Solar-cycle variation of zonal and meridional flow

R Komm, R Howe, F Hill, I González Hernández and D Haber

1 National Solar Observatory, Tucson, AZ 85719, USA
2 JILA, University of Colorado, Boulder, CO, USA
E-mail: rkm@nso.edu

Abstract. We study the variation with the solar cycle of the zonal and meridional flows in the near-surface layers of the solar convection zone. We have analyzed Michelson Doppler Imager (MDI) Dynamics-Program data with ring-diagram analysis covering the rising phase of cycle 23, while the analyzed Global Oscillation Network Group (GONG) high-resolution data cover the maximum and declining phase of cycle 23. For the zonal flow, the migration with latitude of the flow pattern is apparent in the deeper layers, while for the meridional flow, a migration with latitude is apparent only in the layers close to the surface. The faster-than-average bands of the zonal flow associated with the new cycle are clearly visible. Similarly, a pattern related to the new cycle appears in the residual meridional flow. We also study the flow differences between the hemispheres during the course of the solar cycle. The difference pattern of the meridional flow is slanted in latitude straddling the faster-than-average band of the torsional oscillation pattern in the zonal flow. The difference pattern of the zonal flow, on the other hand, resembles the cycle variation of the meridional flow. In addition, the meridional flow during the minimum of cycle 23/24 appears to be slightly stronger than during the previous minimum of cycle 22/23.

1. Introduction
We study the variation with the solar cycle of the zonal and meridional flows in the near-surface layers of the solar convection zone. We have analyzed Michelson Doppler Imager (MDI) Dynamics-Program data with ring-diagram analysis covering the rising phase of cycle 23, while the analyzed Global Oscillation Network Group (GONG) high-resolution data cover the maximum and declining phase of cycle 23. The combination of GONG and MDI data allows us to study the complete cycle 23.

It is well established that the zonal and meridional flow vary with the solar cycle [1]. Alternating bands of faster- and slower-than-average rotation migrate from mid-latitudes to the equator, a pattern called torsional oscillation [2]. The variation of the meridional flow is of similar amplitude with large (small) values during cycle minimum (maximum) [3, 4]. The ring-diagram analysis allows us to study the flows in each hemisphere, unlike global methods that produce north-south averaged results [2]. In this study, we focus on the onset of solar cycle 24 and the flow differences between the hemispheres during the course of solar cycle 23.

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
Figure 1. Zonal and meridional flow of solar cycle 23. Rotation-rate (left) and meridional-flow residuals (right) in m/s from SOHO/MDI (before mid-2001) and GONG (after mid-2001) averaged over three different depth ranges (top: 0.9 – 2.0 Mm, middle: 4.4 – 10.2 Mm; bottom: 10.2 – 15.8 Mm). Positive (negative) values indicate faster (slower) zonal flow and poleward (equatorward) meridional flow. Overlaid contours (5, 10, 20, 40 G) show the gross magnetic field strength derived from NSO Kitt Peak and SOLIS synoptic maps.

15° before calculating three-dimensional power spectra. The data are analyzed in “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 then create synoptic flow maps from the daily ones and calculate the average zonal and
meridional flow for each synoptic map. Here, we use these average flows for each rotation and subtract the mean flow at each latitude. We use 20 Carrington rotations of MDI data covering the rising phase of cycle 23 before mid-2001 and 110 rotations of consecutive GONG data covering cycle 23 after mid-2001 to the beginning of cycle 24.

3. Results

Figure 1 shows the solar-cycle variation of the zonal and meridional flow averaged over three ranges in depth. The zonal flow (left) shows the torsional oscillation pattern for cycle 23 and 24 as bands moving from the mid-latitudes to the equator. The migration with latitude is apparent in the middle and deeper layers that are also probed by global helioseismology [2]. It is less pronounced in the shallow layers, which might be a resolution or observation period issue. The faster-than-average bands of the new cycle are clearly visible and appear before any surface activity of the new cycle is present. The corresponding meridional flow (right) also shows a variation with the solar cycle. However, a migration toward the equator is apparent only in the layers close to the surface. As in the case of the zonal flow, the flow pattern of the new cycle is present before there is new surface activity. The latitudinal pattern of the new cycle appears to be different from the previous one.

Figure 2 shows the north-south difference of zonal (left) and meridional flow (right) averaged over 4.4 – 10.2 Mm in depth. For the zonal flow (left), the band of positive differences in the south at low latitudes coincides with strong magnetic activity, extending cycle 23. At mid-latitude, the new-cycle branch is stronger in the north implying that more activity will appear in this hemisphere during cycle 24 than in the southern one. The north-south difference of the branch poleward of 40° latitude and that of the new-cycle branch (20° – 40°) show opposite signs. The difference pattern is aligned with latitude and thus resembles the cycle variation of the meridional flow. For the meridional flow (right), the north-south difference pattern is slanted in latitude straddling the faster-than-average band of the zonal flow.

Figure 3 shows the average meridional flow during the last two minima obtained from MDI data (minimum of cycle 22/23) and GONG data (minimum of cycle 23/24). The amplitudes at mid-latitudes are clearly larger during both minima than during the maximum phase of cycle 23. The maximum of cycle 23 has been observed by both MDI and GONG, which allows us to cross-calibrate the meridional flow measurements. Taking into account that the data are from different instruments, the meridional flow during the minimum of cycle 23/24 has a slightly

![Figure 2. North-south difference of zonal (left) and meridional flow (right) averaged over 4.4 – 10.2 Mm in depth. White contours show the magnetic field difference (solid: 2, 5 G; dotted: −2, −5 G), while the black ones indicate the residual flows shown in Figure 1 (dashed: 0 m/s).]
4. Discussion

The zonal and the meridional flow clearly vary with the solar cycle. The migration with latitude of the flow pattern is more apparent in the deeper layers than in the shallow ones for the zonal flow, while for the meridional flow it is apparent only in the layers close to the surface. For both large-scale flows, the patterns associated with the new cycle are visible before there is any sign of new-cycle surface activity. For the meridional flow, the latitudinal pattern of the new cycle appears to be different from that of the previous one. We will investigate this more closely as more observations of cycle 24 become available.

We also study the flow differences between the hemispheres during the course of the solar cycle. The difference pattern of the meridional flow is slanted in latitude straddling the faster-than-average band of the torsional oscillation pattern in the zonal flow. The difference pattern of the zonal flow, on the other hand, resembles the cycle variation of the meridional flow. Is this a coincidence or does it indicate a connection between the two flow patterns? We will investigate this relationship in the near future.

Acknowledgments

This work utilizes data obtained by GONG, managed by NSO, which is operated by AURA, 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. SOHO is a mission of international cooperation between ESA and NASA. This work was supported by NASA grant NNG08EI54I to NSO. Haber’s work was partially supported by NASA grants NAS5-02139 and NNX07AH82G.

References

[1] Komm R 2010 Astron. Nachr. (in press)
[2] Howe R, Hill F, Komm R, Christensen-Dalsgaard J, Larson, TP, Schou J, Thompson MJ and Ulrich R 2010 Journal of Physics: Conference Series (these proceedings)
[3] Haber DA, Hindman BW, Toomre J, Bogart RS, Larsen, RM and Hill F 2002 ApJ 570 855–64
[4] González Hernández I, Kholikov S, Hill F, Howe R, Komm R 2008 Solar Phys. 252 235–45