# A quantity characterizing variation of observed magnetic twist in solar active regions

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Abstract An alternative parameter  $R_{J_z}$  is introduced as the ratio of one of two kinds of opposite-sign current to the total current and is used to investigate the relationship between this quantity and the hemispheric helicity sign rule (HSR) that has been established by a series of previous statistical studies. The classification of current in each hemisphere obeys the following rule: if the product of the current and the corresponding longitudinal field component contributes a consistent sign with respect to the HSR, it is called "HSR-compliant" current, otherwise it is called "HSR-noncompliant" current. Firstly, consistency between the butterfly diagram of  $R_{J_z}$  and current helicity was obtained in a statistical study. Active regions with  $R_{J_z}$  smaller than 0.5 tend to obey the HSR whereas those with  $R_{J_z}$  greater than 0.5 tend to disobey it. The "HSR-compliant" current systems have a 60% probability of realization compared to 40% for "HSR-noncompliant" current is greater than the "HSR-compliant" current. Secondly, the parameter  $R_{J_z}$  was subsequently used to study the evolution of current systems in the case analyses of flare-productive active regions NOAA AR 11158 and AR 11283. It is found that there is a " $R_{J_z}$ -quasistationary" phase that is relatively flare quiescent and " $R_{J_z}$ -dynamic" phase that is characterized by the occurrence of large flares.

Key words: Sun: activity — Sun: flares — Sun: magnetic fields — Sun: evolution — Sun: sunspots

# **1 INTRODUCTION**

The chirality of active region magnetic fields has been studied in terms of the current helicity or the linear forcefree field  $\alpha$ . In the northern (southern) solar hemisphere, there is statistically negative (positive) sign preference of helicity quantities; this trend is called the hemispheric helicity sign rule (HSR hereafter in this paper; see Seehafer 1990; Pevtsov et al. 1994, 1995; Abramenko et al. 1996; Bao & Zhang 1998; Hagino & Sakurai 2004; Tiwari et al. 2009; Zhang et al. 2010, for results based on data before solar cycle 24). On the other hand, some case analyses showed that there were opposite electric current systems in several active regions (Wang et al. 1994; Leka et al. 1996; Wang & Abramenko 1999; Wheatland 2000). This implies that both left and right handedness of a magnetic flux tube field coexist in active regions, as has been also supported by the observation of Su et al. (2009), which demonstrated that an  $\alpha$  map may contain mixed signs in sunspots. In addition, a statistical study of helicity sign was carried out for data acquired during the solar minimum (e.g., Hao & Zhang 2011). Recently, the HSR has been further confirmed with studies on helicity injection from emerging active regions (Yang et al. 2009; Zhang & Yang 2013) and *Solar Dynamics Observatory (SDO)*/Helioseismic and Magnetic Imager (HMI) observations by Liu et al. (2014). These studies have shown that the HSR has large dispersion; the ratio of preferred helicity sign is about 60%.

On the other hand, some results implied that the HSR might not hold throughout the solar cycle (Bao et al. 2000; Hagino & Sakurai 2005; Gao 2013; Gao et al. 2013). This observational characteristic was obviously important for the theoretical formulation of dynamo models (Choudhuri et al. 2004; Pipin et al. 2013). It has been further confirmed that there were net currents above both polarities of magnetic field in several active regions (Gao 2013).

Gao (2013) indicates that the HSR can also be investigated in term of electric current distributions in active regions. Corresponding to the locus of sign reversal of helicity found in the helicity butterfly diagram by Zhang et al. (2010), there is also reversal of sign of net electric currents in the butterfly diagram (Gao 2013). On the other hand, the contribution of opposite-sign helical fields to the filament eruptions has been observed by Liu & Kurokawa (2004); Shen et al. (2015). Bi et al. (2016) found that the direction of a sunspot's rotation reversed during an X1.6 flare. As a result, we speculate that the currents which do not conform to the HSR have their own significance and it is important to investigate their properties in a broader context of observations.

In this paper a new quantity  $R_{J_z}$  is introduced; in a given active region it quantifies the ratio of the currents that do not obey the HSR to the total currents. First, the solar-cycle evolution of  $R_{J_z}$  will be studied and used to interpret the distribution of helicity in the butterfly diagram in Section 2 from the viewpoint of dynamic evolution of two kinds of electric currents. In Section 3, using  $R_{J_z}$ , the evolution of current systems above opposite polarities in two active regions that produced large flares is further investigated. Conclusions and discussion are provided in Section 4.

# 2 DATA OBSERVED AT HUAIROU SOLAR OBSERVING STATION

#### 2.1 Definition of Parameters

Our starting point is the well-known definition of electric current

$$J_z = (1/\mu_0)(\partial B_y/\partial x - \partial B_x/\partial y), \qquad (1)$$

where  $\mu_0 = 4\pi \times 10^{-3} \,\mathrm{G}\,\mathrm{m}\,\mathrm{A}^{-1}$ . We define the ratio of currents

$$R_{J_z}^{\pm} = -\frac{\sum_i J_{z_i}}{\sum_j J_{z_j} - \sum_i J_{z_i}},$$
 (2)

where "i" ("j") denote the pixels that have a sign of the current helicity  $H_c = B_z \cdot J_z$  that is inconsistent (consistent) with the sign of current helicity according to the HSR. If  $\theta$  is the latitude of a region under consideration, then "i" pixels are in regions with  $\theta B_z J_z > 0$  where "j" pixels are  $\theta B_z J_z < 0$ . According to the HSR, "i" represents the "HSR-noncompliant" current system and "j" represents the "HSR-compliant" current system. The superscript  $\pm$  in Equation (2) means that  $R_{J_z}$  is computed in regions of positive (+) or negative (-) magnetic polarity, respectively. In either positive or negative polarity regions,  $J_{z_i}$  and  $J_{z_j}$  have opposite signs, and  $R_{J_z}$  is always positive and between 0 and 1. The parameter

 $R_{J_z}$  represents the fraction of "HSR-noncompliant" currents normalized by the total currents. Likewise,  $1 - R_{J_z}$ represents the fraction of "HSR-compliant" currents and the difference between the two is  $1 - 2R_{J_z}$ . The latter quantity might be compared with the helicity imbalance parameter  $\rho_h$  introduced by Bao & Zhang (1998) if we consider the current helicity instead of the current itself.

If  $R_{J_z}$  is defined as a fraction of pixels with consistent sign of  $H_c$ , it will be equivalent to  $1 - R_{J_z}$ . In my definition, the value of  $R_{J_z}$  in each HSR-compliant region tends to be less than 50%, and that in each HSRnoncompliant region tends to be greater than 50%. The distribution of electric current with the longitudinal magnetic field affects the ultimate determination of sign of  $\langle H_c \rangle$  in an active region, as shown in Figure 2(b) and (c) later. This definition is related to the physical scenario of observed opposite-sign current in the magnetogram. How to understand a current which does not conform to the HSR is still an open question. In this paper, the significance of an H<sub>c</sub>-noncompliant current in the observation is in agreement with the fact that the HSR rule has a dispersion presently restricted to only 60% of active regions. That is to say, the variation of  $H_c$ -compliant and  $H_c$ -noncompliant current systems is probably more of an intrinsic property of evolution of twist in solar active regions.

To further investigate the quantity  $R_{J_z}$  and understand its relation with current helicity, it was used in the current helicity butterfly diagram with Huairou Solar Observing Station (HSOS) vector magnetograms acquired over two solar magnetic cycles (Zhang et al. 2010). However, when we study the evolution of  $R_{J_z}$ in an individual active region, high-cadence vector magnetograms observed by a spaceborne instrument like *SDO*/HMI are necessary.

# **2.2** Connection of $R_{J_z}$ with Previous Statistical Observation

The vector magnetograms used were obtained with the Solar Magnetic Field Telescope (SMFT) at HSOS, which is administered by National Astronomical Observatories, Chinese Academy of Sciences. Basic information on the instrument can be referenced in Bao & Zhang (1998). Following Zhang et al. (2010), in computations of the current helicity, pixels with signal that exceeds the noise levels ( $|B_z| > 20$  G and  $B_t > 100$  G) were used.

Gao (2013) showed that the net electric currents follow a butterfly-diagram-like evolution over the solar cycle. The analysis of 6629 vector magnetograms observed at HSOS from 1988 to 2005 has revealed that  $R_{J_z}$  also



**Fig. 1** (a) Butterfly diagrams of  $R_{J_z}$  (colors) associated with averaged current helicity  $\langle H_c \rangle$  (open and filled circles). The vertical axis gives the latitude and the horizontal axis gives the time in years. The values of  $R_{J_z}$  are scaled according to the color square that appears to the right of the panel. The sizes of open/filled circles correspond to the magnitude of  $\langle H_c \rangle$  according to the scale that appears under the horizontal axis labels. (b) The same as panel (a) but for  $R_{J_z}$  associated with negative magnetic fields. These butterfly diagrams of  $\langle H_c \rangle$  were plotted in a similar way except for scaling the size of circles as in Zhang et al. (2010) by keeping at least 30 data samples in each latitude-time bin. However, this requirement was not applied if there were at least two data samples in each latitude-time bin  $R_{J_z}$  so that the sign-reversal features on the edges can be shown.

displays a butterfly diagram (see Figs. 1 and 2). Detailed information about the data used for the production of Figure 1 is given in Zhang et al. (2010).

In Figure 1, the color background represents the values of  $R_{J_z}^+$  (Fig. 1a) and  $R_{J_z}^-$  (Fig. 1b). These values have been averaged over the same intervals in time and latitude as the current helicity. The overplotted filled or open circles are the averaged current helicity  $\langle H_c \rangle$  from the same data sample. The sizes of open and filled circles in Figure 1 are different from those in Zhang et al. (2010) because a different way of display was adopted. The size of open or filled circles is scaled by using the ratio of the value in each bin to the maximum absolute value that can be seen from the label. Meanwhile, the square root value for each bin was adopted so that the sizes of open and filled circles can be visually comparable. From the figure, we can see:

- (1)  $R_{J_z}^+$  in Figure 1(a) and  $R_{J_z}^-$  in Figure 1(b) show similar patterns. The correlation between  $R_{J_z}^+$  and  $R_{J_z}^-$  is shown in Figure 2(a) with a linear correlation coefficient of 0.52. This value is highly significant since the two-tailed test with 100 degrees of freedom at the 99% significance level is 0.254, while the total number of studied active regions is 983. Both average values of  $R_{J_z}$  on the two polarities are around 0.48.
- (2) The color of the background for  $R_{J_z}$  in Figure 1 tends to be green, representing  $R_{J_z} < 0.5$  in accordance with the overplotted filled circles in the northern hemisphere and open circles in the southern hemisphere. On the contrary, the color of the background tends to be blue, representing  $R_{J_z} > 0.5$  in accordance with the overplotted open circles in the northern hemisphere and filled circles in the south-



**Fig.2** (a) Correlation between  $R_{J_z}^+$  and  $R_{J_z}^-$ . (b) Correlation between  $R_{J_z}^+$  and sign of  $(\theta) \cdot \langle H_c \rangle$ . (c) Correlation between  $R_{J_z}^-$  and sign of  $(\theta) \cdot \langle H_c \rangle$ .

ern hemisphere. That is to say, regions with  $R_{J_z}$  less (greater) than 0.5 tend to obey (disobey) the HSR.

- (3) The sign reversal of helicity tends to occur where the fraction of "HSR-noncompliant" current systems is greater than 0.5, which is manifested as blue colors in Figure 1. The two boxes in black in Figure 1 show a typical example. For more quantitative analyses, we use the sign function of latitude, and consider the sign of  $(\theta) \cdot \langle H_c \rangle$ . If the helicity obeys/disobeys the HSR, the sign of  $(\theta) \cdot \langle H_c \rangle$  will be negative/positive. Thus we expect that  $R_{J_z}$  is positively correlated with the sign of  $(\theta) \cdot \langle H_c \rangle$ . Figure 2(b) and 2(c) show that this is really the case. The good correlation between the magnitude of  $R_{J_z}$  and  $\langle H_c \rangle$  indicates the sign of  $\langle H_c \rangle$  reflects the chirality of field rather than its strength.
- (4) We computed the percentage of active region numbers in each quadrant of Figure 2(b) and 2(c), and found that they are 30.6% (first quadrant), 10.4% (second quadrant), 49.1% (third quadrant) and 9.8% (fourth quadrant) in Figure 2(b). The active regions in the second and third quadrants obey the HSR, which are in total 59.5%. Figure 2(c) shows a similar number; the percentages of active regions in the four quadrants are 29.1%, 11.4%, 48.1% and 11.4%, respectively, and again 59.5% of active regions follow the HSR. The first quadrant indicates that the  $R_{J_z}$  and  $\langle H_c \rangle$  both disobey the HSR, while the third quadrant demonstrates that  $R_{J_z}$  and  $\langle H_c \rangle$ both obey the HSR. The percentages are around 30% for the first quadrant and 50% for the third quadrant. Particularly, the second quadrant confirms that the  $R_{J_z}$  disobeys the HSR but the  $\langle H_c \rangle$  obeys the HSR. On the contrary, the fourth quadrant shows that  $R_{J_z}$ obeys the HSR but  $\langle H_c \rangle$  disobeys it. The percentages in the second and fourth quadrants are around

10%. These two parts imply the distribution of electric current with longitudinal magnetic field affects the ultimate determination of sign of  $\langle H_c \rangle$  in an active region.

(5) Statistically, when  $R_{J_z}$  is less (greater) than 0.5, the active region obeys (disobeys) the HSR. As an active region evolves, the current systems evolve as well, and the "HSR-compliant" current systems may become smaller than the "HSR-noncompliant" ones, so that the active region disobeys the HSR, and vice versa. However, over the whole solar activity cycle, in 60% of the active regions the "HSRcompliant" current system is greater than the "HSRnoncompliant" one, hence accounting for the HSR. So from the viewpoint of two current systems with opposite sign coexisting in the same magnetic polarity, these can also account for the hemispheric sign rule of helicity.

## **3 CASE STUDY USING DATA FROM SDO/HMI**

#### 3.1 Detailed Analyses of Two Active Regions

The new generation vector magnetograph *SDO*/HMI provides more stable time-series than ground-based ones and allows us to study whether there is relative variation of a current system in a solar magnetic field with time. If the  $R_{J_z}$  reveals variation of real chirality in the magnetic field, evolution of the two kinds of current systems is expected. To this end, we first study two flare-productive active regions using vector magnetograms obtained with *SDO*/HMI.

Basic information on HMI can be referred to in Schou et al. (2012). It contains a full disk ( $4096 \times 4096$ ) filtergraph with a pixel resolution of 0.5 arcsec. The working spectral line is the Fe I 617.3 nm line through a 0.076 Å passband filter at six wavelength positions across



**Fig. 3** (a) *GOES* X-ray flux from 2011 February 13 to 17. (b) Evolution of  $\sum J_z$  (red and blue represent positive and negative polarities respectively) in NOAA AR 11158. The vertical dashed lines correspond to the times of the flares discussed in the text. (c) Evolution of  $\langle J_z \rangle$ . (d) Evolution of  $R_{J_z}$ . The interval between the two vertical dashed lines corresponds to the " $R_{J_z}$ -dynamic" phase discussed in the text.

the line. The processing of a vector magnetic field by using the Very Fast Inversion of the Stokes Vector algorithm based on the Milne-Eddington atmospheric model can be referenced in Hoeksema et al. (2014). The 180° ambiguity in horizontal field is resolved with the minimum energy method (Leka et al. 2009).

The first region investigated here is NOAA AR 11158; it was a clearly observed rapidly developing active region and widely studied from different viewpoints (Sun et al. 2012; Jing et al. 2012; Nindos et al. 2012; Song et al. 2013; Vemareddy et al. 2015). The other region examined here is NOAA AR 11283.

Detailed information on flares referred to in this study is the same as given in table 1 of Gao et al. (2014).

#### 3.2 Electric Currents in NOAA 11158 and 11283

Figure 3(b) shows all the electric currents in NOAA 11158. This region was located in the southern hemisphere. The net currents can be measured by the difference between the curves of the "HSR-compliant" and "HSR-noncompliant" currents in Figure 3(b). The total net current  $\sum (J_{z_i}^+ + J_{z_i}^+)$  above the positive (negative) re-



Fig. 4 Same as Fig. 3 but for the GOES X-ray flux from 2011 September 3 to 9 and NOAA AR 11283.

gion is positive (negative). Therefore, AR 11158 obeyed the HSR.

Figure 4(b) shows the evolution of total electric currents in NOAA AR 11283. This region was located in the northern hemisphere. If it obeys the HSR, it should have negative helicity. From Figure 4(b), we can see that the net currents were positive in the negative polarity areas and negative in the positive polarity areas, i.e. negative helicity before September 5. The signs of the currents changed after September 5, leading to positive helicity, contradicting the HSR. This is consistent with the results obtained by Gao et al. (2012).

The opposite signs of net electric current above opposite magnetic polarity in Figures 3(c) and 4(c) agree

with the results obtained by Gao (2013). Furthermore, they indicate significant changes in the current systems during the evolution of the regions; the net currents above regions of opposite magnetic polarities show variations in almost precisely the opposite sense, indicating a closure of current systems flowing between the two polarities. The unit of electric current density that was used for  $\Sigma J_z$  and  $\langle J_z \rangle$  represents the integrated and averaged magnitude of electric current density respectively over all selected pixels. The main difference with the unit of electric current applied in some other analyses (e.g., Vemareddy et al. 2015, 2016) is the factor of area in each pixel,  $2.54 \times 10^{11} \text{m}^2$  for these two sets of HMI vec-



Fig. 5 The sample of vector magnetograms (A–H) and corresponding maps of  $J_z$  (a–h) at eight selected moments of NOAA AR 11158. The blue (*orange*) contours show the levels of  $\pm 50$  G.

tor magnetograms with spatial resolution of 0.504" per pixel.

# 3.3 $R_{J_z}$ in NOAA AR 11158 and AR 11283

Figure 3(d) shows the evolution of  $R_{J_z}$  in NOAA AR 11158. The corresponding error is estimated with the method of Monte Carlo simulation. We add random noise that is less than the recorded error in each measured vector magnetic field, then we repeat the computation many times and get the final average value and the corresponding standard deviation. During the time interval we studied, the value of  $R_{J_z}^+$  (red) increased from a minimum of 0.431 at 09:24 UT on February 13 (*some 8.06 h before the first M6.6 flare*) to a maximum of 0.490 at 18:00

UT on February 14 and then decreased to 0.449 at 15:36 UT on February 15 (some 14 h after the X2.2-class flare). The evolution of  $R_{J_z}^-$  (blue) exhibits similar characteristics. The linear correlation coefficient between  $R_{J_z}^+$  and  $R_{J_z}^-$  is 0.85. Such a high correlation indicates a coherent variation of electric currents on the opposite polarity regions during the evolution of this region.

Figure 4(d) displays the evolution of  $R_{J_z}$  in NOAA AR 11283. During the time interval we studied, the value of  $R_{J_z}^+$  increased from a global minimum of 0.484 at 21:36 UT on September 4 (about one day before the first M5.3 flare) to a maximum of 0.533 at 08:48 UT on September 7, and then decreased to reach 0.513 at 11:48 UT on September 8 again (about 12h after the X1.8 flare). The subsequent evolution of  $R_{J_z}$  is not known be-



Fig. 6 The sample of vector magnetograms (A–H) and corresponding maps of  $J_z$  (a–h) at eight selected moments of NOAA AR 11283. The blue (*orange*) contours show the levels of  $\pm 50$  G.

cause no vector magnetograms were available. The time profiles of  $R_{J_z}^+$  and  $R_{J_z}^-$  are similar; the linear correlation coefficient between the two quantities is 0.81.

The above results may indicate that the time variation in  $R_{J_z}$  can be used to identify an " $R_{J_z}$ -dynamic" phase. Therefore, we divide the studied periods into two intervals: " $R_{J_z}$ -quasi-stationary" and " $R_{J_z}$ -dynamic" phases. The start of the " $R_{J_z}$ -dynamic" phase is taken as the time when  $R_{J_z}$  begins to rise to a global maximum. The end of the " $R_{J_z}$ -dynamic" phase is taken as the time when  $R_{J_z}$  returns to a local minimum. Hence the " $R_{J_z}$ quasi-stationary" phase is the time outside of the " $R_{J_z}$ dynamic" phase. In particular, for AR 11158 and AR 11283, the " $R_{J_z}$ -dynamic" phases are intervals between the vertical dashed lines in Figures 3(c) and 4(c), respectively: for AR 11158 the " $R_{J_z}$ -dynamic" phase was from 09:24 UT on February 13 to 15:36 UT on February 15 and for AR 11283 it was from 21:36 UT on September 4 to 11:48 UT on September 8. Interestingly, the behavior of  $R_{J_z}$  in the " $R_{J_z}$ -dynamic" phase was similar in the two analyzed active regions.

In order to see where such variations in the electric currents take place, eight moments were chosen and are marked with arrows in Figures 3(d) and 4(d), in which the corresponding snapshots of electric currents are plotted. The "P" and "Q" regions in panels (a-h) of Figures 5 and 6 respectively indicate the regions in which prominent variation of *HSR-noncompliant* current occurred. Here prominent variations of current are shown with "P" and "Q" regions, but this does not mean the variations only occurred at these regions, because they may also exist in other places that are not clearly shown. At least in

the region of opposite magnetic polarity, there is corresponding well correlated variation of current. This can be inferred from Figures 3(d) and 4(d).

Compared with the evolutional trends of other parameters for AR 11158 (e.g., Song et al. 2013), such as electric current, current helicity, photospheric free energy, angular shear, etc., the curve  $R_{J_z}$  has a similar rising trend in the former half of the " $R_{J_z}$ -dynamic" phase. However, there is an obviously different descending trend in the latter half of the " $R_{J_z}$ -dynamic" phase. After the " $R_{J_z}$ -dynamic" phase,  $R_{J_z}$  returns to the same level as before the " $R_{J_z}$ -dynamic" phase. The decreasing tendency of the parameter measuring free magnetic energy would be expected after the flare, as pointed out by Wiegelmann et al. (2014). Although there are different trends in some particular situations, these parameters are all important to show the storage and release of magnetic energy in different ways.

When the computation was performed, the pixels where  $|B_z| > 50 \,\mathrm{G}$  are taken into the final determination of the parameters so that the uncertainty of the horizontal and vertical field outside of the active region would have little effect on these parameters. For the evolutional curves of AR 11158 and AR 11283, the error propagation was estimated by the Monte Carlo method. In particular, 30 sets of parameters were obtained at each moment by adding the random errors to the inputted field strength. Taking  $J_z$  for example, firstly the  $J_z$  including random error is computed as follows:  $J_z = (1/\mu_0) \{ \partial [B_u + 2 \times$  $(R_0 - 0.5) \times \delta B_y ]/\partial x - \partial [B_x + 2 \times (R_1 - 0.5) \times$  $\delta B_x]/\partial y\}$ , where  $R_0$  and  $R_1$  are random numbers between 0 and 1.  $\delta B_x$  and  $\delta B_y$  are inversion errors of field components provided by HMI. Then the standard deviation of these 30 sets of parameters  $(\delta_{J_z})$  is taken as the error estimation of this moment. The error at each moment is shown with short bars representing the corresponding quantity in panels (b), (c) and (d) of Figure 3 and 4.

## 4 CONCLUSIONS AND DISCUSSION

#### 4.1 Conclusions

From long-term observations obtained at HSOS that covered more than 1.5 solar cycles, two current systems can be identified: they are named "HSR-compliant" and "HSR-noncompliant" current systems according to whether their signs conform to the HSR. It is found that the active regions with  $R_{J_z}$  less than 0.5 tend to obey the HSR while active regions with  $R_{J_z}$  greater than 0.5 tend to disobey the "HSR." It is also found that the "HSR-compliant" current system has about a 60% probability of realization, which is greater than the "HSR- noncompliant" current system. This marginal superiority of the normal current system may explain the reversal of the helicity sign and big scatter in the HSR. At present it is uncertain whether the above picture holds for any given time. From the locus of sign reversal of helicity in Figure 1, it is inferred that the probability of "HSR-compliant" vs. "HSR-noncompliant" current systems may be different for different active regions or in different phases of the solar cycle.

Active regions studied here exhibited an " $R_{J_z}$ dynamic" phase in the time profiles of their  $R_{J_z}$ . The " $R_{J_z}$ -dynamic" phase is the interval characterized by the gradual increase and then decrease in  $R_{J_z}$  on both polarities. In the studied active regions, large flares occurred during this interval. Eight moments were chosen that are marked in Figures 3 and 4, then the corresponding snapshot of the electric current was plotted. The green arrows in panels (a-h) of Figures 5 and 6 indicate the regions of prominent variation with abnormal helicity. This shows a prominent increase and then decrease in one of the current systems in the " $R_{J_z}$ -dynamic" phase, violating the HSR for the two particular active regions in this study. This conjecture still needs further confirmation by a statistical work with a bigger sample. However,  $R_{J_z}$  could be a sensitive indicator highlighting peculiar properties of active regions around large flares compared to their properties in relatively quiescent periods. It was noted that in the two active regions, their long-term evolution of  $R_{J_z}$  that defined their " $R_{J_z}$ -dynamic" was similar. This might indicate that  $R_{J_z}$  reflects the underlying physical process that occurs commonly in current systems of different active regions around the time of large flares.

The high correlation coefficient between the time profiles of  $R_{J_z}$  that are associated with opposite magnetic polarities was also found in AR 11158 and AR 11283. This implies that the current systems in the regions with opposite magnetic polarity evolve coherently, namely the currents connect the two polarities by flowing basically along the field lines.

#### 4.2 Discussion

The  $R_{J_z}$  parameter measures the difference in magnitudes of two opposite current systems which accounts for whether the active region obeys HSR or not. Moreover, it shows large-scale temporal trends associated with the occurrence of large flares for the two different active regions studied. This property may be applied to further study flares in different active regions, though it needs to be stressed again that a statistical work with more examples is needed to confirm the universality of the  $R_{J_z}$ - dynamic phase covering a major flare. In addition, how to quantitatively separate the  $R_{J_z}$ -quasi-stationary phase from the  $R_{J_z}$ -dynamic phase needs further investigation.

It should be pointed out that the dynamic evolution of electric current in the solar active region investigated in the current paper is based on the observation in space. The time-series of vector magnetograms that are obtained with high cadence and snapshots show the evolution of an active region, which is independent of the atmosphere around Earth. Up to now, the *SDO*/HMI instrument has provided unique data for this investigation. Even for this instrument, how many observed active regions we can see that exhibit similar variation is uncertain. This study presents an alternative quantity that possibly reflects the dynamic evolution of two kinds of opposite magnetic twists in an individual polarity longitudinal magnetic field by analyzing two well-observed active regions.

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