PROBING SOLAR DYNAMICS IN THE UPPER CONVECTION ZONE BY TIME-DISTANCE HELIOSEISMOLOGY

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ABSTRACT

By use of time-distance helioseismology, we derived solar rotational rates, meridional flow velocities, as well as synoptic flow maps to a depth of around 12 Mm (Zhao & Kosovichev, 2004). This paper is the beginning of an attempt to derive large scale flow fields and make synoptic flow maps in the deeper solar interior, up to the bottom of the solar convection zone. So far, we have made time-distance measurements and inversions to a depth of around 50 Mm, one fourth of the solar convection zone. In this paper, we present some initial results, including rotational rates, meridional flows, synoptic flow maps for selected Carrington rotations, and flow fields around large active region AR9393 at various depths.

Key words: helioseismology; solar rotation; meridional flows; active region.

1. INTRODUCTION

By use of time-distance helioseismology, we have derived solar rotational rate and meridional flow velocity to a depth of around 12 Mm, and mapped synoptic flow charts for some selected Carrington rotations in different years (Zhao & Kosovichev, 2004). In that study, we found torsional oscillations consistent with previous studies, and an extra meridional circulation of converging flows toward solar activity zones. Now, we attempt to perform similar studies into the deeper interior of the solar convection zone to probe further solar dynamics information. This paper presents our initial efforts of this attempt to reach a depth of around 50 Mm, one fourth of the whole solar convection zone. Such an analysis brings us plentiful information of solar rotation and meridional flows, as well as flow fields around solar active regions.

Time-distance measurements were made based on the procedure given in Giles (1999), and inversions were performed by employing Multi-Channel Deconvolution (MCD) as in Zhao & Kosovichev (2003). Ten different annulus ranges were selected for measurements: 0°96 – 1°68 – 2°64 – 4°08 – 5°52 – 6°96 – 8°40 – 9°84 – 11°28 – 12°72 – 14°16. The studied regions were also divided into ten vertical layers: 0 – 5 – 10 – 15 – 20 – 25 – 30 – 35 – 40 – 45 – 50 Mm, and the horizontal spatial resolution was averaged to 0°48 / pixel. Sensitivity kernels for doing inversions were made based on ray-approximation.

Each set of measurement utilized 1024 minutes continuous Dopplergram observation, and a central meridian solar region covering 60° in longitude and 110° in latitude (from –55° to 55°) was selected for analysis. The next set of data was selected for analysis 1024 minutes after the previous one. As such, about 40 regions were analyzed to cover one whole Carrington rotation.

2. ROTATION RATE AND MERIDIONAL FLOW

As in Zhao & Kosovichev (2004), we selected one Carrington rotation in each year of 1996 – 2002 for this study, and analyzed data of all these seven Carrington rotations that cover from the solar minimum to solar maximum of Solar Cycle 23.

Figure 1 presents rotational rates and meridional flow velocities obtained at different depths for CR1911 of 1996. Basically, the rotational rate increases with depth, which is consistent with previous results from global frequency splitting (e.g., Howe et al., 2000). However, it seems that rotational rates from our analysis increase faster in higher latitude. This may be caused by the imperfect remapping procedure we employed in high latitudes, and may also be affected by the imperfect choice of regularization parameter. We need to look at this again.

Meridional flows are basically poleward in both hemispheres, and the flow speed is around an order of 15 m/s below 10 Mm without significant changes with the depth.

Figure 2 presents torsional oscillation from different Carrington rotations covering 1996 to 2002. Three different depths were displayed: 5 – 10, 15 – 20 and 25 – 30 Mm. These results are generally consistent with previous observations (e.g., Haber et al., 2002). Faster zonal flow...
bands migrate towards the solar equator with the evolution of the solar cycle. It seems that the amplitude of the faster zonal flows is larger in years of 1997, 1998 and 1999, and smaller in other years. Additionally, it seems that in the same year, the amplitude of faster zonal flows does not change much with the increase of depth.

Figure 3 presents meridional flows from different Carrington rotations. As in Figure 2, three different depth intervals were selected for display. Poleward meridional flows are basically seen in different years and at different depths, with larger speed near the surface. There are two things to notice in Figure 3: 1. These meridional flows are displayed without P-angle correction as was done in Zhao & Kosovichev (2004), but the velocity curves look symmetric. This may or may not be related to the imperfect remapping as pointed out earlier. 2. In 1999, 2000 and 2001, there are no return meridional flows observed in the Northern hemisphere even at the depth of 25 – 30 Mm, as observed by (Haber et al., 2002).

It was reported by Gizon (2003) and Zhao & Kosovichev (2004) that the residual meridional flows (the difference after meridional flow profile of 1996 subtracted from meridional flow profiles of other years) converge toward the solar activity zones near the solar surface. And, it was also reported by Chou & Dai (2001) and Beck, Gizon, & Duvall (2002) that the residual meridional flows...
Figure 4. Synoptic flow maps of CR1975, displayed at depths of 0 - 5 Mm and 10 - 15 Mm.

Figure 5. Horizontal averaging kernels for different target depths obtained from this study.

diverge from the activity zones. By looking at meridional flows shown in Figure 3, it is clear that near the solar surface, meridional flow profiles change with years, showing residual flow converging towards the activity belts. However, in deeper interior, it seems that meridional flow profiles do not change much with evolution of solar cycle, showing no signature of divergent flows. Once again, it is not clear how much effect our remapping procedure has in this.

Figure 5 shows the horizontal averaging kernels obtained from this study. This plot indicates that the inverted depths are basically in agreement with the targeted depths, without significant positive and negative side lobes at the depths other than the targeted depth.

3. SYNOPTIC FLOW MAPS

As one example of many synoptic flow maps we have obtained, Figure 4 presents large scale synoptic flow maps from CR1975 of 2001 at two depths.

These flow maps show plentiful solar dynamics information in the solar interior that may help us to better understand the solar convection, and dynamics of solar active regions. It can be seen that the flows around and close to active regions are often more systematic than other quiet regions.

It is also worthwhile to point out that a greater scale of divergence structure are present in some areas, suspected
as “giant cell” by Haber et al. (2004). One example in the upper panel of Figure 4 is at Longitude 70°, Latitude 5°S.

Flow fields around active region AR9393 at different depths are presented in Figure 6. As reported in Zhao & Kosovichev (2004) and Haber et al. (2004), convergent flows towards active region are found near the solar surface, and divergence flows are found farther below. As discussed in the previous two papers, the transition from convergent to divergent seems to occur around depth of 7 Mm. Here, we present results as deep as 30 Mm, and it seems the divergent flows still remain strong at this depth.

Also consistent with report by Haber et al. (2004), a jet stream from the northern pole is seen flowing toward this active region, and the jet keeps to be seen till the depth of 30 Mm, as shown in the last panel of Figure 6.

4. SUMMARY

- Rotational rates, meridional flows and synoptic flow maps have been obtained for various Carrington rotations, from the surface to a depth of about 50 Mm, covering one fourth of the whole solar convection zone;

- Torsional oscillation and meridional flows at different depths for different phase of the solar cycle are presented;

- No return meridional flows were found in the higher latitudes of Northern hemisphere at deeper depths; and it seems no divergent residual flows are seen in the inversion results in the deeper solar interior as reported before. However, we cannot exclude the possibility that our remapping may play some role in causing this;

- Flow maps around AR9393 at different depths show rich information of its dynamics.

REFERENCES