Kinetic helicity of subsurface flows and magnetic flux

Rudolf Komm, Frank Hill and Rachel Howe
National Solar Observatory, Tucson, AZ 85719, USA
E-mail: komm@nso.edu

Abstract. We study the relation between the vorticity of solar subsurface flows and surface magnetic activity, analyzing more than five years of GONG+ data with ring-diagram analysis. We focus on the enstrophy, defined as the square of vorticity, and the kinetic helicity density, defined as the scalar product of velocity and vorticity, and derive them from the surface to a depth of about 16 Mm. We find that enstrophy and helicity density of subsurface flows are rather constant at low flux values (less than about 10 G), while at higher flux values there is a linear relation between flux and the logarithm of enstrophy or unsigned helicity. In addition, we analyze the temporal variation of thirteen emerging active regions. At the locations of these active regions, there is little enstrophy or helicity before the regions emerge, while after flux emergence the vorticity and helicity values are large. The crosscorrelation in time between flux and enstrophy shows that they are correlated and that shallow layers lag behind deeper layers. This signal might be a hint of the emergence of active regions.

1. Introduction
Previous studies show that solar subsurface flows associated with active regions are highly twisted. At locations of high magnetic flux, subsurface flows show large values of vorticity and kinetic helicity density. For example, locations of high magnetic flux show excess cyclonic (clockwise in the northern hemisphere) vorticity [1, 2, 3, 4, 5], which might be due to the Coriolis force acting on the flows. The twist of subsurface flows, as measured by vorticity and helicity, also seems to play a role in the dynamic behavior of active regions. For example, the maximum vorticity of subsurface flows is related to the total flare intensity of active regions [6]. However, the temporal evolution of the twist of subsurface flows and its relation to flare activity is less well studied and these studies are usually limited to a handful of active regions [7, 8].

The aim of this study is to establish the average vorticity and helicity of the quiet Sun and the variation of these quantities with magnetic flux in order to establish a baseline to compare with any temporal variation. For this purpose, we measure subsurface flows analyzing more than five years of Global Oscillation Network Group (GONG) high-resolution data with the dense-pack ring-diagram technique. We then calculate the vorticity of the measured flows from the surface to a depth of about 16 Mm.

In addition, we focus on the temporal variation of the vorticity of subsurface flows and its correlation with magnetic flux and flare activity of active regions. Here, we study thirteen active regions that emerge near the center of the solar disk. The presented results are preliminary in the sense that we have an order of magnitude more active regions in the data to analyze.
Figure 1. Enstrophy at a depth of 8.5 Mm as a function of unsigned magnetic flux, shown as a log-lin plot (top) and a log-log plot (bottom). The data, binned into 200 equally sized subsets, are included for the northern (+, blue) and the southern hemisphere (×, red).

Figure 2. The average enstrophy of quiet regions (top) and the slope of a linear regression between unsigned flux and the logarithm of the enstrophy (bottom) are shown as functions of depth for the northern (⊡, - - - -) and the southern hemisphere (×, · · · · · ·).

2. Data and analysis
We analyze observations obtained during 72 consecutive Carrington Rotations CR 1979–2050 (July 27, 2001 – Dec 11, 2006) for which we have high-resolution full-disk Doppler data from the GONG+ network. We determine the horizontal components of solar subsurface flows with a ring-diagram analysis using the same technique as described by [9] for the dense-pack analysis of Michelson Doppler Imager (MDI) Dynamics Program data. The dense-pack analysis has been implemented as the GONG ring-diagram pipeline [10, 11]. Horizontal velocities, as a function of depth, are derived from the GONG+ data with the regularized least-squares (RLS) inversion technique [12, 9].

The full-disk Doppler images are divided into 189 overlapping regions with centers spaced by 7.5° ranging from ±52.5° in latitude and central meridian distance (CMD). Each region is apodized with a circular function reducing the effective diameter to 15° before calculating three-dimensional power spectra. The data are analyzed in “days” of 1664 minutes corresponding to a shift of 15°25 in Carrington longitude between consecutive days. For each dense-pack day, we derive maps of horizontal velocities at 189 locations in latitude and CMD for 16 depths from 0.6 to 16 Mm. To focus on the variation of the flows, we remove low-order polynomial fits of the average rotation and meridional flow from each synoptic flow map and calculate residual maps of the horizontal flows. From the divergence of the horizontal flows, we estimate the vertical velocity component assuming mass conservation [4].
We then calculate the vorticity vector, $\omega$, defined as the curl of the velocity, $v$:

$$\omega = \nabla \times v$$  \hspace{1cm} (1)$$

and derive two scalar quantities, the enstrophy, defined as the square of vorticity, and the kinetic helicity density, the scalar product of velocity and vorticity vector, for details see [13]. We limit the results, presented here, to a range of $\pm 30^\circ$ in latitude.

As a measure of solar activity, we use the NSO Kitt Peak synoptic charts\(^1\) and the NSO SOLIS synoptic maps\(^2\). We convert the synoptic magnetogram data to absolute values and bin them into circular areas with $15^\circ$ diameter centered on a grid with $7.5^\circ$ spacing in latitude and longitude to match the dense-pack mosaic. For the temporal variation of solar activity, we use MDI magnetograms\(^3\) averaged over 96 minutes. We convert the MDI magnetogram data to absolute values and bin them to match the dense-pack mosaic in grid and scale size and average them in time to match the length of a dense-pack day.

We study the temporal evolution of the subsurface vorticity of thirteen active regions that emerge near disk center, used in a previous study [14]. To find the corresponding dense-pack patches for these active regions, we identify them using the NOAA active region numbers listed in the Active Region Monitor (ARM) at NASA Goddard Space Flight Center’s Solar Data Analysis Center (SDAC)\(^4\) and locate the closest point on the dense-pack grid to the location of maximum unsigned flux.

Each dense-pack patch of a daily flow map can be identified by either CMD and latitude or Carrington longitude and latitude. The Carrington longitude identifies the unique location of an active region on the solar surface, while the CMD tracks its disk passage. A location identified by Carrington longitude corresponds to a dense-pack patch that rotates $15^\circ$ CMD between daily flow maps. The disk passage of a particular location in latitude and Carrington longitude then takes seven dense-pack days ranging from $-45^\circ$ to $+45^\circ$ CMD when its Carrington longitude is divisible by 15, while it takes eight dense-pack days from $-52.5^\circ$ to $+52.5^\circ$ CMD at intermediate positions.

\(^1\) available at http://nsokp.nso.edu/dataarch.html
\(^2\) available at http://solis.nso.edu/solis_data.html
\(^3\) available at http://soi.stanford.edu/magnetic/index5.html
\(^4\) available at http://www.solarmonitor.org
In this way, we estimate the temporal variation of the absolute magnetic flux and that of the subsurface flow parameters for thirteen active regions (AR 9574, 9800, 9912, 10050, 10119, 10226, 10314, 10319, 10323, 10365, 10488, 10493, and 10564).

3. Results

Figure 1 shows the enstrophy at a depth of 8.5 Mm as a function of unsigned magnetic flux derived from 72 Carrington rotations within ±30° latitude. Despite the large scatter, there is clearly a linear relation between the unsigned magnetic flux and the logarithm of enstrophy at high flux values (top), while the enstrophy is more or less constant at low flux values (bottom). Both hemispheres lead to similar results as indicated by the binned values.

The enstrophy values show a similar variation with flux at all depths with the enstrophy being rather constant at low activity and showing a linear relation at high activity. Figure 2 shows the average enstrophy of quiet regions (top), defined as locations with flux values less than 8.6 G, as a function of depth. The enstrophy at low flux levels decreases by about an order of magnitude within the first 2 Mm and remains rather constant at greater depth with a minimum near 10 Mm. Both hemispheres lead to the same depth dependence within the error bars. The bottom panel shows the slope of a linear regression between unsigned magnetic flux and the logarithm of enstrophy at high flux values (greater than 8.6 G). The threshold of 8.6 G has been chosen to ensure a continuous transition between the two fitting regimes. The largest slopes occur at depths between about 8 and 10 Mm. The variation between about 2 and 6 Mm with two local minima and a maximum reflect the sign reversal observed in vorticity (or helicity) at these depths [13]. Both hemispheres lead to the same depth dependence except near 3 Mm where the slope is somewhat greater in the northern hemisphere than in the southern one.

The kinetic helicity density shows essentially the same behavior with magnetic activity as the enstrophy. The key difference is that since helicity is a signed quantity, a scatter plot of helicity as a function of flux, similar to Figure 1, would show large positive as well as large negative values at high flux levels. At low flux values, the helicity values are close to zero. The absolute value of helicity shows the same depth dependence as in Figure 2.

To check the variation with latitude, we average the kinetic helicity density in longitude and divide the data into subsets depending on magnetic activity. We define a quiet subset as the locations with flux values less than 5 G and an active subset with flux values between 50 and 100 G. This choice leads to an average flux for each subset that is more or less constant with latitude, as seen in Figure 3. In this way, we can separate latitudinal variation from variation with magnetic flux. The largest flux values occur at 15° latitude in either hemisphere. Figure 4 shows the vertical contribution to the kinetic helicity density, the product of the vertical velocity and vorticity components. For the quiet and the active subset, the vertical contribution to helicity
is positive in the southern hemisphere and negative in the northern one, with few exceptions. The values of the active subset are generally larger than the values of the quiet subset. The two horizontal contributions to the kinetic helicity density show a rather weak variation with latitude.

We now focus on the temporal variation of subsurface enstrophy and kinetic helicity density associated with the locations of thirteen active regions. Figure 5 shows an example of the variation of the enstrophy at 8.5 Mm and the corresponding surface flux during the disk passage of AR 10488. The active region emerges near disk center and remains strong at the end of its disk passage, which is typical for all regions used in this study. The enstrophy of the associated subsurface flows increases with time and thus with increasing magnetic flux.

Figure 6 shows the average enstrophy values corresponding to the dates before (top) and after flux emergence (2nd) of the thirteen active regions as a function of magnetic flux averaged over the same time period. The enstrophy values have been averaged over a range in depth from 8.5 to 13.1 Mm. Before flux emergence when magnetic activity is low, the average enstrophy is very small, while after flux emergence when the activity is high, the average enstrophy is quite large. As a consequence, there is a large increase in enstrophy with time (bottom).

Figure 7 shows the same as Figure 6 for kinetic helicity density averaged over the same depth range of 8.5 to 13.1 Mm.

Figure 8 shows the same as Figure 7 for kinetic helicity density averaged over 2.0 to 5.8 Mm in depth.
depth range. As in the case of enstrophy, the helicity values are close to zero before magnetic flux emerges and large after flux emergence. This leads to a large increase in positive helicity with time. When averaging the kinetic helicity density over 2.0 to 5.8 Mm in depth, the values are again close to zero before emergence, but they are mainly negative after flux emergence, as shown in Figure 8. This sign change is not surprising, since the helicity has the opposite sign at these shallow depths compared to deeper layers [13].

To see whether the increase in enstrophy coincides with the emergence of flux, we calculate the crosscorrelation between the temporal variation of surface flux and subsurface enstrophy averaged over some depth range. Figure 9 shows the average crosscorrelation averaged over thirteen emerging active regions as a function of time lag. When the enstrophy is averaged over deeper layers (——), the crosscorrelation peaks at zero lag. The crosscorrelation is not symmetric in time; the values are higher at positive lag compared to the corresponding negative lag. When the enstrophy is averaged over shallower layers (- - - -), the crosscorrelation peaks at a positive lag of one day; the enstrophy in shallow layers lags behind the enstrophy in deeper layers. This might be an indication of the emerging magnetic flux.

Figure 9. Crosscorrelation of unsigned surface flux and enstrophy averaged over 8.5 to 13.1 Mm (——) and 2.0 to 5.8 Mm (- - - -) averaged over 13 active regions. The autocorrelation of the flux is included for comparison (·······). The lag is in ring days of 1664 minutes.

4. Summary and conclusions
In this preliminary work, we study the relation between the vorticity of subsurface flows and surface magnetic activity, analyzing more than five years of GONG+ data. We study two scalar quantities derived from the vorticity of subsurface flows, the enstrophy and the kinetic helicity density. These quantities are rather constant at low flux values (less than about 10 G), while they show a linear relation between flux and the logarithm of enstrophy or the logarithm of unsigned helicity at high flux values. The regression slope is largest near 10 Mm; the twist of subsurface flows at these depths correlates best with surface magnetic activity. For low activity levels, the largest enstrophy values occur close to the surface. The enstrophy decreases by an order of magnitude within the first 2 Mm which might reflect the boundary layer between the turbulent convection zone and the solar atmosphere.

The vertical contribution to the kinetic helicity density, the product of vertical velocity and vorticity, changes sign at the equator. This North-South asymmetry agrees with previous results [15] and is expected from numerical simulations [16, 17]. The two horizontal contributions to helicity do not show such a hemispheric dependence and since they are larger than the vertical contribution, the kinetic helicity density does not show any hemispheric asymmetry either. The large horizontal size of the dense-pack patches might be responsible for the difference in size between the horizontal and vertical contributions to helicity.

The temporal variations of enstrophy and kinetic helicity density correlate with the temporal variation of surface magnetic flux. The analysis of thirteen emerging active regions shows little
enstrophy or helicity before the regions emerge and large values after flux emergence. The crosscorrelation in time between flux and enstrophy shows that shallow layers lag behind deeper layers. This might be a hint of the emergence of active regions in the vorticity signal. However, the analyzed sample of active regions is quite small. More active regions need to be studied and we will have to customize the ring analysis to better suit it to such a task. An improvement in the temporal variation will be crucial to answer the question whether the observable kinetic helicity of subsurface flows can be used as a proxy for the magnetic helicity of fluxtubes below the surface.

Acknowledgments
This work utilizes data obtained by the Global Oscillation Network Group (GONG) program, managed by the National Solar Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofísica de Canarias, and Cerro Tololo Interamerican Observatory. NSO/Kitt Peak data used here are produced cooperatively by NSF/NSO, NASA/GSFC, and NOAA/SEC. SOLIS VSM data used here are produced cooperatively by NSF/NSO and NASA/GSFC. SOHO is a mission of international cooperation between ESA and NASA. This work was supported by NASA grant NNG 05HL41 to the National Solar Observatory.

References
[1] Duvall, T L, Jr and Gizon, L 2000 Solar Phys. 192 177
[2] Gizon, L and Duvall, T L, Jr 2003 Local and Global Helioseismology: The Present and Future ed H Sawaya-Lacoste (ESA SP-517: Noordwijk: ESA) p 43
[3] Braun, D C, Birch, A C and Lindsey, C 2004 Helio- and Asteroseismology: Towards a golden future ed Danesy, D (ESA SP-559; Noordwijk: ESA) p 337
[4] Komm, R W, Corbard, T, Durney, B R, González Hernández, I, Hill, F, Howe, R and Toner, C 2004 Astrophys. J. 605 554
[5] Zhao, J and Kosovichev, A G 2004 Astrophys. J. 603 776
[6] Mason, D, Komm, R, Hill, F, Howe, R, Haber, D and Hindman, B 2006 Astrophys. J. 645 1543
[7] Zhao, J and Kosovichev, A G 2003 Astrophys. J. 591 446
[8] Komm, R W, Howe, R, González Hernández, I, Hill, F, Sudol, J and Toner, C 2004 SOHO 14 – GONG 2004, Helio- and Asteroseismology: Towards a golden future ed D Danesy (ESA SP-559; Noordwijk: ESA) p 158
[9] Haber D A, Hindman, B W, Toomre, J, Bogart, R S, Larsen, R M and Hill, F 2002 Astrophys. J. 570 885
[10] Corbard, T, Toner, C, Hill, F, Hanna, K D, Haber, D A, Hindman, B W and Bogart, R S 2003 Local and Global Helioseismology: The Present and Future ed H Sawaya-Lacoste (ESA SP-517: Noordwijk: ESA) p 255
[11] Hill, F, Bolding, J, Toner, C, Corbard, T, Wampler, S, Goodrich, B, Goodrich, J, Eliasen, P and Hanna, K D 2003 Local and Global Helioseismology: The Present and Future ed H Sawaya-Lacoste (ESA SP-517: Noordwijk: ESA) p 295
[12] Thompson, M J, et al. 1996 Science 272 1300
[13] Komm, R 2007 Astron. Nachr. 328 269
[14] Komm, R, Morita, S, Howe, R and Hill, F 2008 Astrophys. J. 673 (in press)
[15] Komm, R, Howe, R, Hill, F, Miesch, M, Haber, D and Hindman, B 2007 Astrophys. J. 667 584
[16] Brun, A S, Miesch, M S and Toomre, J 2004 Astrophys. J. 614 1073
[17] Egorov, P, Rüdiger, G and Ziegler, U 2004 Astron. Astrophys. 425 725