Kinetic and magnetic helicities in solar active regions

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Abstract. We have studied the kinetic and magnetic helicities in sub-photospheric flows and photospheric magnetic fields, respectively, of a sample of 91 ARs of solar cycle 23. Hemispheric trend is investigated in the kinetic helicity of sub-photospheric flows averaged in the depth range of 2.5-12 Mms. Magnetic helicity parameters for the ARs are derived using photospheric vector magnetograms to examine their correlation with the corresponding kinetic helicities. We found no significant association between the two helicity parameters.

1. Introduction
Ordering of magnetic fields at various layers and scales in active regions (ARs) are observationally evident which may result from coherent patterns of surface flows [1], subphotospheric flows [2], and/or emergence of twisted sub-photospheric fluxes [3]. A photospheric manifestation of these patterns is the large-scale non-potential fields in flaring ARs. These non-potential fields are generally marked by twisted, or sheared, photospheric magnetic fields near flare sites [4].

In recent years, a topological property called magnetic helicity has been used to characterize the observed large-scale magnetic patterns which includes a subset of twisted or sheared fields, and also provides a measure of magnetic linking and kinking [5]. It is believed that the main source of the magnetic fields on the solar surface is a dynamo action [6] which sits somewhere either at the bottom of the convection zone or in a thin region called overshoot zone; a layer between the convection and radiation zones.

The necessary condition for the kinetic dynamo action is that the underlying velocity field \( \mathbf{u} \) lacks reflection symmetry, i.e., it has handedness [7, 8]. One of the natural measures of the lack of the reflection symmetry is the kinetic helicity \( H_k \), representing the extent to a corkscrew-like motion. If a parcel of fluid is moving and rotating about an axis parallel to the direction of motion, it will have positive helicity. The existence of kinetic helicity has been observed in several physical and astrophysical systems, often a consequence of differential rotation. Therefore, kinetic helicity provides an important mechanism for the production of large scale hydrodynamic and magnetic structures.

The main source of magnetic helicity observed on the Sun is assumed to be the kinetic helicity of turbulent flows in the convection zone [9]. It twists the rising flux tube [2] and the observed photospheric magnetic fields. The other possibility of twists is the dynamo action [10]. Magnetic helicity of solar ARs shows a hemispheric trend; it is positive (negative) in the southern (northern) hemisphere. This phenomenon is called the “hemispheric sign rule (HSR)” of helicity. Photospheric vector magnetic fields of ARs reveal that on an average solar ARs have a small but
statistically significant mean twist in magnetic helicity \([2, 11]\) that is left-handed (right-handed) in the northern (southern) hemisphere. However, some theoretical \([12]\) and observational \([13]\) analyses show opposite hemispheric trends during the beginning of a cycle.

Kinetic helicity measurement in the solar convection zone may provide a direct inference of \(\alpha\)-effect. Its measurement in the interior of solar ARs has become possible after the advent of local helioseismology, albeit only to a limited depth of a few Mms. Therefore, as to what extent the kinetic helicity measurements would explain the \(\alpha\)-effect is somewhat uncertain. The hemispheric trend of kinetic helicity has been studied by several workers \([14–19]\). However, the relation between \(H_k\) of the underlying flows and \(H_m\) of external magnetic fields in ARs is, in general, still not well understood.

In this paper, we report on the statistics of the hemispheric trend of kinetic and magnetic helicities and their association. In Section 2, we describe the methodology to determine these helicity parameters. Section 3 describes the observational data and the method of analysis. Results and conclusions of our analysis are given in Sections 4 - 5.

2. The Basic Formalism
Magnetic helicity is a global quantity. But one cannot observe a full flux system volume because an AR is extended both below and above the visible surface. Therefore, information of the twist in magnetic fields is derived from the force-free parameter \(\alpha\), used as a measure of magnetic helicity. For a linear force-free field, it is given by (cf., \([9]\)),

\[
\alpha_z = \frac{\langle \nabla \times B \rangle_z}{B_z} = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \frac{1}{B_z} \tag{1}
\]

While calculating the values of \(\alpha_z\) in an AR, we selected only those pixels where the values are above the accuracy of measurements. Further, to get the imbalance of twist (right/left handedness) in an AR, we took the average (\(\alpha_{z,av}\)) over the entire region. Similarly, for calculating the kinetic helicity of an AR, we have considered only the vertical component of kinetic helicity density \([20]\), which is given by

\[
h_k^z = \left( \frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y} \right) u_z \tag{2}
\]

3. The Observational Data and Analysis
We obtained the photospheric vector magnetograms from MSFC and Hinode/SOT, while, Doppler observations were taken from GONG for 91 ARs having good data sets. For selecting these ARs for our analysis, we used the following procedure: First, we selected ARs observed from July 2001 to August 2007 lying within the central longitude and latitude range of \((-40, 40)\). Then we shortlisted the ARs depending upon their areas and the availability of required data.

The magnetic field components corresponding to the Hinode observations were derived from the Stokes’ profiles using Unno-Rachkowsky \([21, 22]\) inversion code provided in SolarSoft. We resolved the usual 180° ambiguity in the transverse components of all vector magnetograms using the acute angle method. Further, to avoid any projection effects, we transformed the maps to the disc center \([23]\).

All three components \((u_x, u_y\) and \(u_z)\) of the velocity vector \((u)\) are required to determine the parameter \(h_k^z\) of an AR with depth (see Eqn.2). We derived the horizontal components \((u_x, u_y)\) using inversion \([24]\) of p-mode parameters obtained from ring-diagrams of 128×128×1664 data cubes \([25]\). The vertical component \((u_z)\) was derived from the divergence of horizontal components, assuming mass conservation \([20, 26]\). This gives the average flow in an AR with a
horizontal spatial resolution of $16^\circ$ while the vertical resolution varies from 0.1 to 0.2 Mm with depth in the depth range of 0.0 – 14.0 Mm.

Previous studies have revealed the presence of bipolar structure in sub-photospheric flows of several ARs [27–30]. This implies that there are two different types of twists in their underlying flows. To deal with this issue, we have computed vertical kinetic helicity densities $(h_{k1})_{av}$ and $(h_{k2})_{av}$ averaged over the two depth ranges corresponding to the bipolar flow structures, viz., 0.0-2.5 and 2.5-12 Mm, respectively.

4. Results and Discussions

Results of our analysis of the 91 selected ARs are shown in Figures 1 - 3.

![Figure 1](image.png)

**Figure 1.** Latitudinal distribution of the force-free parameter $\alpha_{av}$. The solid line represents a straight line fit through the data points while the dashed curves correspond to 95% confidence intervals.

**4.1. Latitudinal Distribution of Magnetic Helicity**

Figure 1 shows the latitudinal distribution of magnetic helicity parameter $\alpha_{av}$ obtained for our sample of ARs. We found 66% (63%) ARs located in the northern (southern) hemisphere with negative (positive) $\alpha_{av}$, in agreement with previous reports [2, 11, 18]. The data points, however, show a large scatter in both the hemispheres raising the following questions: Is the hemispheric sign statistically significant? Do the $\alpha_{av}$ values have any relation with latitude? To address these questions, we fitted a straight line through the measured data points using a linear regression model (the solid line in Figure 1). Slope of the fitted line implies that the magnitude of $\alpha_{av}$ increases with latitude. However, this inference is not fully satisfactory because there is no known reason for a straight line to be the appropriate fit. But at the same time, one can not justify higher order polynomial fits. We calculated the average $\alpha_{av}$ to evaluate statistical significance of the hemispheric trend. These are found to be $-1.39 \times 10^{-8}$ ($+3.05 \times 10^{-9}$) m$^{-1}$ for the northern (southern) hemispheres, confirming the hemispheric trend of the estimated $\alpha_{av}$ values for the ARs.
4.2. Latitudinal Distribution of Kinetic Helicity

Figure 2 shows the latitudinal distribution of the vertical component of kinetic helicity densities \((h_z^2)_{av}\) and \((h_z^k)_{av}\) averaged over depth ranges 0.0-2.5 Mm (left panel) and 2.5-12 Mm (right panel), respectively. There is no obvious hemispheric preference observed for \((h_z^2)_{av}\) as there are 47% (53%) ARs in the northern (southern) hemisphere having negative (positive) values. But \((h_z^k)_{av}\) shows a significant trend of HSR as 69% (56%) ARs in the northern (southern) hemisphere show negative (positive) helicity. The average value of \((h_z^2)_{av}\) for northern (southern) hemisphere is found to be \(+1.88 \times 10^{-9} (-7.62 \times 10^{-9})\) m s\(^{-2}\). This confirms the opposite hemispheric trend for \((h_z^2)_{av}\). The average value of \((h_z^k)_{av}\) for northern (southern) hemisphere is \(-7.0 \times 10^{-8} (+1.7 \times 10^{-8})\) m s\(^{-2}\), which further confirms the HSR for \((h_z^k)_{av}\).

4.3. Relation between the Kinetic and Magnetic Helicities

As mentioned in Section 1, magnetic field lines are rooted beneath the photosphere where they interact with the sub-photospheric flows. Therefore, one may expect the twists of magnetic and velocity fields to have some association. To examine this possibility, we plotted the force-free parameter \(\alpha_{av}^z\) against the sub-photosphere twist parameters, \((h_z^2)_{av}\), as shown in Figure 3. Further, to get a quantitative measure of their relationship, we computed the Pearson correlation coefficients \(r\) among these parameters.

Figure 3 shows that there is no significant correlation between the force-free parameter \(\alpha_{av}^z\) and the twist of sub-photospheric flows. The correlation parameter suggests that \(\alpha_{av}^z\) is anti-correlated \((r \approx -0.03\) and \(-0.07)\) with \((\omega_z^2)_{av}\) and, \((h_z^2)_{av}\) and mildly correlated \((r \approx +0.11\) and \(+0.23)\) with \((\omega_z^1)_{av}\) and \((h_z^k)_{av}\).

5. Summary and Conclusions

From our study of the twists in photospheric magnetic and sub-photospheric velocity fields of 91 ARs selected in the period of July 2001-August 2007, we derive the following conclusions:
Figure 3. Association of magnetic helicity parameter $\alpha_{av}$ with the twist parameters of sub-photospheric flows for the sample of 91 ARs.

- Magnetic helicity parameter $\alpha_{av}$ shows a significant hemispheric trend, in agreement with previous reports.
- No clear hemispheric trend is observed for average vertical kinetic helicity in the depth range 0.0-2.5 Mm while a strong hemispheric trend is discernible in the depth range 2.5-12 Mm.
- No unambiguous association is found between the twists of surface magnetic fields and sub-surface flows.

In summary, statistically significant and unambiguous association is not found between the topology of photospheric magnetic field and the sub-photospheric flows. Our analysis further supports the results from a recent study by Gao et al. [18]. It should be noted that there are some factors which may have affected these results. We have used only a single vector magnetogram map corresponding to an AR to derive the photospheric twist, while, the twist in sub-photospheric flow is derived using 1664 minutes’ data cubes. Also, the magnetic and Doppler field observations were obtained from different instruments. The results are expected to improve with the recent availability of higher resolution observations from space borne instruments, such as, the Solar Dynamics Observatory (SDO).

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