A search for coherent structures in subsurface flows

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Abstract. We search for coherent patterns in horizontal subsurface flows obtained from Global Oscillation Network Group (GONG) Dopplergram data using ring-diagram analysis. The existence of north-south aligned downflow patterns near the equator has been predicted by numerical models of the solar convection zone. We analyze time series of daily flow measurements near the solar equator focusing on the vertical velocity component and the derivative of the zonal flow in the east-west direction. To reduce the influence of surface magnetic activity, we analyze observations during the minimum phase of the solar cycle. We find coherent equatorial structures that persist for several days in the zonal velocity derivative and the vertical velocity component and are not associated with surface magnetic activity. We use a cross-correlation analysis to measure the strength and rotation rate of these coherent patterns. Our results are consistent with other studies that have observed north-south aligned patterns in supergranulation.

1. Introduction

Global numerical models of the solar convection zone show coherent downflow patterns aligned in the north-south direction in the equatorial region [1, 2]. Such downflow lanes, associated with giant cells, represent the largest and longest lived features of the convection zone in these models. These patterns are detectable in the radial velocity, but they are most noticeable in the derivative of the zonal flow in the east-west direction [2]. While the north-south aligned patterns might be obscured near the surface by granular and supergranular motions, they should be observable with local helioseismic techniques in deeper layers.

We search for such patterns in horizontal subsurface flows obtained from Global Oscillation Network Group (GONG) Dopplergram data using ring-diagram analysis. To reduce the influence of magnetic features, we study subsurface flows during the recent solar cycle minimum. Since the resolution of the standard ring-diagram analysis is comparable to the size of active regions and thus much larger than the narrow downflow lanes, we cannot resolve these lanes directly. Instead we look for persistent patterns near the equator that rotate across the solar disk.

2. Data and Analysis

We determine the horizontal components of solar subsurface flows with a ring-diagram analysis using the dense-pack technique [3]. 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 ring-diagram “days” of 1664 minutes. Each of these regions is tracked throughout the sequence of images.
using the appropriate surface rate. 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.

We calculate daily flow maps from GONG Dopplergram data for a period with minimum solar magnetic activity (Carrington rotation 2071–2079; 2008 June 9–2009 Feb. 9) that includes the recent solar cycle minimum. For each daily flow map, we calculate the vertical velocity component using mass conservation [4] and the derivative of the zonal flow in the east-west direction or zonal velocity derivative for short. Then, we extract an equatorial strip from each daily flow map by averaging over all values centered within ±22.5° latitude. We limit this strip to ±45° CMD to avoid artifacts due to the increased errors near the limb. Large-scale trends with CMD have been subtracted [5]. To increase the signal-to-noise ratio, we average in depth and calculate the values for three depth ranges. Even though we study the epoch of the extended solar minimum, active regions or remnants of regions are occasionally present, as shown in Figure 1.

Figure 1. MDI magnetograms of two days during Carrington rotation 2071 showing active region 10999 on 2008 June 21 (left) and no obvious magnetic activity on 2008 June 26 (right).

3. Results
Figure 2 shows, as example, the unsigned magnetic flux averaged over equatorial strips as a function of CMD for all 1664-minute days of Carrington rotation 2071. Except for two small active regions, the unsigned flux is rather flat during most days. The disk passage of these two regions is visible in the zonal velocity derivative as a series of troughs moving across the disk, which implies converging flows or downflows, as expected for active regions. The most obvious pattern that is not related to an active region rotates across the disk from day 13 to 17 crossing disk center on day 15 which is 26 June 2008 (see Figure 1). The corresponding unsigned magnetic flux shows only a slight bump that is small compared to the flux values of the two regions. The flow pattern is noticeable at all depth ranges and is clearly stronger than expected from the unsigned flux variation.

Figure 3 shows the same as Figure 2 for the nine rotations analyzed in this study. Even during this epoch of minimum activity, there are many remnants of activity that rotate across the solar disk. The zonal velocity derivative shows patterns related to magnetic activity but also others that rotate across the disk without a corresponding pattern in the unsigned flux.

To quantify the strength of these features and to determine their rotation rate, we correlate the time series of the central meridian (0° CMD) with the time series at other CMD locations. Figure 4 shows a strong correlation signal in the unsigned flux from −45° CMD and a lag of −3 days to +45° CMD and a lag of +3 days. These locations of strong correlation align with the
average rotation rate of 15 degree CMD per ring-diagram day, which corresponds to a rotation rate of 27.7 days. The zonal velocity derivative shows a similar but weaker pattern. To reduce the influence of magnetic activity, we eliminate 25% of all data points with the highest magnetic activity values. The corresponding correlation signal is greatly reduced for the unsigned flux but only slightly reduced for the zonal velocity derivative. For comparison, we include the correlation of the corresponding error of the zonal velocity derivative. The error is expected to track the presence of magnetic activity and indeed shows a greatly reduced correlation signal when locations with the highest activity level are excluded.

Figure 5 shows the cross-correlation values at 15°-CMD intervals from −30° to +30° CMD as a function of lag time for the three depth ranges. The locations of relative high activity have been excluded from the analysis. The corresponding correlation maxima are shifting from near −2 to +2 days in lag time tracking the average rotation rate. This rotation-rate pattern is noticeable at all three depths and in both flow parameters. For the ±15°-CMD correlations,
the peak values at ±1 days are greatest in the near-surface layer and smallest in the deeper layer. The correlation values of the vertical velocity measurements are slightly smaller than the values of the zonal velocity derivative. The largest difference in amplitude between the two flow parameters occurs for the ±30°-CMD correlations with maxima at ±2 days.

We have repeated the analysis after randomizing the time series. The correlation values of the randomized data sets are much smaller than the correlation values of the original data. In addition, their maxima are not organized in a sequence from −2 to +2 days lag time as is the case for the original data.

4. Discussion
We find equatorial structures that persist for several days in the values of the zonal velocity derivative and the vertical velocity component. We are not aware of any artifact that might introduce such a coherent pattern and it seems unlikely that they are just a random phenomenon.
Our results are consistent with other studies that have observed north-south aligned patterns in supergranulation [6, 7]. The observed pattern seems to be strongest in the near-surface layers, which might suggest that this is indeed a supergranular phenomenon. However, measurements at deeper layers are noisier and have larger error bars. Therefore, the decrease in correlation with increasing depth does not necessarily imply that the coherent structures are a near-surface phenomenon. In addition, it has been suggested that the north-south aligned supergranular patterns are a consequence of large convective structures [6]. The convection zone models [2] and the supergranulation measurements [6] suggest that our results are indications of large-scale convective structures.

We have limited our analysis to subsurface flows during solar cycle minimum, since these flows are sensitive to the presence of magnetic activity. However, the results have shown that weak magnetic patterns that rotate across the solar disk can be present even during an epoch of minimum activity. To further reduce the influence of magnetic activity, we have excluded locations of relative high magnetic activity from the minimum epoch. Still, some systematic flow variations coincide with very small variations of surface magnetic activity, which are too small to produce the observed flow pattern. This raises the question whether in some cases the bulk of magnetic activity is submerged. We plan to look more closely at the magnetic information and to identify the locations of remnants of active regions. This will allow us to further reduce the influence of magnetic activity in the search for coherent convective structures.
Figure 5. The cross-correlation of the zonal velocity derivative (left) and the vertical velocity (right) at three depth ranges (top: 0.9 – 2.0, middle: 3.1 – 8.5; bottom: 7.1 – 13.1 Mm) in steps of 15° CMD (dashed: −30°; dot-dashed: −15°; solid: 0°; dot-dot-dashed: 15°; long dashed: 30°). The lag time is in units of days; the correlation values are spline-interpolated for smoothness. Dotted lines indicate results of randomized data sets.

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