ON THE INJECTION OF HELICITY BY THE SHEARING MOTION OF FLUXES IN RELATION TO FLARES AND CORONAL MASS EJECTIONS

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Abstract

An investigation of helicity injection by photospheric shear motions is carried out for two active regions (ARs), NOAA 11158 and 11166, using line-of-sight magnetic field observations obtained from the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory. We derived the horizontal velocities in the ARs from the differential affine velocity estimator (DAVE) technique. Persistent strong shear motions at maximum velocities in the range of 0.6–0.9 km s⁻¹ along the magnetic polarity inversion line and outward flows from the peripheral regions of the sunspots were observed in the two ARs. The helicities injected in NOAA 11158 and 11166 during their six-day evolution period were estimated as 1.46 x 10¹² Mx² and 9.5 x 10¹² Mx², respectively. The estimated injection rates decreased up to 13% by increasing the time interval between the magnetograms from 12 minutes to 36 minutes, and increased up to 9% by decreasing the DAVE window size from 21 x 18 to 9 x 6 pixels, resulting in 10% variation in the accumulated helicity. In both ARs, the flare-prone regions (R2) had inhomogeneous helicity flux distribution with mixed helicities of both signs and coronal mass ejection (CME) prone regions had almost homogeneous distribution of helicity flux dominated by a single sign. The temporal profiles of helicity injection showed impulsive variations during some flares/CMEs due to negative helicity injection into the dominant region of positive helicity flux. A quantitative analysis reveals a marginally significant association of helicity flux with CMEs but not flares in AR 11158, while for the AR 11166, we find a marginally significant association of helicity flux with flares but not CMEs, providing evidence of the role of helicity injection at localized sites of the events. These short-term variations of helicity flux are further discussed in view of possible flare-related effects. This study suggests that flux motions and spatial distribution of helicity injection are important to understanding the complex nature of the magnetic flux system of the AR, and how it can lead to conditions favorable for eruptive events.

Key words: Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: surface magnetism

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1. Introduction

Magnetic helicity is an important topological property of solar active regions (ARs) and is a measure of twist and writhe of the field lines (Berger & Field 1984; Finn & Antonsen 1985). It is a gauge invariant for a closed volume of space. The Sun’s outer atmosphere is dominated by a magnetic field at all scales. Dynamic phenomena such as energetic flares and coronal mass ejections (CMEs), occur due to the loss of equilibrium during the evolution of magnetic fields in solar ARs. Magnetic helicity has become an important physical parameter in the context of solar transient phenomena. It is one of the few global quantities that is conserved, even in resistive magnetohydrodynamics, on a timescale less than that of the global diffusion. There exists no absolute measure of helicity within a sub-volume of space if that sub-volume is not bounded by a magnetic surface. However, a topologically meaningful and gauge invariant relative helicity for such volumes can be defined.

There are several methods for estimating helicity in solar ARs. By the force-free field assumption of the coronal magnetic field, we have

\[ \nabla \cdot B = \alpha B, \]

where \( \alpha \) is the force-free parameter, also known as the helicity or twist parameter. Assuming \( \alpha \) to be constant for the whole AR, we can fit observed vector magnetograms to deduce the value of \( \alpha \) (Pevtsov et al. 1995; Hagyard & Pevtsov 1999; Tiwari et al. 2009). The latitudinal variation of the helicity of photospheric magnetic fields and the statistical significance of the observed temporal variations of the ARs’ hemispheric helicity rule, as measured by the latitudinal gradient of the best-fit linear force-free parameter \( \alpha \), etc., have been discussed by Pevtsov et al. (2008).

The Poynting-like theorem for helicity in an open volume as derived by Berger & Field (1984) is given by

\[ \frac{dH}{dt} = \oint (2B_t \cdot A_p) v \cdot ds - \oint 2(A_p \cdot v) B_z ds, \] (2)

where \( A_p \) is the vector potential of the potential magnetic field, \( B_p \), which is uniquely specified by the observed flux distribution on the surface (x–y plane) as

\[ \nabla \times A_p \cdot \hat{z} = B_z; \quad \nabla \cdot A_p = 0; \quad A_p \cdot \hat{z} = 0, \] (3)

where \( \hat{z} \) refers to the unit vector along the vertical direction of the Cartesian geometry. Equation (2) shows that the helicity of magnetic fields in an open volume may change by the passage of helical field lines through the surface (first term) and/or by photospheric footpoint motions of the field lines (second term). The temporal evolution of magnetic helicity flux across the photosphere characterizes the injection of magnetic helicity from the sub-photospheric layers into the solar atmosphere, horizontal flux motions, and the changes in the coronal magnetic field configurations related to eruptive events, such as the CMEs, propagating into the interplanetary medium.
Over the past several years, many attempts have been made to estimate magnetic helicity from suitable solar observations. Chae (2001) developed a method for determining the helicity flux (the second term in Equation (2)) passing through the photosphere. He used a time series of photospheric line-of-sight (LOS) magnetograms to determine horizontal velocities by the local correlation tracking (LCT) technique (November & Simon 1988). Using this method, vector potential $A_p$ was constructed by using the photospheric LOS field (as an approximation of the $B_z$ field) as boundary conditions with Coulomb gauge in terms of Fourier transform (FT) as

$$A_{p,x} = \text{FT}^{-1} \left[ \frac{j k_x}{k_x^2 + k_y^2} \text{FT} (B_z) \right]$$

$$A_{p,y} = \text{FT}^{-1} \left[ -\frac{j k_y}{k_x^2 + k_y^2} \text{FT} (B_z) \right],$$

where $k_x$ and $k_y$ are spatial frequencies in the $x$- and $y$-directions, respectively. Later, this method was applied to many ARs by several authors (Chae et al. 2001, 2004; Moon et al. 2002; Nindos et al. 2003). However, Pariat et al. (2005) showed that this method of calculation introduced artificial polarities of both signs with many flow patterns in the helicity flux density maps. Therefore, they suggested using relative velocities for calculating the helicity injection rate:

$$\frac{dH}{dt} = -\frac{1}{2 \pi} \int \int \int_S \frac{[(\mathbf{x} - \mathbf{x}) \times (\mathbf{u} - \mathbf{u})']_n}{|x - x'|^2} B'_z(x')B_z(x)dS'dS,$$

(4)

where $\mathbf{u}$ is the footpoint velocity at the position vector $\mathbf{x}$ and $B_z$ is the vertical component of the observed magnetic field. This equation shows that the helicity injection rate can be understood as the summation of the relative rotation rates of all the pairs of elementary fluxes weighted with their magnetic flux.

Furthermore, Schuck (2005) has shown that the LCT method is inconsistent with the magnetic induction equation, which governs the temporal evolution of the photospheric magnetic fields. Tracking methods have serious practical limitations that might result in the failure of detecting significant shear velocity fields and hence in the underestimation of the amount of helicity injected by such velocity fields. Démoulin & Berger (2003) reported that the magnetic energy and helicity fluxes should be computed only from the horizontal motions deduced by tracking the photospheric cross-section of magnetic flux tubes. These authors contended that the apparent horizontal motions include the effect of both the emergence and shearing motions. They analyzed the observational difficulties involved in deriving such fluxes and, in particular, the limitations of the correlation tracking methods. One of the main limitations in previous studies has been the coarse spatial resolution of the available observations, which limited the deduced velocities to the velocity corresponding to the group motion of an unresolved bunch of thin flux tubes covered by a pixel. Also, tracking motions faced difficulties in the areas lacking sufficient contrast, such as in the sunspot umbrae.

Several improved methods have been developed for inferring plasma velocities consistent with the induction equation at the photospheric level, based on the LOS and vector magnetograms. The induction method (IM; Kusano et al. 2002), induction local correlation tracking (ILCT; Welsch et al. 2004), minimum energy fit (MEF; Longcope 2004), the differential affine velocity estimator (DAVE; Schuck 2005, 2006), and DAVE for vector magnetograms (DAVE4VM; Schuck 2008) have been developed to determine the horizontal component of motion. In contrast, the normal component of velocity can be determined from the Doppler observations of ARs located near the disk center. The DAVE4VM method requires vector magnetograms. The performance of different techniques has been examined in Welsch et al. (2007), which showed that the MEF, DAVE, FLCT, IM, and ILCT algorithms performed comparably. Furthermore, they reported that while the DAVE estimated the magnitude and direction of velocities slightly more accurately than the other methods, MEF’s estimates of the fluxes of magnetic energy and helicity were more accurate.

Time series data of photospheric magnetograms have been extensively used to derive magnetic helicity and its evolution in order to examine its role in the level of transient activity of the ARs. Moon et al. (2002) reported impulsive variations of helicity during some M- and X-class flares. In a survey, LaBonte et al. (2007) revealed that X-flaring ARs have a higher net helicity change with peak helicity rate $> 6 \times 10^{36}$ Mx$^2$ s$^{-1}$ than with weak hemispheric preference. Park et al. (2010b) have also studied solar flare productivity in relation to helicity injection using a large sample of 378 ARs. Using SOHO-MDI magnetograms, they reported variation of helicity injection rates and a significant helicity accumulation of $3-45 \times 10^{36}$ Mx$^2$ over several days around the time of flares above M5.0. Most of the previous studies that used data from the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) had a time resolution of 96 minutes. The rather coarse time resolution between two consecutive observations has been a matter of concern in the above calculations because the contribution from the motion of short-lived magnetic features in small intervals is difficult to account for suitably (e.g., Chae et al. 2004). This underlines the need for observations of magnetic fields with higher temporal resolution.

The above-mentioned issues can now be addressed with the availability of a better cadence of 12 minutes by the recently launched Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO). Our main objective in the present work is to reinvestigate the role of helicity injection in relation to flares and CMEs using the high-resolution data obtained from SDO-HMI. We intend to utilize this opportunity to revisit some of the previous studies involving computations of the helicity rate for two ARs, NOAA 11158 and NOAA 11166, that appeared during 2011 February and March, respectively, in the ascending phase of the current Solar Cycle 24.

Using the high-quality HMI data obtained for the two ARs, we intend to examine whether the variations as reported by Moon et al. (2002) and Park et al. (2010a) for energetic flares also occurred during the flares of lower magnitude. It is of particular interest to investigate if such changes were associated with the CMEs as well. For our analysis, we use the DAVE technique for retrieving horizontal footpoint velocity from the LOS magnetograms. Thereafter, using Equation (4), we determine helicity injection rates and the accumulated helicity in the two ARs, which results from footpoint shearing motions during their disk transit. It has been inferred from previous studies that most of the helicity injection corresponds to magnetic flux emergence in the ARs (Jeong & Chae 2007). We therefore attempt to interpret the variations found in these physical parameters in relation to the occurrence of flares and CMEs. In particular, we investigate whether the transport of magnetic helicity plays a role in solar eruptions.
We organize this paper as follows: a description of the data used in this study and the procedures of the data processing are given in Section 2. The results obtained for the two selected ARs are presented in Section 3 and the following discussions in Section 4. This article is summarized in Section 5.

2. DATA AND METHOD OF ANALYSIS

For our study, we have used high-resolution LOS magnetograms at a cadence of 12 minutes obtained from the HMI (Schou et al. 2012) on board SDO. HMI observes the full solar disk in the Fe i 6173 Å spectral line with a spatial resolution of 1 arcsec. HMI provides four main types of data: Dopplergrams (maps of solar surface LOS velocity), continuum filtergrams (broad-wavelength maps of the solar photosphere), LOS, and vector magnetograms (maps of the photospheric magnetic field).

NOAAs 11158 (19°S) and 11166 (10°N) appeared on the disk during 2011 February 11–20 and 2011 March 3–16, respectively. These ARs were very active and produced some intense X-class flares associated with CMEs in addition to many M- and C-class flares during their disk transits. From the AIA observations, intermittent mass expulsions were seen, many of which turned into large, fast moving CMEs, as confirmed by STEREO. Table 1 gives a list of flares (as recorded by GOES) and CMEs.

Magnetograms obtained at different times were aligned by the method used in Chae et al. (2004). In this method, an image of the AR taken at the central meridian is considered the reference image. All other images, in time accounted for differential rotation (Howard et al. 1990) along with the latitudinal difference of center of the reference image and the ephemeris information, were remapped on to the disk center. This method is intended to reduce errors due to geometrical foreshortening, and the AR is transformed into the disk center. Since at the disk center normal and vertical components of magnetic fields are same, the difference between the normal and LOS components was corrected by the cosine of the distance of the AR center from the disk center by assuming the horizontal field contribution for the transformation to be negligible (Venkatakrishnan & Gary 1989).

We followed the transits of the two selected ARs from east to west on the solar disk. In order to have negligible errors in geometric correction, we restricted ourselves to a region within ±40° longitude from the central meridian. With this constraint, we confined our study of the temporal evolution of the ARs to a six-day period around their central meridian passage.

We derived the horizontal velocities of footpoints on the photosphere by using the DAVE technique (Schuck 2006). The DAVE technique is essentially a local optical flow method that determines the magnetic footpoint velocities within the windowed region. Further, it adopts an affine velocity profile specifying velocity field in the windowed region around a point and constrains that profile to satisfy the induction equation. Any tracking method depends on two parameters, viz., the window size and the time interval. For a given time interval $\Delta t$, the

### Table 1

| AR (NOAA) | Date (dd/mm/yyyy) | Flares | CMEs |
|-----------|-------------------|--------|------|
| 11158     | 11/02/2011        | No flares | No CMEs |
|           | 12/02/2011        | No flares | No CMEs |
|           | 13/02/2011        | C1.1(12:29), C4.7(13:44), M6.6(17:28) | C1.2(23:14), C2.7(23:40) |
|           | 14/02/2011        | C1.6(02:35), C8.3(04:29), C7.1(06:51) | C1.2(23:14), C2.7(23:40) |
|           | 15/02/2011        | C2.7(00:31), X2.2(01:44) | C4.8(04:27), C4.8(14:32), C1.7(18:07) |
|           | 16/02/2011        | C2.0(00:58), M1.0(01:32), C2.2(01:56) | C4.6(19:30), C1.3(22:49) |
| 11166     | 06/03/2011        | C5.1(11:56), C3.9(15:21) | No flares |
|           | 07/03/2011        | M1.9(13:45) | 02:00,15:20 |
|           | 08/03/2011        | C7.7(23:10) | 14:25,22:10 |
|           | 09/03/2011        | C9.4(08:23), M1.7(10:35), M1.7(13:17) | 14:30,19:00 |
|           | 10/03/2011        | C4.2(03:50), C6.2(07:03), C4.2(13:19) | 09:00 |
|           | 11/03/2011        | C1.4(00:29), C1.1(01:46), C2.8(02:24) | 04:50,07:10 |

Note. All flares (CMEs) are associated with the source region R2 (R1) of respective ARs except those marked by *.
The window should be large enough so that tracked features remain confined within the window. Also, it should be small enough to be consistent with an affine velocity profile. Schuck (2008) presented a way to select an optimal window objectively, using the degree of consistency between the change in the observed magnetic field ($\Delta B/\Delta t$) and the expected magnetic field change based on the flow estimated with several trial windows. They found the best performance of this method at approximately a square window of pixels. Since the ARs evolved rapidly, we chose a window size of $21 \times 18$ pixel$^2$ after a careful verification of the physical flux motions and directions of estimated flows. The dependence of the helicity injection rate on the window size and time difference between the tracked maps using this method were investigated. Moreover, as the HMI magnetic field measurement precision is 10 G (Schou et al. 2012), we have set this as the threshold to avoid errors while retrieving velocities. Further details of this method are given in a recent work of Tian et al. (2011).

Computation of the helicity rate using the method (direct integration) proposed by Pariat et al. (2005) at each pixel of the AR map (cf. Equation (4)) is a tedious, time-consuming process. However, we chose to use this method to reduce the effect of fake polarities of helicity flux. Restricting the calculations at pixels with the magnetic field above the threshold ($\geq 10$ G) helps to reduce the typical computation time by 15%–25%. Parallelization in integrand computation further reduces the time by approximately a factor of the number of processors used. The same equation as rewritten by Chae (2007) to suit the convolution algorithm by FT is faster than the direct integration method. The intrinsic problem of FT with periodicity could be overcome by padding the array corresponding to the data points with rows and columns of zeros to get the results obtained by the direct integration method. In this study, we have implemented the former approach (direct integration) to get sufficiently accurate results.

3. EVOLUTION OF MAGNETIC FLUX AND HELICITY

The evolution of the observed magnetic flux and the computed helicity rates are presented in the following for the two selected ARs NOAA 11158 and NOAA 11166 with the methods and procedures explained in Section 2.

3.1. AR NOAA 11158

This AR appeared as small pores at the heliographic location E33S19 on 2011 February 11 as seen in the full disk HMI photoheliograms. Thereafter, it grew very rapidly during the next two days as the small pores merged and formed bigger sunspots. It was a newly emerging region that developed into a large AR with $\beta\gamma\delta$ magnetic complexity during its rapid evolution. The AR consisted of four large regions of opposite polarities in quadrupolar configuration. Figure 1 (top row) shows the evolution of NOAA 11158 during 2011 February 13–15 in HMI intensity maps. The prominent positive polarity sunspots of the AR are labeled as SP1, SP2, and SP3 and the negative polarity spots as SN1, SN2, and SN3. LOS contours are overlaid on the intensity image showing the respective polarity distribution.

The spatial evolution of the AR shows a large shearing motion of SP2 that rotated around SN2 about its umbral axis during 2011 February 13–15. It then detached and moved toward SP3 along with small patches of both polarities appearing and disappearing over short periods of time. This motion appears to have created a twist in magnetic field lines connecting these spots. A careful examination of the animation made from magnetograms and intensity maps reveals a significant counterclockwise (CCW) rotation of SN1 during the same period, while a small positive polarity region, SP1, located to the north of SN1 rotated in the CCW direction along with a proper motion away from SN1. The rotations of SN1 and SP1 increased the twist of the field lines and the magnetic non-potentiality of the sigmoid structure.
Figure 2. Top: solar disk-integrated GOES Soft X-ray flux during 2011 February 11–16. The arrows in the top panel indicate the start times of flares in AR NOAA 11158. Middle: time profiles of the magnetic fluxes and flux imbalance in the AR. Bottom: computed helicity rates integrated over the whole AR. Arrows in this panel indicate the onset time of CMEs that were launched from this AR.

(Canfield et al. 1999). Several mass expulsions were launched intermittently from this region, as can be seen from the quick look images in AIA. These turned into CMEs, as confirmed by STEREO observations.

In order to quantitatively analyze the magnetic complexity or twist contributed by the observed shearing motions of the magnetic footpoints, we computed the helicity injection rates using the temporal sequence of magnetograms of the AR. Figure 1 (bottom row) shows the computed helicity flux density maps corresponding to the HMI continuum intensity images (top row). The dark (white) patches in the right panel represent negative (positive) helicity flux density according to the usual convention. Contours of the LOS magnetic field at $[-150, 150]$ G levels are overlaid for a better visualization of helicity flux density with respect to the magnetic polarity. Evidently, the negative polarity region of SN1 injected negative (dark) helicity during 2011 February 14–15, which is also consistent with its physical CCW rotation. In contrast, SP2, SN2, and SN3 injected positive (white) helicity along with negative (dark) helicity in some small patches. We expect that the nature of motions in these areas could have influenced the helicity pattern there.

The photospheric maps of helicity flux (and its injection rate) provide spatial information about the basic properties of a link between the activity and its sub-photospheric roots as reflected by the flux emergence process. In a sample of four ARs, Jeong & Chae (2007) found that helicity was mostly injected while fluxes emerged in the AR, suggesting that it is the major source of helicity injection. The flux cancellation process, on the other hand, resulted in a loss of coronal magnetic helicity, or inverse helicity injection. We thus infer that the AR possessed two main sites of unstable energy storage systems marked by the rectangular boxes R1 and R2 in Figure 1. These sites had distinctly different injections of helicity flux density corresponding to the flux (or footpoint) motions, polarities, and activity.

In order to show the transient activity of the AR as it evolved, we have plotted the disk-integrated GOES soft X-ray flux (1–8 Å channel) during February 11–17 in Figure 2 (top), where the start times of flares of NOAA 11158 are marked.
Figure 3. Transverse velocity field vectors, as inferred from the DAVE technique, superposed on helicity flux density maps, with the LOS magnetic field contours for the rectangular regions of Figure 1—R1 (top row) and R2 (bottom row). Spiral or vortex-like velocity patterns in sunspot penumbra in panels (b) and (c) are due to the umbral rotation of sunspot SN1. Sites of negative helicity injection are seen around the magnetic polarity inversion line in panels (d)–(f) at the peak times of the flares noted in each panel.

(A color version of this figure is available in the online journal.)
in both SP2 and SN2. We hypothesize that the field lines were stressed and twisted by this motion, leading to the storage of free energy adequate to account for the release in the energetic X2.2 flare of February 15 at 01:44 UT. As almost all flares (except M2.2 at 14/17:20) occurred in R2, we examined the spatial distribution of the helicity flux before and after the flare events to find out whether any sudden changes are related to the occurrence of the flare. During some events, we noticed negative patches of helicity flux in the regions of positive helicity flux. Especially in panels (e)–(g), a negative helicity flux distribution near the PIL during the M6.6, C7.0, and X2.2 flares can be observed. There may be some concern about these flare-related changes, as it is known that during the impulsive phase of large flares the spectral line profile itself may undergo some change affecting the magnetic (and velocity) field measurements.

Most of these flares occurred in R2 while the mass expulsions (or CMEs) were associated with R1. In order to relate helicity rate changes to these events, therefore, we have computed and plotted the total injected quantities for R1 and R2 in Figures 4(a) and (b). Injection of helicity in a region of dominant opposite sign can be understood as a sudden dip in the time profile plot. Of course, the corresponding spatial information is lost in the averaged quantity. The advantage of using localized analysis of selected sub-areas in the ARs is that it reduces complex variations occurring over a much larger area of the entire AR while showing only the variations occurring in the areas of interest. It also enhances the dips corresponding to the identified events (marked by the arrows). However, it is important to identify the location of the individual event in order to correctly attribute a particular change of the helicity rate to it. NOAA 11158 was essentially a positive helicity injecting region, while its sub-region R1 had a negative injection rate and accumulated quantity due to the presence of rotational motion. We expect that as the sunspots SN1 and SP1 rotated, the injection rate increased to a maximum of \(-16 \times 10^{40} \text{ Mx}^2 \text{ h}^{-1}\) on February 14 at 18:00 UT. A total helicity accumulation of \(-5.60 \times 10^{42} \text{ Mx}^2\) occurred in this region during the six-day period. Noticeably, a steep accumulation occurred during February 14 and 15 along with many observed mass expulsions shown by arrows. This could be interpreted as shedding of excess helicity from the corona in the form of eruptive events. The steep accumulation of helicity by the monotonic injection rate, therefore, is suggested to be a cause of expulsions. Accumulated helicity amounting to \(14.44 \times 10^{43} \text{ Mx}^2\) in sub-region R2 with steep accumulation observed from February 13 onward could be mostly associated with the observed large shear motion of SP2.

For a quantitative study of the association of short-term variations in the helicity rate with the flaring or CME, the following analysis is carried out. The absolute time difference of the helicity flux \((\Delta \frac{dH}{dt})\), having units the same as \(\frac{dH}{dt}\) averaged over the start and stop times of GOES flares above C2.0 is computed. This is compared to that of randomly selected but equal length time intervals containing no flares. A
significantly higher mean of \(|\Delta(dH/dt)|\) during flares compared to quiet times would indicate a robust association between flaring and helicity fluxes. A similar analysis is undertaken for time windows around CMEs to look for a CME–helicity flux association. We assume that there is no time lag between flaring and helicity flux signal while carrying out this analysis. We first interpolate the signal at the 1 minute interval from the 12 minute interval to get values as required by the GOES flare times, then it is smoothed to a boxcar width of 30 minutes. Within start and stop times of flares, the averaged value of absolute variation is computed to compare with that calculated during randomly selected, constant interval (30 minute) quiet times.

The time difference of the helicity rate in R1–R2 is shown in Figures 4(c) and (d), with CMEs and flares marked by arrows. Large amplitude variations are discernible during M6.6, X2.2, and the CME at 12:30 UT, indicating some association, but similar variations are present around the mean position even in quiet times. From the above-described analysis, we find a significantly higher mean during CMEs (0.054 ± 0.007) compared to quiet times (0.032 ± 0.008). The difference in CME versus quiet time helicity fluctuations is marginally statistically significant, at better than 1σ. Similarly, a mean of 0.044 ± 0.004 (0.049 ± 0.008) during flare (quiet) times indicates poor or no association of flaring with helicity flux variations. The same analysis for the helicity flux over the entire AR improved the association (in terms of mean absolute helicity variation) slightly for CMEs but worsened it for flaring. We shall further discuss these helicity variations during flare/CMEs in view of the involved flare-related effects in Section 3.3.

3.2. AR NOAA 11166

AR NOAA 11166 appeared on the east limb of the solar disk on 2011 March 3 at the location N10E64. We monitored its activity during the period of 2011 March 6–11 in which it produced a large X1.5 flare, two M-class flares, and several C-class flares, some of which were also associated with plasmaoid ejections or CMEs. Table 1 lists the flares and CMEs of this AR. The daily evolution of the AR in the period of 2011 March 8–11 is shown in Figure 5 (top row).

The major sunspots of the AR are labeled as SP1, SP2, SN1, and SN2. The identification of SP2 was somewhat unclear before March 10 as several small umbrae were spread over its location. They moved and coalesced to form SP2. Polarities of the respective sunspots are identified by the overlaid LOS magnetic field contours. This AR also consisted of a complex magnetic configuration with two positive (SP1 and SP2) and two negative (SN1 and SN2) polarity sunspots located within the surrounding diffused fluxes. Emerging and moving flux regions, FP3 and FN2, were identified in the course of the evolution in the sunspot periphery (March 11 at 22:00 UT panel), as they have an opposite sign to that of their native sunspots. However, there were no intrinsic rotating sunspots or flux patches as observed in the case of AR NOAA 11158.

We computed the helicity flux density for AR NOAA 11166 during its evolution in the period of 2011 March 6–11. The corresponding maps for three successive days are plotted in Figure 5 (bottom row). Locations of helicity flux density of mixed sign were distributed all over the AR throughout the evolution period. The peripheral sites of the sunspots exhibited helicity flux density predominantly a negative sign. However, patches of the negative helicity flux were also observed embedded in the positive helicity flux site of the flare (March 9 at 23:00 UT panel). For a further close examination, we consider two sub-areas, R1 and R2, as marked by the boxes in Figure 5.

The disk-integrated GOES soft X-ray flux (1–8 Å channel) during 2011 March 6–11 is plotted in Figure 6 (top). The arrows in this panel indicate the start time of flares in NOAA 11166. During the disk transit of the AR, fluxes of both polarities...
increased corresponding to $5 \times 10^{21} \text{ Mx}$, with the imbalance varying below 6% (Figure 6, middle). As observed for NOAA 11158, a rapid flux emergence also occurred in this AR during March 7–9. Thereafter, only small variations associated with local cancellations/emergence of about $\sim 1 \times 10^{21} \text{ Mx}$ took place pertaining to the gradual evolution of the AR. Positive flux dominated in the AR during March 7–11, and then a near balance was established. It is worth noting that magnetic fluxes in both polarities decreased by $\sim 0.9 \times 10^{21} \text{ Mx}$ and that the evolution of fluxes leads to the occurrence of a CME following the X1.5 flare. However, it is not clear whether this decrease in flux six hours before the flare/CME has some role in these events. But, the flux imbalance, increasing prior to the flare, reduced significantly after the flare consistent with observations reported by Wang & Liu (2010). Most of the flares and CME activity of this AR occurred only after March 8, suggesting that the rapid emergence of fluxes could be an important factor in triggering these transients.

Temporal evolution of the helicity injection rate and the accumulated helicity for NOAA 11166 are shown in Figure 6 (bottom) with arrows marking the times of the CMEs. A five-magnetogram boxcar was used to smooth the profile and reduce fluctuations in it. As expected, these parameters increased in the first phase corresponding to the flux emergence, which agrees with Jeong & Chae (2007) that helicity is mostly injected while the fluxes emerged. The total helicity accumulated during the six-day period of the AR’s evolution is estimated to be $\sim 9.5 \times 10^{42} \text{ Mx}^2$. The maximum helicity injection occurred during 2011 March 8 at the rate of $30 \times 10^{40} \text{ Mx}^2 \text{ h}^{-1}$. Thereafter, it reduced gradually to the minimum rate at $-10 \times 10^{40} \text{ Mx}^2 \text{ h}^{-1}$ on 2011 March 10. The coronal helicity of the AR is likely to be positive as a result of this positive helicity injection.

Horizontal or transverse velocity vectors corresponding to the tracked flux motions are plotted in Figure 7 separately for R1 (top row) and R2 (bottom row). The rms velocities of flux motions are found to have the maximum values in the range 0.5–0.9 km s$^{-1}$. Strong moat flows were systematically dominant in both regions from the peripheral regions of sunspots in addition to the shear flows. Persistent strong shear motions due to the merging SP2 group are identified in R2. These flows appear to collide head on with those from SP1 resulting in the flux submergence/cancellation. Flux emergence is also
identified from the diverging flow field observed in animated flows from R1. From this region, flux moved toward R2 as the AR evolved. Such motions appear to be associated with the injection of negative helicity into a region with predominantly positive flux, increasing the complexity of the magnetic flux system as shown in panels (d)–(f) of R2. Further, these negative helicity injections often coincided with some observed events, such as the three of them shown in this plot. For the X1.5 flare, the distribution of helicity flux is shown in panel (e) on March 9 at 23:36 UT.

The injection rates and accumulated helicities deduced from sub-regions R1 and R2 are plotted in Figures 8(a) and (b). Also the contribution of each signed helicity flux in the net helicity flux is plotted separately. The time profile of R1 shows it to have positive helicity injection, with a steep increasing phase during March 7–9, at a peak rate of $27 \times 10^{40} \text{ Mx}^2 \text{ h}^{-1}$. Thereafter, a gradual decrease in the rate of injection is evident from the plot. As mentioned earlier, R1 was a site of emerging flux that resulted in contributing to accumulation of helicity amounting to $11 \times 10^{42} \text{ Mx}^2$, while R2 exhibited mixed sign injection rates during its evolution. As in the previous AR, continuous injection of dominant positive helicity from R1 is suggested to be the cause of observed mass expulsions, whereas the injection from R2 is of mixed signs suggested to result in flares. An enhanced peak of the helicity rate seen around the time of the X1.5 flare in R2 of AR 11166 that is not obvious in Figure 6 (bottom panel) since we reduced fluctuations occurring over the entire AR by selecting a small area. After this event, the negative injection rate increasingly dominated on March 10, turning the net injection of the entire AR negative. The implication of this transition of the injection rate from a positive to negative sign over a day is not clear in the observed events shown by the arrows.

The time variation of helicity flux in both R1 and R2 is plotted in Figures 8(c) and (d) along with the arrows pointing to start times of CMEs and flares in the AR. Some of the large amplitude variations of helicity flux about the mean position appear to be related to these events. As in the previous AR, we have analyzed the association of flare/CMEs that originated from sub-regions R1 and R2 of this AR with their respective helicity flux. The calculated mean of variation in helicity flux ($|\Delta(dH/dt)|$) during flaring ($0.099 \pm 0.020$) is marginally statistically different, at about $2\sigma$ level over that during quiet times ($0.057 \pm 0.007$), reflecting a robust association of flaring and helicity fluxes. The mean of $|\Delta(dH/dt)|$ obtained in quiet times does not have any information or bias of flaring or CME, therefore a higher mean during flares/CMEs implies some impact of helicity flux variations on them. A similar analysis undertaken for CMEs also showed a similar association (during which CMEs of $0.052 \pm 0.006$ dominated over quiet times of $0.047 \pm 0.006$, but not to a statistically significant degree). However, the association strengthened for flaring and weakened for CMEs when the helicity flux over the entire AR was considered in the analysis.

3.3. Flare-related Effects on Helicity Flux

It is well known that the photospheric magnetic (and Doppler) field measurements are affected by flares. During an energetic flare, the profile of the spectral line used for the measurement was reported to change from absorption to emission, resulting in a change of sign in the deduced magnetic polarity (Qiu & Gary 2003 and references therein). This abnormal polarity reversal was observed to last for a few minutes during the impulsive phase of the flare (typically 3–4 minutes). Similar abnormal, transient changes have also been reported for some other large,
white light flares (Maurya & Ambastha 2009; Maurya et al. 2012). The change in the line profile may arise due to both thermal effects and non-thermal excitation and ionization by the penetrating electron jets produced during the large flares. We call these flare-related transient changes, considered to be artifacts as they do not correspond to real magnetic field changes.

There is increasing evidence that flares may change the magnetic field more significantly in a persistent and permanent manner (Sudol & Harvey 2005; Petrie & Sudol 2010; Wang & Liu 2010). The persistence of the observed field changes implies that they are not artifacts of changes in the photospheric plasma parameters during the flare, and the temporal and spatial coincidences between flare emission and field changes suggest the link of the field changes to the flare. We call these permanent flare-related changes. With these known transient and permanent flare-related effects on magnetic fields, it would not be clear, particularly during the impulsive phase of the flare, if the change in helicity flux can be interpreted as genuine transport of helicity across the photosphere.

In addition, an implicit assumption made in our approach of calculating helicity injection is the ideal evolution of photospheric magnetic fields in the induction equation used to derive velocities of flux motions. Moreover, the same assumption is involved in the derivation of helicity injection from the relative helicity formula (Berger & Field 1984; Finn & Antonsen 1985). This assumption is valid and reasonable outside the flaring time intervals (at least during permanent changes of fields), as the typical observed photospheric velocities are far less than the Alfvén velocities. In the real conditions of rapid, transient changes in photospheric magnetic fields spanning the impulsive period of the flare, the assumption of ideal magnetic evolution may not be applicable. Therefore, there is theoretical uncertainty regarding the interpretation of helicity fluxes during flares.

In order to inspect these aspects in the signal of the helicity change rate, we procured 45 s cadence magnetograms for some selected flare events and averaged them to 3 minute cadence after processing the previous data set. A mosaic of distribution of the helicity flux around the X2.2 flare is shown in Figure 9. During the impulsive period (01:48–02:02 UT) of this flare, negative helicity flux is distributed about the PIL, which we believe to be due to the transient flare-related effect. The magnetic (and Doppler) transients and locations of spectral line reversal associated with this flare, which are spatially and temporally consistent with this negative helicity flux distribution, have already been reported by Maurya et al. (2012). Therefore, the observed negative helicity flux distribution in the dominant positive site can be attributed to the transient flare effect, and is likely to be an artifact, i.e., not a true transfer of helicity.

Similar mosaics of helicity flux distribution maps were made and examined for other events. The computed magnetic and helicity fluxes are plotted by time in Figure 10. The flare start time is shown in the vertical dotted line labeled with magnitude of the flare. It should be noted that we have not applied any smoothing to the computed helicity rate signal in these panels. The magnetic fluxes of both signs decreased abruptly, with a dip during the impulsive period following with injection of negative helicity flux in the dominant positive helicity flux, during the M6.6 and X2.2 flare events. Magnetic field measurements could also be underestimated by 18%–25% due to enhanced core emission of the spectral line by the heating of the impulsive flare (Abramenko & Baranovsky 2004). As a result, the integrated flux profile could show such a dip during the peak phase of the flare. Interpretation of flux annihilation through reconnection

Figure 8. Same as Figure 4 but for AR NOAA 11166. (A color version of this figure is available in the online journal.)
Figure 9. Mosaic of the injection of the helicity flux distribution around the time of the X2.2 flare in AR 11158 with an iso-contour of LOS positive (negative) flux in black (white). Intense negative helicity flux around the PIL during the peak time (01:48–02:00 UT) of the flare is evident, possibly due to the flare-related transient effect on the magnetic field measurements during the impulsive period.

during this peak phase might be ambiguous due to this fact, although it could be a possible consideration. In the post-flare phase, fluxes increased in both polarities as field lines reorganized as a post-reconnection process. This falls under the “permanent” real change related to the flare.

For smaller magnitude flares, transient effects may be absent or may not be prominent in the impulsive phase. Therefore, the measurements of magnetic fields and the computed helicity rate signal are not expected to be affected during the flare. Hence, while aware of the theoretical uncertainties mentioned above, they may indicate true transfer of helicity flux. In the case of the February 14 at 13:47 UT (C7.0) flare, shown in panels (b1) and (b2), the variation of the helicity signal indeed occurs without the variations in magnetic fluxes associated with the flare-related effects. This may be an example of true transfer of helicity of the flux system, not withstanding the theoretical uncertainty in our approach.

There are no significant variations in magnetic and helicity fluxes corresponding to the March 9 at 09:23 UT (C9.4) and 10:35 UT (M1.7) flares. Large amplitude fluctuations in both signs of helicity signals during the CME just before the March 9 at 22:03 UT (C9.4) flare are apparent in panels (e1) and (e2). We speculate that these fluctuations subsequently led to the initiation of the prominent CME that followed the March 9 at 23:13 UT (X1.5) flare an hour later. Similarly, the transient flare effects might be responsible for the abrupt changes in magnetic fluxes resulting in variations of the helicity injection signal during the X1.5 flare (panels (f1) and (f2)). During the March 10 at 13:19 UT (C4.2) and 13:42 UT (C4.7) flares, the transfers of helicity flux from positive to negative and negative to positive sign are clear from panels (f1) and (f2), respectively. These flares are of small magnitude, with no obvious flare-related artifacts. Therefore, the observed helicity flux changes are expected to be true (with the implicit theoretical uncertainty in the approach). A point to be noted is that all large flares (M- and X-class) may be involved with transient flare effects. Therefore, it is better to look for helicity variations in small flares where magnetic fields are expected to be less affected, making it easier to examine the possible role of the transfer of helicity flux. Thus, we consider the February 14 at 13:47 UT (C7.0), March 10 at 13:19 UT (C4.2), and 13:42 UT (C4.7) flares to be the best examples here that support the true transfer of helicity. It is not clear whether the helicity transfer in these cases is related to permanent flare effects.

At present, it is difficult to say much about the physical significance of these variations over the AR in the corona, i.e., at the primary sites of the flares. It would be particularly interesting to study the physical significance of such injections along with
the information on coronal connectivities (e.g., Chae et al. 2010), as suggested by Pariat et al. (2005), to understand the possible role of the transfer of helicity flux during flares/CMEs.

3.4. Dependence of the Helicity Injection Rate on the DAVE Parameters

Computation of the helicity injection rate involves the measurement of the magnetic field and inferred horizontal velocities. Apart from the errors in the measurements, the computations involving the DAVE method for deriving velocities depend on two main parameters, viz., the time interval between two successive magnetic maps, \( \Delta t \), and the DAVE window size. To obtain optimized results, horizontal displacements of features during the time interval \( \Delta t \) should be large enough to be well determined by DAVE. Also, these displacements should be smaller than the selected window size. To check our results for consistency, we carried out the DAVE calculations using the time intervals \( \Delta t = 12, 24, \) and 36 minutes, while keeping the window size fixed at \( 21 \times 18 \) pixels. Then, calculations were carried out for different window sizes, viz., \( 21 \times 18, 15 \times 12, \) and \( 9 \times 6 \) while keeping \( \Delta t \) fixed at 36 minutes. Furthermore, to avoid the effect arising from noise, we used a threshold of magnetic field of 10 G, which maximized HMI precision. As the HMI provides 12 minute averaged data products, we averaged them corresponding to our calculations at 24 (two maps) and 36 (three maps) minutes.

The dependence of helicity injection rates on time interval \( \Delta t \) is shown in Figure 11 (top row) for NOAA 11158. The scattered data are fitted by the straight line in the least-squares sense. Due to the large volume of data, this computation is tedious and time consuming. Therefore, results are shown here only for NOAA 11158, but we expect they are also valid for other ARs observed by the HMI. There is an additional issue of unequally spaced data points to be addressed in case, for example, we intend to plot the results for \( \Delta t = 36 \) with \( \Delta t = 24 \) minutes. For such cases, we used a cubic spline interpolation (cf. Press et al. 1992) to get corresponding abscissa values for the ordinate points or vice versa. Essentially, this algorithm employs a cubic polynomial between each pair of data points with the constraint that the second and first derivatives of that polynomial are the same at the end points so that the resulting values are smooth. Table 2 lists the minimum and maximum values of helicity injection rates \( (dH/dt_1, \) in units of \( 10^{21} \text{ Mx}^2 \text{ h}^{-1} \)) and the accumulated helicity \( (\Delta H, \) in units of \( 10^{21} \text{ Mx}^2 \)) for the computational runs carried out with the various DAVE parameters mentioned above.

It can be observed from the scatter plots that the helicity rates decrease slightly as the time interval \( \Delta t \) is increased from 12 minutes to 36 minutes. The fitted straight line deviates at
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Figure 11. Dependence of the helicity injection rate (in units of $10^{40}$ Mx$^2$ h$^{-1}$) for AR NOAA 11158 on (top row) the time interval $\Delta t$ (minutes) and (bottom row) the window size (pixel$^2$). The solid line represents the straight line fit to the scattered data points, whereas the dotted line indicates the slope = 1 line for reference. The correlation coefficient and slope of the fitting are noted in each panel.

Table 2

| Helicity Injection Rates and Accumulated Helicities at Different DAVE Parameters |
|---------------------------------|---------------------------------|
| DAVE Parameters                 | AR 11158                        |
| $\Delta t$ (minutes)            | Window Size (pixel$^2$)         | $dH/dt$ | $\Delta H$ |
| 12                              | $21 \times 18$                 | $-18.98$ | 31.54 | 14.16 |
| 24                              | $21 \times 18$                 | $-7.48$  | 27.27 | 13.09 |
| 36                              | $21 \times 18$                 | $-1.06$  | 22.52 | 12.96 |
| 36                              | $21 \times 18$                 | $-1.06$  | 22.52 | 12.96 |
| 36                              | $15 \times 12$                 | $-1.06$  | 25.02 | 13.51 |
| 36                              | $9 \times 6$                   | $-1.28$  | 26.8  | 14.22 |

Note. Units of $dH/dt$ are $10^{40}$ Mx$^2$ h$^{-1}$ and $\Delta H$ are $10^{42}$ Mx$^2$.

a significant effect on injected helicity rates of up to 13%, corresponding to 9% of the variation in accumulated helicity.

The dependence of the helicity injection rate on the window size by keeping the time interval $\Delta t$ fixed at 36 minutes is shown in Figure 11 (bottom row). The slopes of 1.09 and 1.05 for the DAVE windows $21 \times 18$ versus $15 \times 12$ and $15 \times 12$ versus $9 \times 6$, respectively, show an increasing trend of helicity rates with decreasing window size. Indeed, a scalable factor of 14% reduction of the helicity rate is evident for windows $21 \times 18$ compared to $9 \times 6$. Accumulated helicity also showed this increased trend with decreased window size. A total variation of 10% is found, however, with the same trend of helicity injection rate profiles, which is discernible in the correlation coefficient with the plots. A maximum velocity of 1 km s$^{-1}$ during the time interval of 12 minutes corresponds to a plasma displacement of an arcsec. Hence, for the window size $4.5 \times 3''$ ($9 \times 6$ pixel$^2$), the issue of features overflowing out of the window should not pose problem.

These results are consistent with those reported by Chae et al. (2004, their Figure 7). They deduced and compared velocity and helicity rates by combinations of time difference between magnetograms and LCT window size. Their rms velocity values varied up to 0.6 km s$^{-1}$ at a time interval of 5 minutes. They found that smaller values of LCT parameters result in larger amplitude fluctuations of the rate of helicity, with variation within 10%. In our computations, we found maximum rms...
velocities for 12 minutes, 24 minutes, and 36 minutes in the
AR as 0.95, 0.85, and 0.8 km s\(^{-1}\), respectively. However, for
the window sizes \(21 \times 18\), \(15 \times 12\), and \(9 \times 6\), we obtained
the rms velocities as 0.8, 0.9, and 1.5 km s\(^{-1}\), respectively.
These are higher by a factor of two compared to their values,
probably due to the higher resolution and sensitivity of HMI as
against the coarser spatial resolution of the MDI \(1^\prime\)98 pixel\(^{-1}\).
Nevertheless, the variation in accumulated helicity found in our
analysis is within 10%; consistent with their result.

We thus find the measured helicity injection rate to depend
on the time interval between the two successive magnetograms,
i.e., the observational cadence. The selected window size also
influences the measured quantities. Our analysis suggests that it
is better to use images averaged up to and over 24 minutes with
relatively small DAVE window size subjected to the overflow
condition mentioned above. These are important considerations
to derive reasonable and meaningful results in addition to
optimizing the computations involving large data sets.

4. DISCUSSIONS

Free energy storage and release are some of the most
important problems in the eruption physics of the Sun. There
are essentially two effects that can supply magnetic free energy
and helicity from below the solar surface to the corona. Flux
emergence is the process in which vertical motions carry
magnetic fluxes through the photosphere. If the sub-surface
fluxes emerging through the photosphere are already twisted,
then it will contribute to the injection of helicity (cf. the first term
in Equation (2)). Computation of this term requires knowledge
of the vertical component of velocity and the horizontal or
transverse component of the magnetic field. Flux motions in
the form of rotation or proper motions are another process that
can efficiently supply helicity injection (cf. the second term in
Equation (2)). The helicity injected by solar differential rotation
is rather small, less than 10% of that contributed by the flux
motions (Chae et al. 2004; Démoulin et al. 2002), and only has
a much longer term effect on helicity accumulation (DeVore
2000).

Magnetic helicity is a physical quantity having a positive or a
negative sign, representing a right-handed or left-handed linkage
of magnetic fluxes, respectively. This means that if positive
and negative helicities coexist in a single domain, magnetic
reconnection can cancel magnetic helicity by merging magnetic
flux systems of opposite helicities. Helicity densities are not
gauge invariant; it is only area-integrated relative helicity flux
that is gauge invariant. In order to define true helicity flux
density, the coronal linkage needs to be provided (Pariat et al.
2005), meaning the helicity flux density inferred from tracking
will not be precisely accurate. Our computations of magnetic
helicity injection in both ARs revealed that the distribution of
helicity flux is highly complicated in time and space. Even the
sign of helicity flux often changed within the AR.

It has been suggested earlier by several authors that magnetic
helicity must play an important role in flares as a substantial
amount of helicity accumulation is found before many events
(Kusano et al. 1995, 2002; Kusano & Nishikawa 1996). How-
ever, the correlation between various magnetic field parameters
and the flare index of an AR is not high irrespective of the
method used. This is an intrinsic problem for flare forecasting
as the occurrence of a flare depends not only on the amount
of magnetic energy stored in an AR, but also on how it is triggered.
Thus, it appears that helicity accumulation might be a necessary
but insufficient condition for the flares requiring a trigger, even
if a magnetic system has enough non-potentiality. For instance,
Kusano et al. (2003) suggested that coexistence of positive and
negative helicities may be important for the onset of flares.

Careful three-dimensional simulations have been carried
out by Linton et al. (2001) to explore the physics of flux tube
interaction for co-helicity (same sign) or counter-helicity
(opposite sign). According to them, counter-helicity presented
the most energetic type of slingshot interaction in which flux
is annihilated and twist is canceled. In contrast, co-helicity
exhibited very little interaction, and the flux tubes bounced off,
resulting in negligible magnetic energy release.

Magnetic helicity in the solar corona is closely related to
the photospheric magnetic shear, which is usually defined as the
extent of alignment of the transverse component of the magnetic
field along the neutral or PIL (Ambastha et al. 1993). Based on
this idea, Kusano et al. (2004) performed a numerical simulation
by applying a slow footpoint motion. This motion can reverse the
preloaded magnetic shear at the PIL, resulting in a large-scale
eruption of the magnetic arcade through a series of two different
kinds of magnetic reconnections. They proposed a model for
solar flares in which magnetic reconnection converts oppositely
sheared field into shear-free fields.

We interpret our observations according to the above observ-
rational and simulation aspects as follows. We have found flux
interactions during the X-class flares and associated CMEs as
seen in Figure 3 in the form of continued shearing motion of
SP2 around SN2 in AR 11158. Similar motions are also associ-
ated with SP2 in AR 11166. In both AR cases, the flare-prone
regions (R2) had inhomogeneous helicity flux distribution with
mixed helicities of both signs. Correspondingly, sudden impul-
seve peaks appeared in the profiles of helicity injection due to
the injection of negative signed helicity during some flare events.
These were also spatially correlated with the observed flares.
Opposite helicity flux tubes can interact easily, leading to re-
connection and consequently unleashing explosions of magnetic
energy. Impulsive variations of the magnetic helicity injection
rate associated with eruptive X- and M-class flares accompanied
with CMEs were reported also by Moon et al. (2002). Recently,
Park et al. (2010a) speculated that the occurrence of the X3.4
flare on 2006 December 13 was influenced by the positive helic-
ity injection into an existing system of negative helicity. Further,
a solar eruption triggered by the interaction of two opposite he-
licity flux systems (Chandra et al. 2010; Romano et al. 2011)
and the occurrence of flares in relation to the spatial distribu-
tion of helicity flux density (Romano & Zuccarello 2011) were
reported. The main drawback of these findings is that the time
span between two magnetograms is more than the duration of
the flare (\(\geq 96\) m), so the time rate of helicity could not be easily
resolved at the onset time of the flare. Therefore, our results
appear to be consistent with the reports of opposite helicity flux
tubes reconnecting to trigger transient events.

However, it should be cautioned that we have not found such
clear variations of helicity flux in all flare/CME events. From a
quantitative analysis, we find poor association of the difference
in helicity rates during flares compared to that of quiet times
in AR NOAA 11158. This indicates that such variations are
not prominent or present during all flares. Moreover, a more
statistically significant association of such impulsive variations
was found during CMEs as compared to quiet times. There are
many possible reasons for this poor association; one of them is
the time duration of helicity flux change. We first interpolated
the signal at a 1 minute interval from the 12 minute interval
to get values as required by the GOES flare times. Then, it was
Smoothed to a boxcar-averaging window of 30 minutes to reduce fluctuations arising due to interpolation. Within the start and stop times of the flares, the averaged values of absolute variation were computed. Here, averaging might have diluted the original helicity variation, so comparison with the helicity variation during quiet times might not be valid. In any case, there is no better way to find appreciable variation in the helicity flux over background fluctuations for incorporation into the correlation analysis, unless individual events are monitored manually to get variation timings. Despite these difficulties, statistically significant association of helicity flux is found during flares, but the dominant association is not statistically significant during CMEs in the AR 11166 by following the same approach.

Further, there are concerns about the flare-related effects on magnetic field measurements resulting in a misleading interpretation of helicity flux transfer, in addition to the theoretical uncertainty of the assumption of ideal magnetic field evolution in the approach. We therefore investigated this issue using three minute interval time sequence magnetograms. We find transient flare effects resulting in spurious negative helicity flux distribution during the X2.2, M6.6, and X1.5 flare events. Also, we indeed observed the true transfer of helicity flux with variations of opposite sign helicity without such flare-related effects in small flares, such as the C7.0 at 13:47 UT on February 14, C4.2 at 13:19 UT, and C4.7 at 13:42 UT on March 10. The important point to note is that we find statistically significant association of helicity flux variations with flares/CMEs in the above ARs at zero time lags. Also, these variations are clear during the flare events (see Figure 10) but were not before their commencement. Therefore, it is difficult to suggest that these variations triggered the flares. A study with the information of field line connectivity from coronal observations may be expected to reveal the physical significance of the role of helicity transfer during these events.

Our computed helicity rates involving photospheric flux motions include the flux emergence term as explained by Démoulin & Berger (2003). By a simple geometrical argument, horizontal footpoint velocity (u, here the DAVE velocity) can be written in terms of horizontal and vertical plasma velocities, vh and vn, respectively:

$$u = v_h - \frac{v_n}{B_n} B_h.$$  (5)

From this relation, it is not possible to infer which term, viz., the flux emergence or flux motions, governs the level of activity of the ARs. To resolve this difficulty, we have plotted the integrated absolute flux and accumulated helicity computed over the ARs, as shown in Figure 12.

Evidently, the accumulated helicity increased monotonically with the emergence of the magnetic flux in the AR in its first phase (marked by the vertical dashed line for NOAA 11158). After this phase followed the next, the active phase, where an appreciable increase of helicity occurred with only a small variation in the flux, i.e., where little emergence of fluxes occurred. This rapid increase in helicity in the second phase could be interpreted as the dominant contribution of the flux motions. Intermittent mass expulsions in the form of CMEs transferred away the excess helicity. The extent of this transfer, however, is not clear from this plot, although one can draw plausible conclusions from the timings of the flares and CMEs. The X-class flares with associated CMEs in both ARs occurred at a slowing phase of helicity accumulation caused by negative helicity injection. These facts add to the cases reported by Park et al. (2010b).

Moreover, it can be inferred for AR 11158 that less than 25% of the total helicity flux accumulated with the emergence of the first 75% of the magnetic flux. Most of the helicity flux (from about $3\times10^{42}$ Mx$^2$) was accompanied by very little flux emergence (about $3\times10^{21}$ Mx out of the $30\times10^{21}$ Mx). Therefore, more than 75% of the helicity flux came with only 10% of the total magnetic flux. Similarly, the first 60% (19.5–28.0 $\times 10^{21}$ Mx) of the total magnetic flux was associated with less than 30% ($3\times10^{42}$ Mx$^2$ of $9.5 \times 10^{42}$ Mx$^2$) of the total helicity flux in AR 11166. This implies that more
than 70% of the total helicity flux was accompanied with less than 40% of the total magnetic flux. These two cases are thus contrary to the findings of Jeong & Chae (2007), which stated that most of the helicity flux occurs during flux emergence. Our study suggests that flux emergence may not always play a major role in accumulating helicity flux. It is also evident that although flux emergence is necessary, horizontal motions also play a crucial and dominant role over the emergence term in increasing the complexity of magnetic structures contributing to the helicity flux. Therefore, we suggest that the horizontal flux motions contributed further, in addition to the emergence term, in creating more complex magnetic structures that caused the observed eruptive phenomena.

5. SUMMARY

We have studied the evolution of magnetic fluxes, horizontal flux motions, helicity injection, and their relationship with the eruptive transient events in two recent flare (CME) productive ARs, NOAA 11158 and NOAA 11166 of 2011 February and March, respectively. We have used high-resolution, high-cadence data, provided by SDO-HMI, of these ARs, which were in their emerging and active phases. The emerging AR consisted of rotating sunspots with increasing flux, indicating emergence of twisted flux from the sub-photospheric layers. This indicated the transfer of twist or helicity injection through the photosphere to the outer atmosphere.

We suggest that strong shear motions that include rotational and proper motions played a significant role in most of the events, as did the flux emergence. Such motions are crucial in twisting or shearing the magnetic field lines and for further flux interactions. AR NOAA 11158 consisted of a CME-prone site rotating the main sunspot along with an emerging flux of opposite sign and a moving magnetic feature. It also had a flare-prone site consisting of a self-rotating sunspot (SP2) moving around a sunspot of opposite sign (SN2), leading to flux interaction. These motions are likely to form the sigmoidal structures, which are unstable, and more likely to produce eruptive events. A huge expulsion CME on 2011 February 14 at 17:30 UT occurred in the former site and a white light, energetic X2.2 flare on 2011 February 15 at 01:44 UT occurred in the latter site. The other case, AR NOAA 11166, was already in its active phase, with a further increase in the flux content as it evolved. Group motions of diffused fluxes merging to form a bigger sunspot manifested major shear motions in addition to outward flows from the sunspot. A large CME on 2011 March 9 at 21:45 UT; followed by an X1.5 flare, was one of the major events in this AR.

AR NOAA 11158 injected $14.16 \times 10^{42}$ Mx$^2$ while AR NOAA 11166 injected $9.5 \times 10^{42}$ Mx$^2$ of helicity during the six-day period of their evolution. These are consistent with the previously reported order of helicity accumulation (e.g., Park et al. 2010b). It appears that due to the presence of rotational motions, the former AR accumulated a larger amount of helicity, which accounts for its greater activity in the form of flares and CMEs. It is also evident that flux emergence is necessary and its motions are crucial in accounting for the accumulated amount of helicity to the emergence term. In both ARs, X-class flares with associated CMEs were observed in the decreasing phase of helicity accumulation caused by the injection of opposite helicity.

Apart from the instrumental and computational errors, the estimation of helicity injection rates is also affected by the choice of DAVE parameters used to track the motion of the fluxes. Helicity injection rates are found to decrease up to 13% by increasing the time interval between magnetograms from 12 to 36 minutes, whereas an increasing trend of up to 9% resulted by decreasing the window size from $21 \times 18$ to $9 \times 6 \text{pix}^2$, with a total variation of 10% in the deduced value of accumulated helicity.

The time profile of the helicity rate exhibited sudden sharp variations during some flare events due to the injection of opposite helicity flux into the existing system of helicity flux. In both ARs, the flare-prone regions (R2) had inhomogeneous helicity flux distribution with mixed helicities of both signs, and that of CME-prone regions had an almost homogeneous distribution of helicity flux dominated by single sign. A quantitative analysis was carried out to show the association of these variations with the timings of flares/CMEs. For AR 11158, we find a marginally significant association of helicity flux with CMEs but not flares, while for the AR 11166, we find a marginally significant association of helicity flux with flares but not CMEs. Moreover, these variations of helicity flux may not reflect true transfer; there exists flare-related transient effects and theoretical uncertainties resulting to these variations. We believe the helicity transfer in the cases of C7.0 at 13:47 UT on February 14 and of C4.2 at 13:19 UT, C4.7 at 13:42 UT on March 10 to be true, without the flare-related transient effect but with theoretical uncertainty in the approach.

Therefore, to further strengthen the above evidence of true helicity transfer, it would be worthwhile to scrutinize more flare/CME cases using three minute cadence magnetic observations, over a period of a day or so. This will enable one to find detectable changes in the helicity flux signal during smaller magnitude flares with fewer transient-flare effects. Interpreting the physical significance of such variations using the information of coronal connectivities will be another important aspect to add to the present knowledge of helicity physics. Our study reveals that the spatial information of helicity injection is a key factor to understand its role in flares/CMEs.

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REFERENCES

Abramenko, V. I., & Baranovsky, E. A. 2004, Sol. Phys., 220, 81
Ambastha, A., Hagyard, M. J., & West, E. A. 1993, Sol. Phys., 148, 277
Berger, M. A., & Field, G. B. 1984, J. Fluid Mech., 147, 133
Canfield, R. C., Hudson, H. S., & McKenzie, D. E. 1999, Geophys. Res. Lett., 26, 627
Chae, J. 2001, ApJ, 560, L95
Chae, J. 2007, Adv. Space Res., 39, 1700
Chae, J., Goode, P. R., Ahn, K., et al. 2010, ApJ, 713, L6
Chae, J., Moon, Y.-J., & Park, Y.-D. 2004, Sol. Phys., 223, 39
Chae, J., Wang, H., Qiu, J., et al. 2001, ApJ, 560, 476
Chandra, R., Pariat, E., Schmieder, B., Mandrini, C. H., & Uddin, W. 2010, Sol. Phys., 261, 127
Démoulin, P., & Berger, M. A. 2003, Sol. Phys., 215, 203
