Are subsurface flows and coronal holes related?

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Abstract. We study synoptic maps of solar subsurface flows covering six Carrington rotations (2050 to 2055). The subsurface flows are determined with a ring-diagram analysis of GONG high-resolution Doppler data. We identify the locations of coronal holes in synoptic maps of EUV images at 195 Å from the EIT instrument and determine the characteristics of associated subsurface flows. We study two long-lived coronal holes that are present during this epoch. We find that large-scale patterns are present in the subsurface flows but appear to be unrelated to these coronal holes. The horizontal subsurface flows associated with the two long-lived coronal holes are weakly divergent (upflows) with small cyclonic vorticity. These flows are thus similar to subsurface flows of quiet regions with regard to the vertical flows and similar to flows of active regions with regard to vorticity.

1. Introduction

We study solar subsurface flows measured with a ring-diagram analysis of high-resolution Doppler data obtained by Global Oscillation Network Group (GONG) instruments. In previous studies, we have focused on the relationship between active regions and subsurface flows associated with them [1, 2]. Here, we explore whether there is a relationship between subsurface flows and coronal features. Synoptic subsurface flow maps show large-scale patterns that are not obviously associated with active regions. It is unknown whether these flow patterns correlate with any large-scale magnetic features. We also want to determine whether subsurface flows associated with coronal holes are different from subsurface flows of active or quiet regions.

We analyze synoptic maps of subsurface flows covering six Carrington rotations during the years 2006 and 2007. Long-lived coronal holes are present during this epoch at latitudes that are accessible by ring-diagram analysis of GONG data. To compare the subsurface flows with coronal images, we use synoptic observations in the EUV from the EUV Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SOHO) spacecraft.

2. Data and analysis

We analyze observations obtained during Carrington Rotations 2050 – 2055 (14 November 2006 – 27 April 2007). To derive solar subsurface flows, we use high-resolution full-disk Doppler data from the GONG network (http://gong.nso.edu/data). We determine the horizontal components of subsurface flows with a ring-diagram analysis using the dense-pack technique.
Figure 1. Top: The subsurface flows at a depth of 2 Mm (arrows) averaged over Carrington rotation 2050 – 2055 are superposed on the corresponding average EIT map (log-scale). Middle: The flows at 2 Mm and the corresponding photospheric magnetogram. Bottom: The subsurface flows at 7 Mm are superposed on the magnetogram.

[3] adapted to GONG data [4]. The full-disk Doppler images are divided into 189 overlapping regions with centers spaced by 7.5° ranging over ±52.5° in latitude and central meridian distance.
Figure 2. The unsigned magnetic activity (top), the vertical velocity (middle), and the vertical vorticity (bottom) averaged over Carrington rotation 2050–2055 as a function of latitude and depth at 105° (left) and 270° longitude (right). Positive vertical-velocity values imply upflows, negative values imply downflows. The coronal holes are centered at $-22.5^\circ$ (left) and $-30^\circ$ latitude (right), as seen in Figure 1.

Each region is tracked for 1664 minutes and a three-dimensional power spectrum is calculated for each tracked region. Horizontal flows advect the acoustic modes and shift their temporal frequency, which appears as a shift of the rings in spatial frequency. The shift of these rings in spatial frequency is a measure of the subsurface flows. We derive daily flow maps of horizontal velocities from the 189 dense-pack patches and combine them to form synoptic flow maps at 16 depths from 0.6 to 16 Mm. To remove the large-scale trends in latitude of the differential rotation and the meridional flow, we subtract a low-order polynomial fit in latitude of the longitudinal average of the flows for each Carrington rotation and study the resulting residual synoptic flow maps [1, 2]. We estimate the vertical-velocity component from the divergence of horizontal flows using mass conservation [1, 5] and also calculate maps of the vertical component of the vorticity vector (curl of the horizontal velocities).

To compare synoptic subsurface flow maps with observations of the solar corona, we use synoptic observations in the EUV at 195Å from the EIT instrument onboard the SOHO spacecraft (http://sun.stanford.edu/synop/EIT/). The synoptic maps of EUV images represent the values of the line intensity centered on the central meridian and they have a resolution of 1° in both longitude and latitude [6]. As a measure of photospheric magnetic activity, we use NSO SOLIS magnetograms (http://solis.nso.edu/solis_data.html).

3. Results

We average the synoptic flow maps of the six Carrington rotations to improve the signal-to-noise ratio and to study long-lived structures (Figure 1). Two long-lived coronal holes are present in the southern hemisphere near 105° and 270° longitude. The subsurface residual flows are large
and complicated near active regions but small and simple near coronal holes. Small subsurface residual flows is a characteristic that coronal holes have in common with quiet regions. Large-scale flow patterns are present near 180° to 210°, for example. These large-scale flows are present to varying degree in the six synoptic flow maps and do not seem to be associated with coronal holes or active regions.

We also derive the vertical velocity and vorticity averaged over the six rotations (Figure 2). The large values at high latitudes are unreliable [1, 5]. At the locations of the coronal holes near −22.5° latitude and 105° longitude (left) and −30° latitude and 270° longitude (right), the average vertical velocity shows weak upflows and the vertical vorticity is small and mainly negative (cyclonic or clockwise in the southern hemisphere). The signal-to-error ratio is greater than three at shallow depths less than about 6 Mm and smaller at greater depths. The long-lived active region near 30° shows downflows and mainly negative vorticity values (not shown).

4. Summary and conclusions

Large-scale flow patterns are present in the average synoptic flow maps. They are unrelated to coronal holes or active regions; they seem to almost avoid or separate regions of magnetic activity. The horizontal subsurface flows associated with the two long-lived coronal holes are weakly divergent (upflows) with small cyclonic vorticity. Quiet regions are characterized by weakly divergent subsurface flows with small anticyclonic vorticity, while active regions are characterized by convergent subsurface flows with cyclonic vorticity [7]. The sign of subsurface-flow vorticity thus distinguishes these coronal holes from quiet regions, while the sign of the vertical-flow component distinguishes them from active regions.

These are encouraging results. However, we have studied only two long-lived coronal holes so far. We clearly need to analyze a larger data set. For this purpose, we plan to analyze synoptic maps of GONG and EIT data covering Carrington rotation 1979 to 2118 and characterize each dense-pack patch by their dominant magnetic feature.

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