B_0-angle effect on zonal and meridional flow determinations from 3 years ring diagram analysis of GONG++ data

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Introduction

We study zonal and meridional components of horizontal solar subsurface flows during the years 2001–2004 which cover the declining phase of solar cycle 23. We measure the horizontal flows from the near surface layers to 16 Mm in depth by analyzing 44 consecutive Carrington rotations of Global Oscillation Network Group (GONG) Doppler images with a ring-diagram analysis technique. The meridional flow shows an annual variation related to the B_0 angle variation, while the zonal flow is less affected by the B_0 angle variation. After correcting for this effect, the meridional flow is mainly poleward but it shows a counter cell close to the surface at high latitudes in both hemispheres.

RESULTS

Data Analysis

The data used in this work consists of continuous high resolution Dopplergrams from the Global Oscillation Network Group (GONG) covering 44 consecutive Carrington rotations from CR 1979 to CR 2022 (July 27, 2001 –October 12, 2004). Full-disk Dopplergrams at 1 minute cadence are recorded on a 1024 × 1024 pixel CCD (Harvey *et al.* 1998) and then registered so that the solar image covers an area of 800 pixel in diameter. We use ring diagram analysis in order to measure the horizontal components of the solar subsurface flows as a function of depth (Hill 1988). For this work, we average the horizontal flows over the length of a Carrington rotation and study the temporal variation of zonal and meridional flows from more than three years of consecutive GONG data.

Meridional flow variability

Meridional flows are mainly poleward in each hemisphere (upper panel of figure.1), except at high latitudes and very close to the surface (±52.5° and 0.6 Mm) where flows are equatorward (**counter cell**) in both hemispheres. At high latitudes and low depths, these meridional flows exhibit periodic trends recurring on a yearly basis. This periodic variation seems to be well correlated with that of the B_0 angle in these regions. This correlation is shown by linear regression of the flow with the B_0 angle included on the same chart. Moreover, correlation coefficients shown in Figure 2 at the same latitudes and depths show overall a good correlation between the B_0 angle and flow variabilities. Large correlation coefficients occur mainly at high latitudes, while the values are generally small close to the equator. The correlation values are very similar in both hemispheres except at shallow layers equatorward of about 30° and at depths greater than about 10 Mm poleward of about 30°.

We remove the B_0-angle effect from the meridional flow variability by subtracting the fit of a linear regression between flow and B_0 angle variation (lower panel of figure.1). The 1-year periodicity disappears. Consequently, one can conclude that such a periodicity is purely a systematic effect due to the B_0 angle. However, the "counter cell" still appears at high latitude in shallow layers in both hemispheres.

We calculate the meridional flow averaged over CR 1979–2022 corrected for the B_0 angle variation (figure.3). Steep gradients at latitudes of about 35° or 40° and higher are shown. At these latitudes, the flow amplitudes decrease with increasing latitude at shallow depths (below about 2 Mm), while they increase with latitude at greater depths and then decrease again at depths greater than about 13 Mm (not shown). The counter cell is noticeable close to the surface at the highest latitudes.

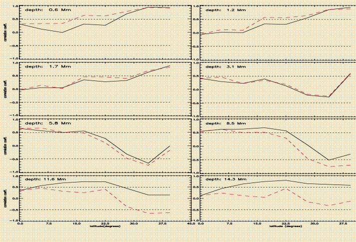

Fig.2: Linear correlation between meridional flow and B_0-angle variation. The dotted lines indicate the 99.9% significance levels.

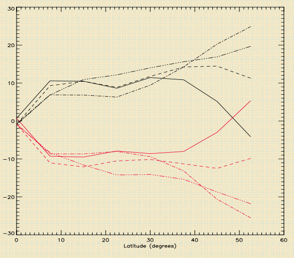

Fig.3: Average meridional flow as a function of latitude at four different depths (0.6 Mm: solid, 1.7 Mm: dashed, 5.8 Mm: dot-dashed, 11.6 Mm: 3dot-dashed) for the northern (black) and the southern hemisphere (red).

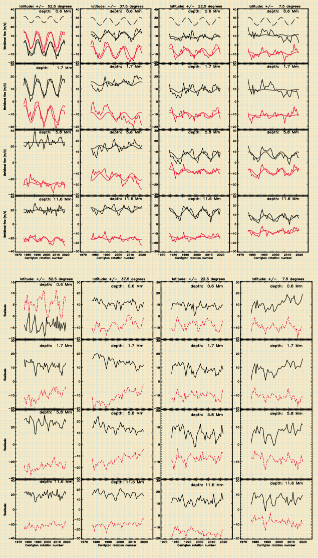

Fig. 1: Top:Temporal variation of the meridional flow in the northern (black) and southern hemisphere (red). The B_0-angle variation (in degree) is indicated as dashed line in the top row (shifted by 30 m/s in the y-direction). Thin solid lines represent linear fits of the B_0 angle to the flows. Bottom: temporal variation of the meridional flow after removing the B_0-angle variation in the northern (black) and southern hemisphere (red-dot-dashed).

Zonal flow variability

Figure 4 shows the long term pattern of the zonal flow at 4 latitudes and 4 depths. As for the meridional flow variability, we incorporate a low-degree polynomial fit of the flow with the B_0 angle for the 16 panels. In contrast to meridional flows, The temporal variation of the zonal flow is less correlated with the B_0 angle variation (figure.5). It is significantly correlated with the B_0 angle only in the southern hemisphere at depths between 2 and 11 Mm. At the same depth range in the northern hemisphere, the correlation is negative and increases in amplitude with increasing latitude but remains below the 99.9% significance level.

In Zaatri *et al.* (2006), we show that the correlation between the zonal flow and the B_0 angle reveals the same pattern with latitude and depth as the correlation between the errors of the zonal flow and the B_0 angle. For this reason, we decided to remove the B_0 angle effect from the zonal flow, as shown in the upper panel of figure 4.

The zonal flow shows strong fluctuations on time scales shorter than one year, which appear to be correlated between the hemispheres at 7.5° and 22.5° latitude. At latitudes poleward of about 40°, the variation of the zonal flow appears to have a larger amplitude compared to more equatorward latitudes.

The averaged zonal flow corrected for the B_0 angle variation is shown in Figure 6. It increases in amplitude with increasing depth, as expected from measurements of the rotation rate (Howe *et al.* (2006), for example). The zonal flow is predominantly faster in the southern hemisphere than in the northern one. The differences generally increase with increasing latitude for latitudes greater than 25°. Furthermore, the difference in amplitude between the hemispheres increases with depth with a local maximum near 15° latitude.

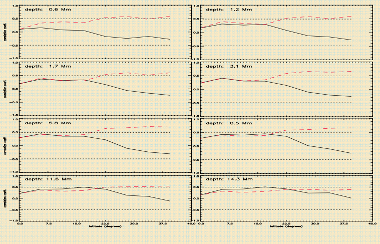

Fig.5: Same as fig.2 for zonal flow

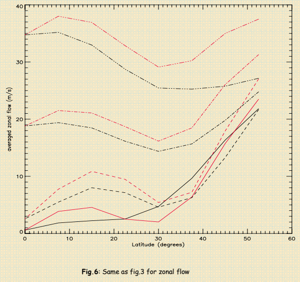

Fig.6: Same as fig.3 for zonal flow

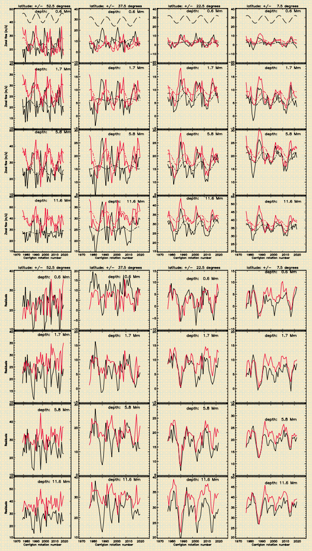

Fig. 4: Top:Temporal variation of the zonal flow in the northern (black) and southern hemisphere (red). The B0-angle variation (in degree) is indicated as dashed line in the top row (shifted by 30 m/s in the y-direction). Thin dot-dashed lines represent linear fits of the B0 angle to the flows. Bottom: temporal variation of the zonal flow after removing the B0-angle in the northern (black) and southern hemisphere (red).

Conclusion

- We have analyzed 44 consecutive Carrington rotations of Global Oscillation Network Group (GONG) Doppler images with a ring-diagram analysis technique and explored the horizontal flow components and their temporal variation. We mainly focused on the B_0 angle effect on flows variations in time.
- The variability of the meridional flow is much more affected than the zonal flow by the B_0 angle temporal variation .
- The B_0 angle variation affects flows differently in the two hemispheres and at different layers for a given latitude.
- To correct the horizontal flows for these annual variations, we subtract a linear regression in B_0 angle from the flows.
- The presence of the counter cell at high latitudes and low depths does not disappear after removing the B_0 angle effect. Moreover, it's location differs from other studies (Gonzalez Hernandez *et al.* 2005 , Haber *et al.* 2002). Consequently, we can't rule out the possibility that it is due to some systematic effects.
- The meridional and zonal flow patterns are strongly related to the distribution of magnetic activity and hence to the solar cycle. Further discussion of this view is given in Zaatri *et al.* (2006).

References

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CRAAG Observatoire de la Côte d'Azur GONG