CORONAL HOLES AND FLARE INDEX: A CORRELATION STUDY

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Abstract. The correlation between the presence of coronal holes and flare indices has been investigated for the period from 1976 to 1995. The analysis shows that in the cases of 227 Carrington rotations (CRs) backward time lags yield the highest correlation between the coronal holes and flare indices. The maximum correlations were found at time lags of 222 and 142 CRs for polar and equatorial coronal holes, respectively. The period of study covers the past two solar cycles (21 and 22). Correlation analysis of both solar cycles has also been studied individually. The correlation analysis reveals that there is in general a forward shift in the maximum correlation for polar coronal holes, but it cannot be recommended to use polar coronal hole numbers for forecasting the next solar cycle.

1. Introduction

Coronal holes are regions of low density and temperature in solar corona, and appear as dark features in X-ray and radio images, and as weak areas in infrared He I (10 830 Å) images of the Sun. The magnetic field inside coronal holes is not different from that derived from the large scale structure of the corona. The magnetic field in them is weak, unipolar and open (Levine, 1977). Coronal holes have special importance because of their strong association with high-speed streams in the solar wind and with geomagnetic storms on Earth (Krieger, Timothy, and Roeloff, 1973; Bravo *et al.*, 1988). Bravo and Otaola (1989) have shown that the annual number of aurorae are well correlated with the size of coronal holes, whereas aurorae are mainly produced by the interaction of high-speed solar wind streams with the magnetosphere. Speich *et al.*(1978) found that active regions near coronal holes generally produced very little activity, had relatively short lifetimes, and were magnetically simple. Ibarra (1990) reported a strong inverse association between the longitudinal position of sunspot groups and the size and number of coronal holes. Bravo and Otaola (1989), Bravo (1992), Das, Chatterjee, and Sen (1993), Bravo and Stewart (1994, 1997), and Dorotovič (1996) found that a strong correlation exists between the coronal hole cycle (identified by the size of polar coronal holes) and the solar cycle (identified by the sunspot numbers). As regards the variation of coronal holes with solar cycle, in this paper we have attempted to analyze the correlation between the number of coronal holes and flare index (coronal holes are structure while flares are events, they have special importance because of their strong association with geomagnetic storms on Earth). Here, the

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solar cycle is identified by the flare-index cycle. Ataç and Özgüç (1998) have also identified flare-index cycle by solar cycle and found that the flare index is in good agreement with indices of magnetic changes, area and number of sunspots in the photosphere, as well as the changes in the corona.

Coronal holes were first observed in 1970 by instruments on the orbiting solar observatory (OSO) satellites. Since 1970 (CR 1558) coronal holes were identified by a consecutive number (coronal hole number CH) following the chronological order of apparition, and from higher to lower value of Carrington longitude (from 360 to 0 deg), independent of their heliographic latitude. The flare index (FI), a measure of the activity level on the Sun, is defined as it (Kleczek, 1952) where i represents the importance and t the duration of the flare in minutes.

2. Data Used

Figure 1 shows variation of polar (a), equatorial (b), and total (c) coronal hole numbers with CRs from 1558 to 1897; and variation of flare index (d) with CRs from 1637 to 1914. For coronal hole numbers data we used catalogues of polar and equatorial holes from 1970 to July 1995 (CR 1558–1897). These catalogues were accessed on-line via ftp anonymous (ftp.ngdc.noaa.gov/STP/SOLAR-DATA/CORONA/HOLES) or via the World Wide Web (http://www.ngdc.noaa.gov). Similarly, for flare index data we used a catalogue of daily flare index from 1976 to October 1996 (CR 1637–1914). This catalogue was also accessed on-line via ftp anonymous (ftp.ngdc.noaa.gov/STP/SOLAR-DATA/SOLAR-FLARES/INDEX) or via the World Wide Web (as given above).

For the correlation study we selected the period 1976 to 1995 (CR 1637–1897) which covers solar cycles 21 and 22. Figure 2 shows the variation of polar (a), equatorial (b), and total (c) coronal hole numbers with flare index for CR 1637–1897. Polar coronal hole numbers show a somewhat opposite tendency to that of flare index whereas equatorial coronal hole numbers vary with the flare index (this is more efficient for cycle 22, i.e., for CR 1780–1897); and there seems to be no relation between total coronal hole numbers and flare index variation. Therefore, in the next section is presented a detailed correlation study between coronal holes and flare indices (i.e., polar coronal holes vs. flare index, equatorial coronal holes vs. flare index, total coronal holes vs. flare index).

3. Correlation Analysis

For the study of correlation between the number of coronal holes and flare index, we calculated the correlation coefficient and 95% confidence intervals as a function of the shift (backward and forward) of the number of coronal holes. For the pairs of quantities (x_i, y_i), $i = 1, \dots, N$, the correlation coefficient r is given by the formula

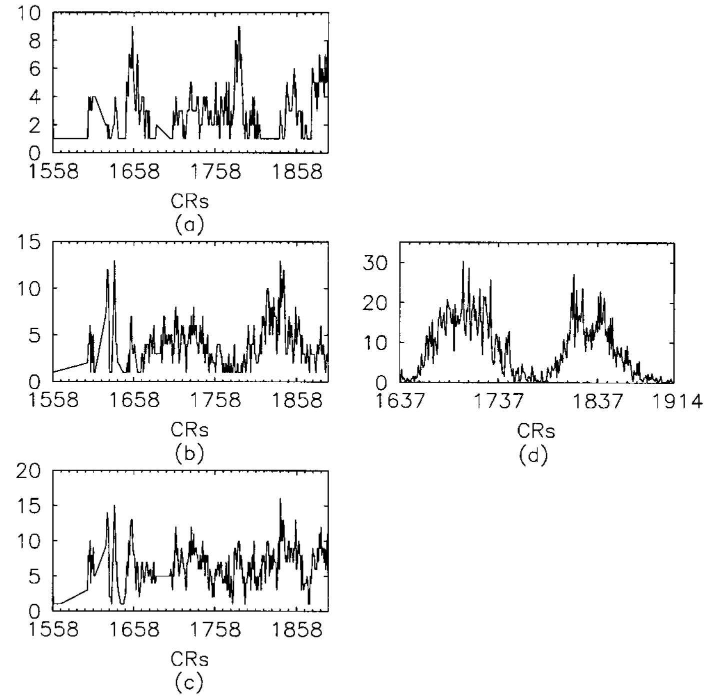

Figure 1. Polar (a), equatorial (b), total (c) coronal hole numbers for CR 1558–1897 and flare index (d) for CR 1637–1914.

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}},$$

where, as usual, $\bar{x}$ is the mean of the x_i's and $\bar{y}$ is the mean of the y_i's. The value of r lies between $+1$ (complete positive correlation) and -1 (complete negative correlation), inclusive.

The 95% confidence intervals were estimated by means of the standard 'Fisher's Z-transformation'. Intervals via Fisher's Z-transformation were obtained by the following steps:

(1) Transform the sample value of r by

$$Zr = 0.5 \log_e[(1 + r)/(1 - r)].$$

(2) To the obtained Zr value, add and subtract

$$1.96\ [1/\sqrt{(n-3)}].$$

The results of this step are denoted $Z1$ and $Z2$.

(3) Now, subject $Z1$ and $Z2$ to the reverse of the Fisher's Z-transformation, i.e., set first step equation equal to $Z1$ and solve for r and then set it equal to $Z2$

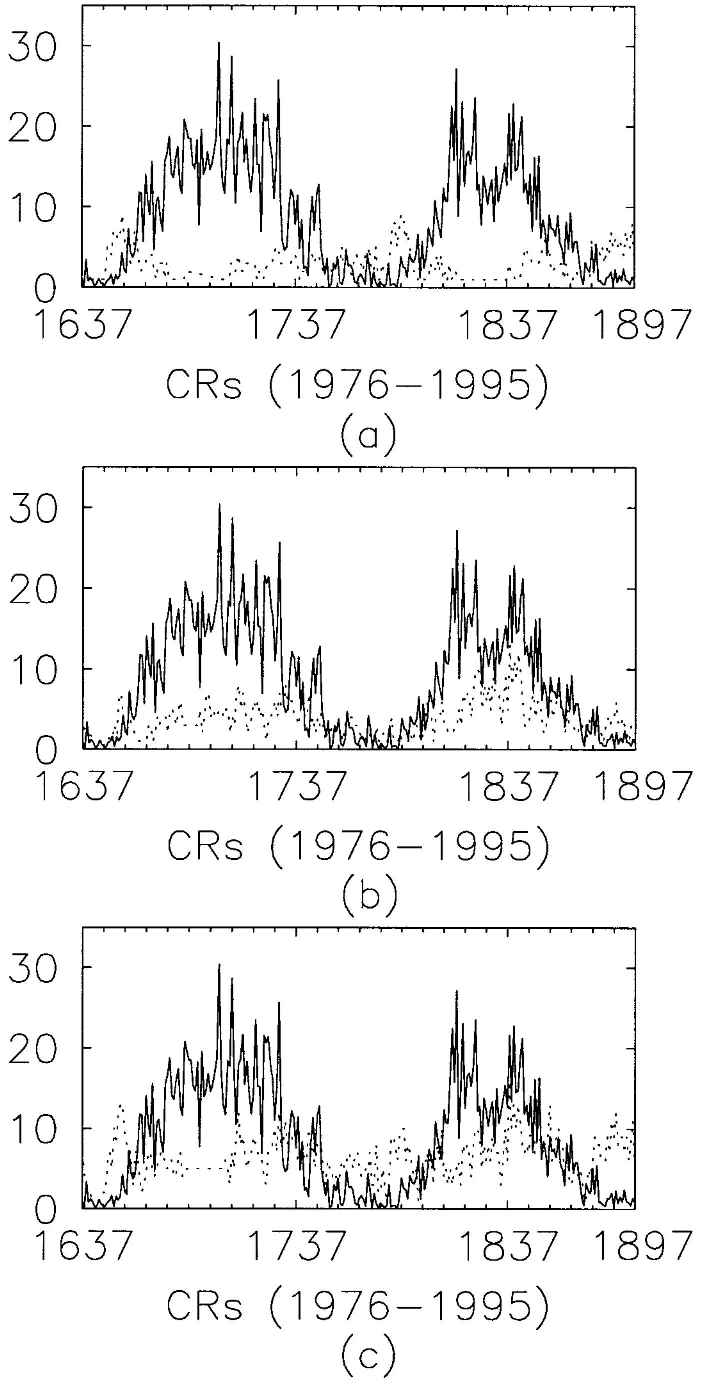

Figure 2. Number of polar (a), equatorial (b), and total (c) coronal holes (*dotted lines*) with flare index (*solid line*) for CR 1637–1897.

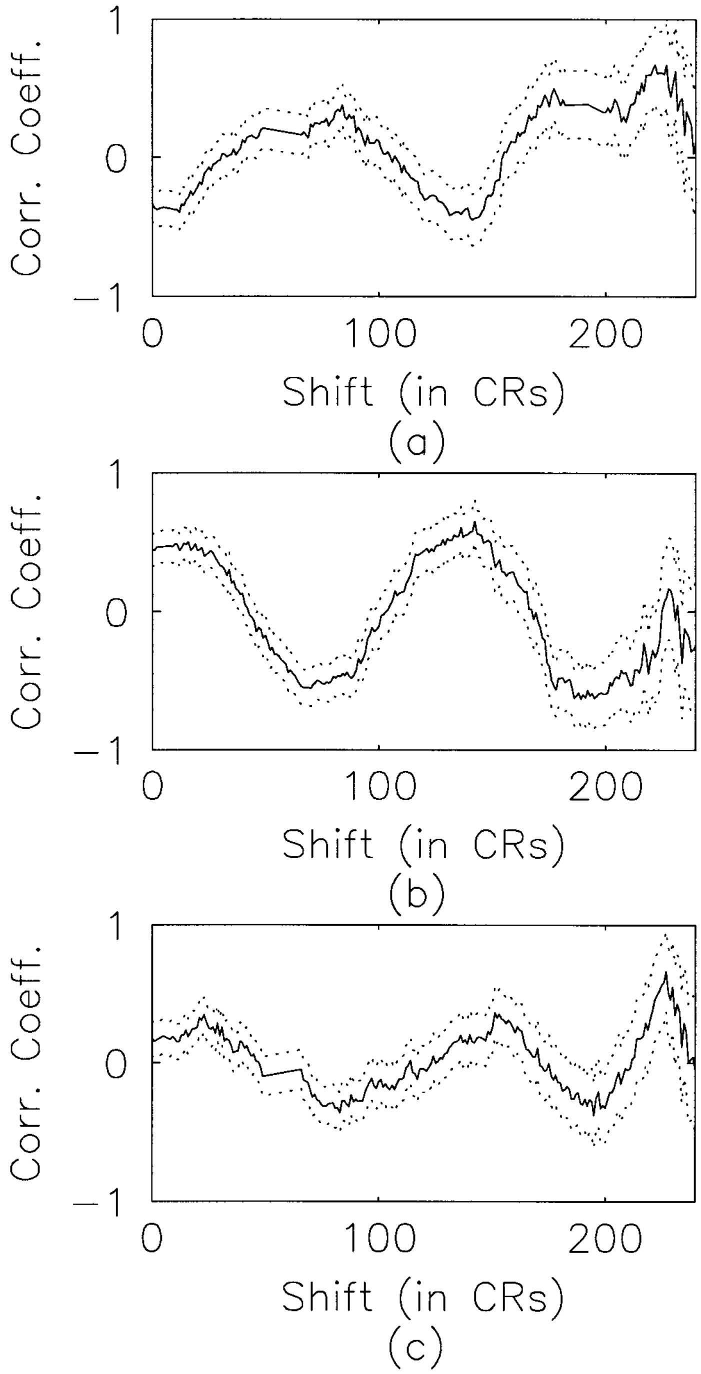

Figure 3. Correlation coefficient (*solid line*) and 95% confidence limits (*dotted lines*) between the number of coronal holes (polar (a), equatorial (b), total (c)) and flare index for the period CR 1637 to 1897 as a function of backward time shift (in CRs) of coronal hole numbers.

and solve for r. The two solution for r are the lower and upper bounds of the 95% confidence intervals.

A correlation study was done between the number of coronal holes and flare index for the periods (in CRs) 1637–1897 (Figures 3 and 4), 1637–1779 (Figures 5 and 6) and 1780–1897 (Figures 7 and 8), respectively. The figures show the correlation coefficient and 95% confidence limits for mentioned periods respectively as functions of the backward and forward shift of the polar (a), equatorial (b) and total (c) coronal hole numbers. The shifts in CRs for the best correlation between coronal holes (polar, equatorial, total) and flare index were found and corresponding correlation coefficients were obtained.

3.1. 1637–1897

Figures 3(a–c) show peaks at backward shifts of 222, 142, and 227 CRs, correlation coefficient 0.670, 0.656, and 0.664, confidence intervals 213–234, 130–149, and 221–233 CRs, respectively. The peak value of anti-correlation for Figures 3(a) and 3(b) occurs at shifts of 141 (−0.450) and 189 (−0.630) CRs.

Figures 4(a) and 4(b) show correlation maxima at forward shifts of, respectively, 179 and 112 CRs, with correlation coefficients 0.559 and 0.584, and confidence intervals 174–192 and 108–126 CRs. Maximum anti-correlation occurs at shifts of 236 (−0.524) and 66 (−0.578) CRs.

3.2. 1637–1779 (CYCLE 21)

Figures 5(a) and 5(b) show peaks at backward shifts by, respectively, 36 and 19 CRs, correlation coefficients 0.464 and 0.589, confidence intervals 35–44 and 2–27 CRs, respectively. Figure 5(c) shows two peaks at shift of 22 and 28 CRs, with correlation coefficients of 0.492 and 0.459, respectively. We estimated a mean shift of 25 CRs and confidence interval of 18–31 CRs. The highest negative values of correlation coefficients for Figures 5(b) and 5(c) correspond to shifts of 90 (−0.731) and 95 (−0.643) CRs.

Figures 6(a) and 6(b) show highest values of correlation at forward shifts of 79 (0.507) and 67 (−0.596) CRs, and confidence intervals 71–82 and 61–73 CRs, respectively.

3.3. 1780–1897 (CYCLE 22)

Figures 7(a) and 7(c) show peaks at backward shifts by 81 and 83 CRs, while Figure 7(b) shows a peak without shifting the data points (i.e., at 0 CRs). The respective correlation coefficients and confidence intervals are 0.673, 0.601, 0.528 and 65–92, 0–21, 74–93 CRs. Maximum anti-correlation occurs for shifts of 1 (−0.479), 55 (−0.611) and 57 (−0.519) CRs.

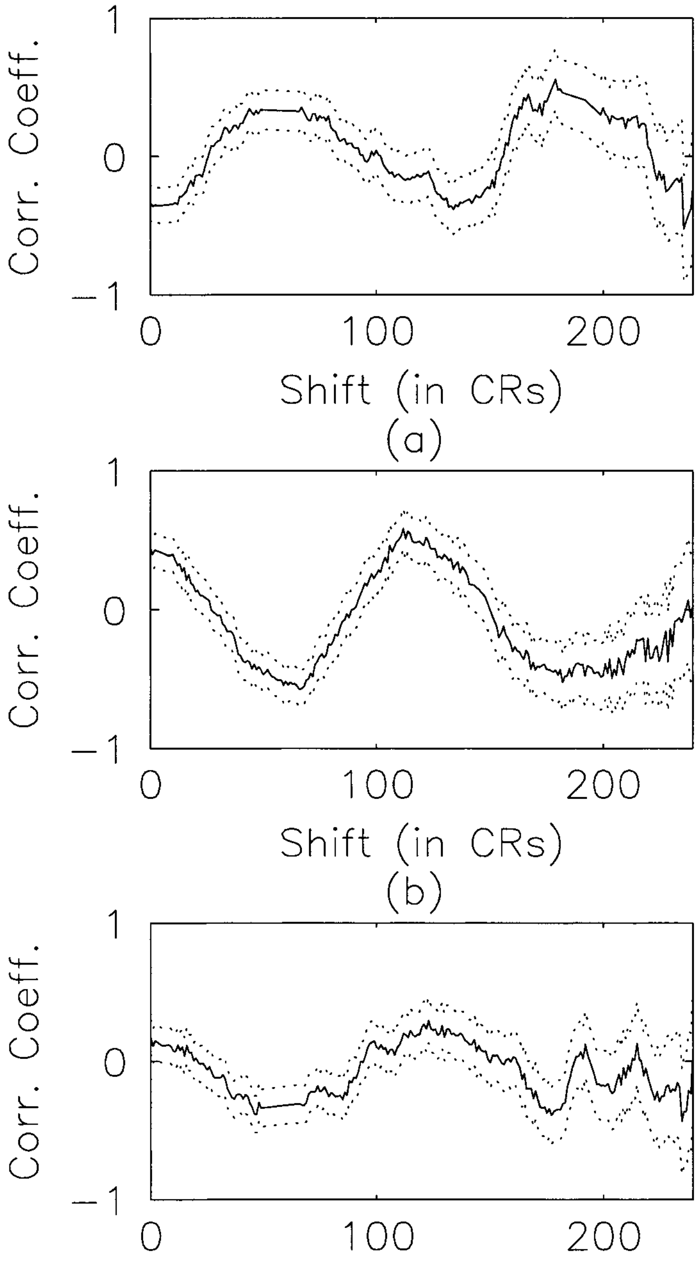

Figure 4. Correlation coefficient (*solid line*) and 95% confidence limits (*dotted lines*) between the number of coronal holes (polar (a), equatorial (b), total (c)) and flare index for the period CR 1637 to 1897 as a function of forward time shift (in CRs) of coronal hole numbers.

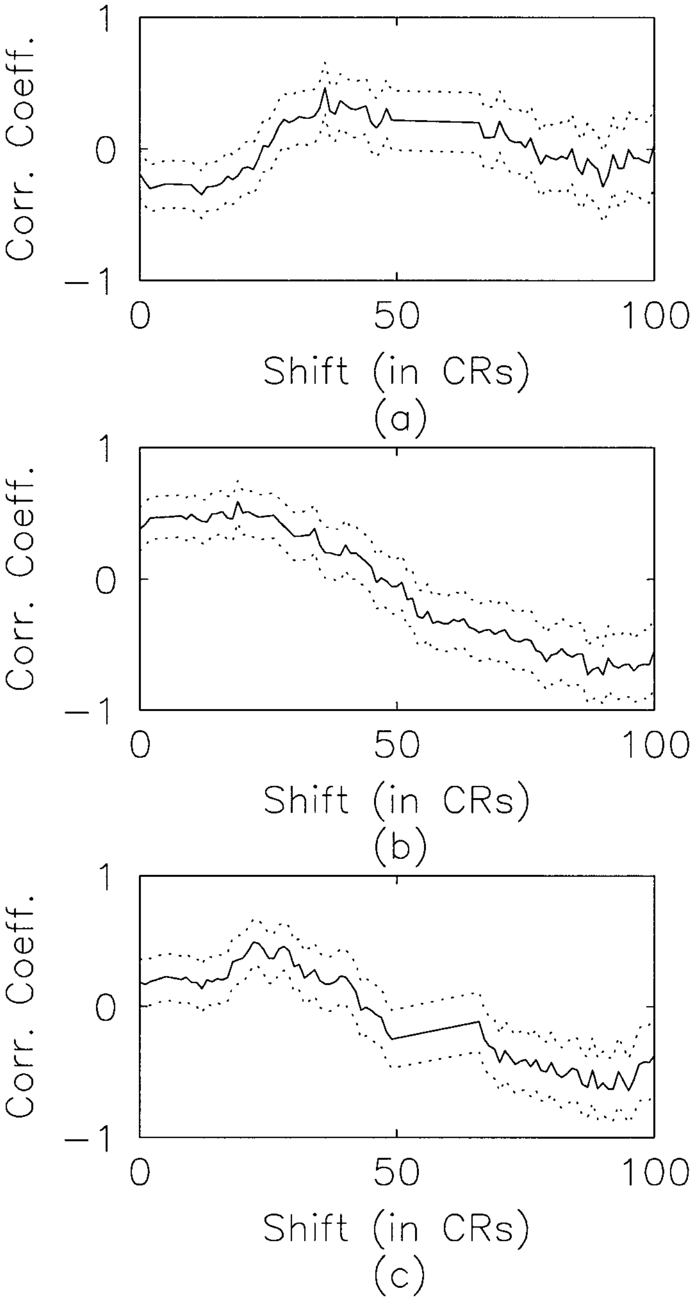

Figure 5. Same as Figure 3 but for the period CR 1637−1779.

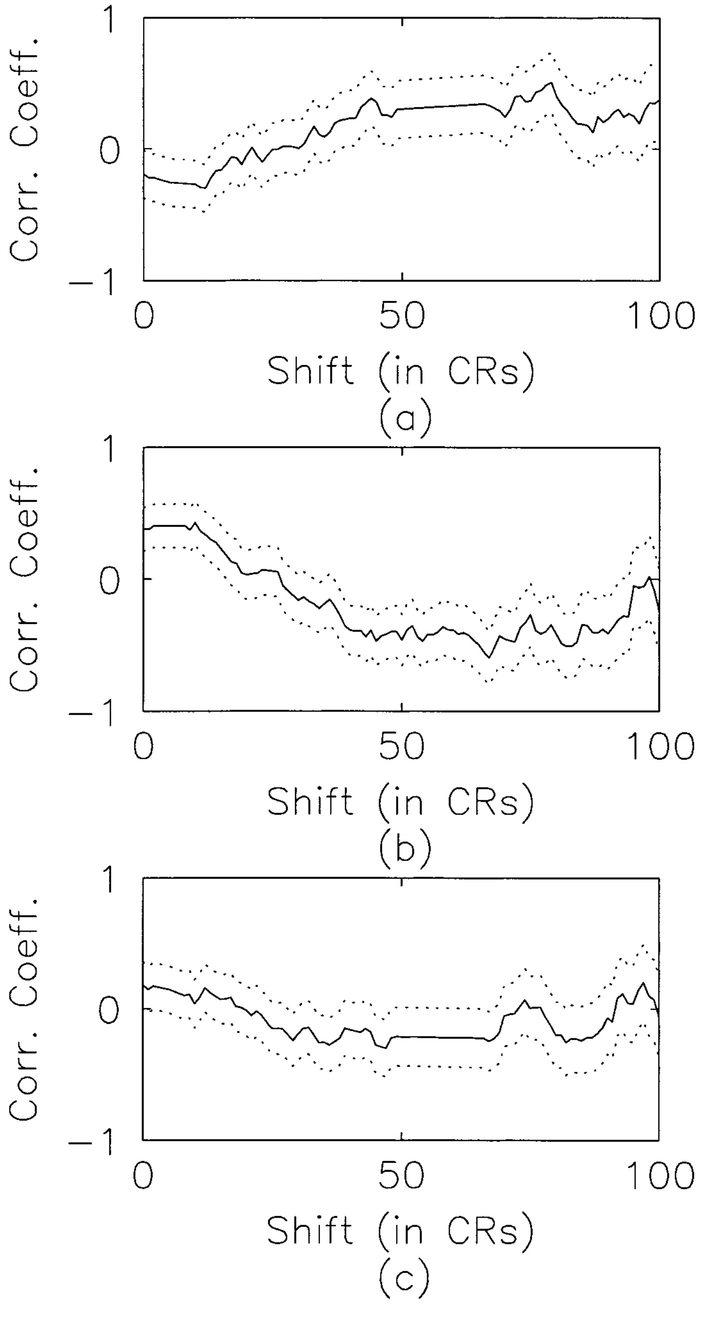

Figure 6. Same as Figure 4 but for the period CR 1637−1779.

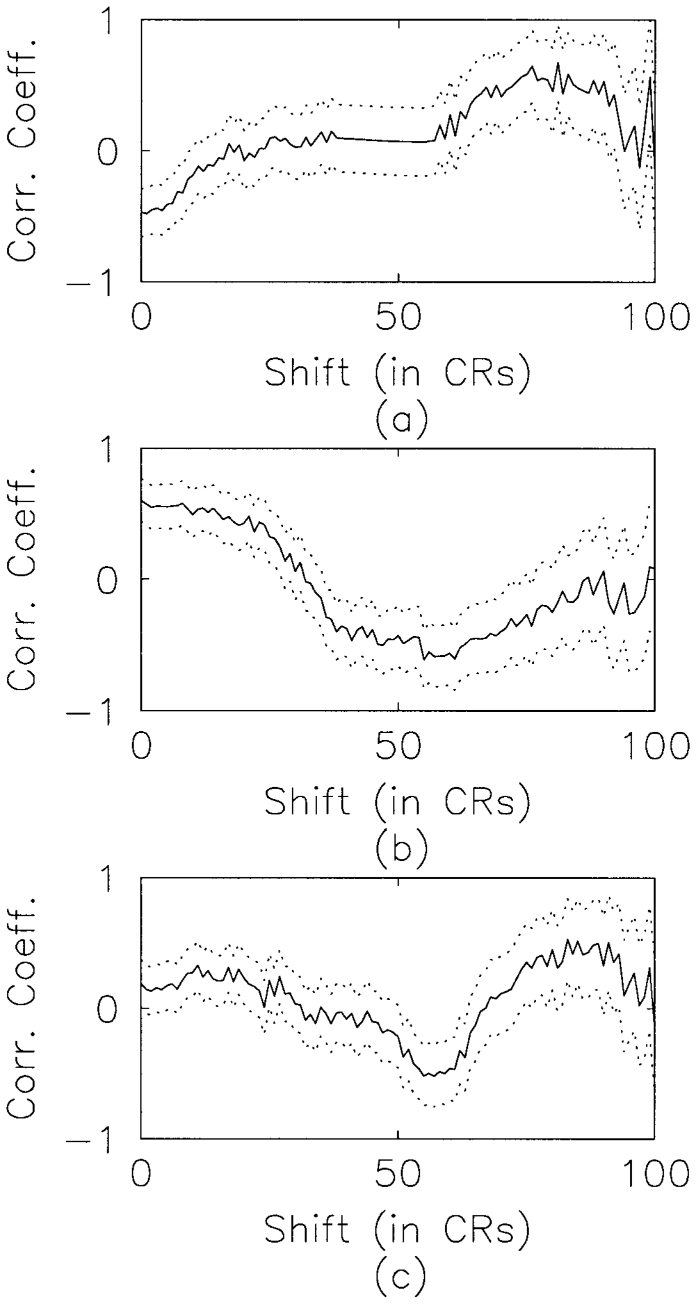

Figure 7. Same as Figure 3 but for the period CR 1780−1897.

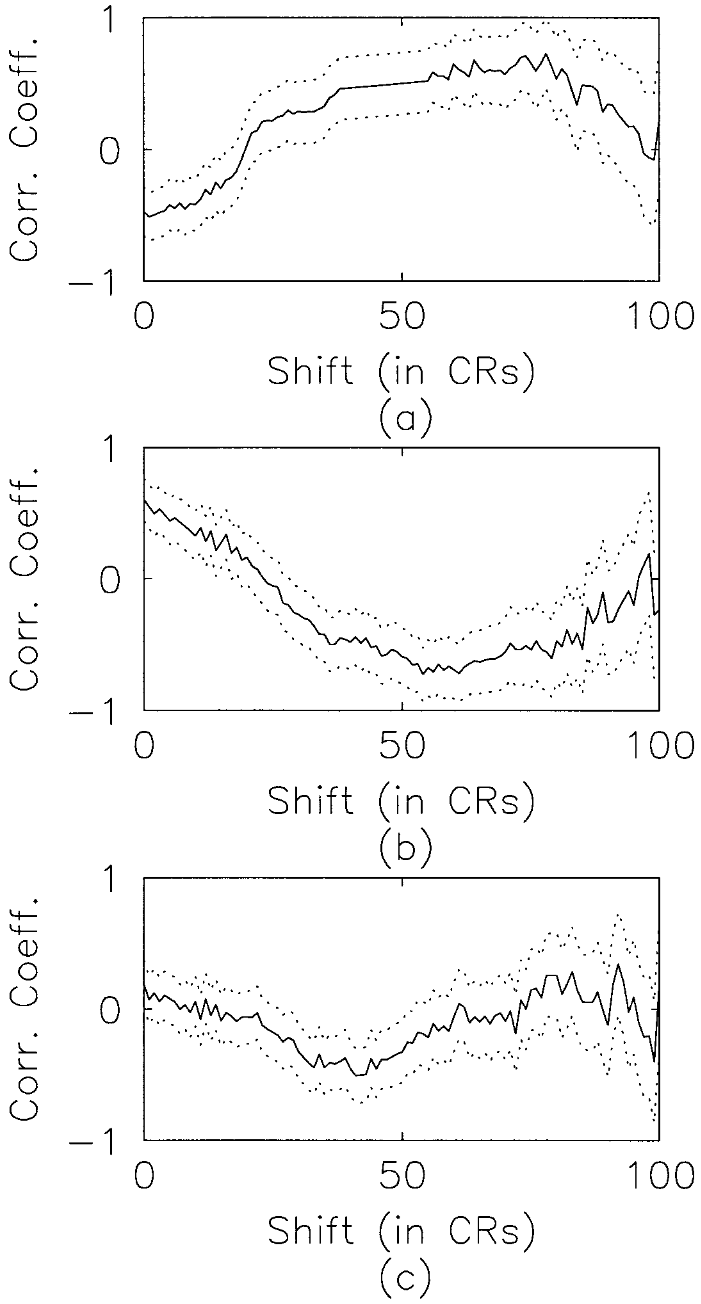

Figure 8. Same as Figure 4 but for the period CR 1780–1897.

Figures 8(a) and 8(b) show peaks at forward shifts of 78 (0.727, 48−83) and 0 (0.601, 0−7) CRs. Maximum anti-correlation is found for shifts of 1 (−0.510), 54 (−0.728), and 41 (−0.506) CRs, respectively.

From Figures 3(a) and 3(c) and Figures 7(a) and 7(c) it is clear that confidence intervals for polar and total coronal holes overlap. Cycle 22 (Figures 7 and 8) shows a good order of correlation in comparison of cycle 21 (Figures 5 and 6). For solar cycles 21 and 22 forward shifts of polar coronal holes yield higher correlations than backward shifts.

4. Discussion and Conclusions

From Figure 2 we conclude that only polar coronal holes (a) show a somewhat opposite tendency to that of flare index (cf., negative value of correlation coefficient around zero lag, see Figure 3(a)). Larger polar coronal holes during the minimum are related to poloidal field, while the larger flare index during maximum is related to the toroidal field. In the standard solar dynamo model (Babcock, 1961; Parker, 1977; Hoyng, 1992) an initially dipolar poloidal field at solar minimum is wound by differential rotation into a strong toroidal field at solar maximum. The correlation found to equatorial coronal hole numbers around zero lag (Figure 3(b)) shows that equatorial coronal hole numbers vary with flare activity. This tendency is more obvious for cycle 22 (cf., Figure 7(b), with correlation coefficient of 0.601 around zero time lag).

Over the period from 1976 to 1995 we found that polar, equatorial and total coronal holes were best correlated with the flare index at backward shifts of 222, 142 and 227 CRs (Figure 3). For solar cycles 21 and 22 this was 79 (Figure 6(a)), 19 (Figure 5(b)), 25 (Figure 5(c)) and 78 (Figure 8(a)), 0 (Figures 7(b) and 8(b)), 83 (Figure 7(c)) CRs, respectively. It appears that the best correlations for equatorial coronal holes are obtained for the smallest time lags. In the case of solar cycle 22 maximum correlation was obtained for zero shift.

The correlation analysis of solar cycles 21 and 22 shows only a slight difference in forward correlation time lag for polar coronal holes. The difference is, however, not statistically significant with 95% confidence limits. We see that with this shift the peaks of both series do not coincide in cycles 21 and 22. The time difference between successive correlation maxima between polar coronal holes and flare indices differ in the two cycles. In fact, the maximum number of coronal holes reached in the period before cycle 21 was in CR 1656, and the maximum flare index in cycle 21 was found for CR 1701, which corresponds to a lag time between maxima of 45 CRs. On the other hand, in cycle 22 the maximum number of coronal holes occurred in CR 1788 and the maximum flare index in CR 1813. The lag time between the maxima was only 25 CRs. This means that we cannot use polar coronal hole numbers as a tool for predicting the next solar cycle. This result implies that we cannot predict the evolution of the flare index based upon coronal hole numbers, and does not invalidate any other relationship found. Bravo and Stewart (1994) found that polar coronal hole size could provide a possibility for forecasting future solar cycles. More recently, taking the total coronal hole area into account, Bravo and Stewart (1997) predicted the next sunspot maximum about 5 years and 6 months (74 CRs) in advance, i.e., in 2001.

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