspot Cycles 1–24 indicated that Cycle 25 will take place at the minimum of the current Gleissberg cycle (Javaraiah et al. 2005; Javaraiah 2017). This supports a low value predicted here for the amplitude of Sunspot Cycle 25. Recently, (Javaraiah 2019), we predicted around May/2025 for the maximum epoch of Cycle 25 of sunspot-group area (Area Cycle 25). Since no significant correlation between the rise-times of sunspot- and area-cycles was found, hence, in that article we did not predict the maximum epoch of Sunspot Cycle 25. On the other hand, in Solar Cycles 22, 23, and 24—which are in the descending phase of the current Gleissberg cycle—the highest peaks of ISSN coincided with those of sunspot-group area (see Figure 8). Hence, the highest peaks of ISSN and area of Cycle 25 may coincide. Therefore, here we predict around May/2025 also for the maximum epoch of ISSN Cycle 25.

Many authors predicted the amplitude of Solar Cycle 25 by using various methods: non-linear approaches, precursors, dynamo models, etc. (also see Sarp et al. 2018; Labonville et al. 2019; Piskalo 2019; Maio et al. 2020). In Table 3 we have given a list of some of the earlier predictions. The recent international panel of experts coordinated by the NOAA and NASA, to which the WDC-SILSO contributed, reached a consensus indicating that Cycle 25 will be most likely peak between 2023 and 2026 with a maximum sunspot number between 95 and 130. The value we have predicted here for the peak of Sunspot Cycle 25 is close to (slightly less than) the low value indicated by the penal.

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Table 3  Predictions of Solar Cycle 25.

| Authors                  | Prediction                  | Approach                                                                 |
|--------------------------|-----------------------------|--------------------------------------------------------------------------|
| Larger than Cycle 24:    |                              |                                                                          |
| Helal and Galal (2012)   | 1.5 times of Cycle 24       | From the statistics of spotless events.                                  |
| Jiang and Cao (2017)     | Stronger than Cycle 24      | Surface flux transport model-based method.                               |
| Jiang et al. (2018)      | 93 – 155                    | Solar surface Flux transport dynamo model.                               |
| Sarp et al. (2018)       | 154 ± 12                    | The empirical dynamical modeling method to the revised Version-2 of ISSN series starting from 1749 July to 2018 January. |
| Pesnell and Schatten (2018) | 135 ± 25                  | SODA Index determined by polar magnetic fields and spectral index as precursors. |
| Gopalswamy et al. (2018) | 89 (south) 59 (north)       | Used a precursor method (used microwave imaging observations).            |
|                         |                              |                                                                          |
| Similar to Cycle 24:     |                              |                                                                          |
| Du (2006)                | 102.6 ± 22.4                | Maximum-maximum cycle length as an indicator to predict the amplitude.   |
| Cameron et al. (2016)    | Not much higher than Cycle 24 | Expecting a value of dipole moment around 2020.                         |
| Wang (2017)              | Similar to Cycle 24         | Based on the observed evolution of polar fields and the axial dipole component of the Sun’s global magnetic field at the end of 2015. |
| Singh and Bhargawa (2017)| 102.8 ± 24.6                | A statistical test for persistence of solar activity based on the value of Hurst exponent (H). |
| Okoh et al. (2018)       | 122.1 ± 18.2                | Using the Ap-index as a precursor.                                       |
| Bhownik and Nandy (2018) | Slightly stronger than Cycle 25 | Using magnetic field evolution models for the Sun’s surface and interior. |
| Hawkes and Berger (2018) | Similar as Cycle 24         | By employing magnetic helicity as a predictor.                           |
| Pishkalo (2019)          | 116 ± 12                    | Using the maximal value of filtered Wilcox Solar Observatory polar field strength before the cycle minimum as precursor. |
| Maio et al. (2020)       | 121                         | Based on the linear regression relationship between sunspot maxima and aa-index minima. |
| Smaller than Cycle 24:   |                              |                                                                          |
| Javaraiah et al. (2005), | Current Gleissberg cycle’s minimum | A cosine-fit of amplitudes of Cycles 1–24, etc.                     |
| Javaraiah (2017)         | 72 ± 14                     | The same as the method used in this article.                             |
| Javaraiah (2015)         | (converted to Version 2)    |                                                                          |
| Hathaway and Upton (2016)| A weak Cycle 25 (95 % of Cycle 24) | Using an Advective Flux Transport code.                                |
| Upton and Hathaway (2018)| South more than North       |                                                                          |
| Labonville et al. (2019) | 89 ± 29                     | Data-driven solar cycle model.                                          |
|                         | North 20 % more than South  |                                                                          |
|                         | 6 month onset delay in North|                                                                          |
| Covas et al. (2019)      | 57 ± 17                     | Based on the feed-forward artificial neural networks.                    |
| Kitiashvili (2020)       | 50 ± 15 (whole)             | By using the Ensemble Kalman Filter method assimilated the poloidal and toroidal magnetic field components. |
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