Meridional Circulation in the Active Belts

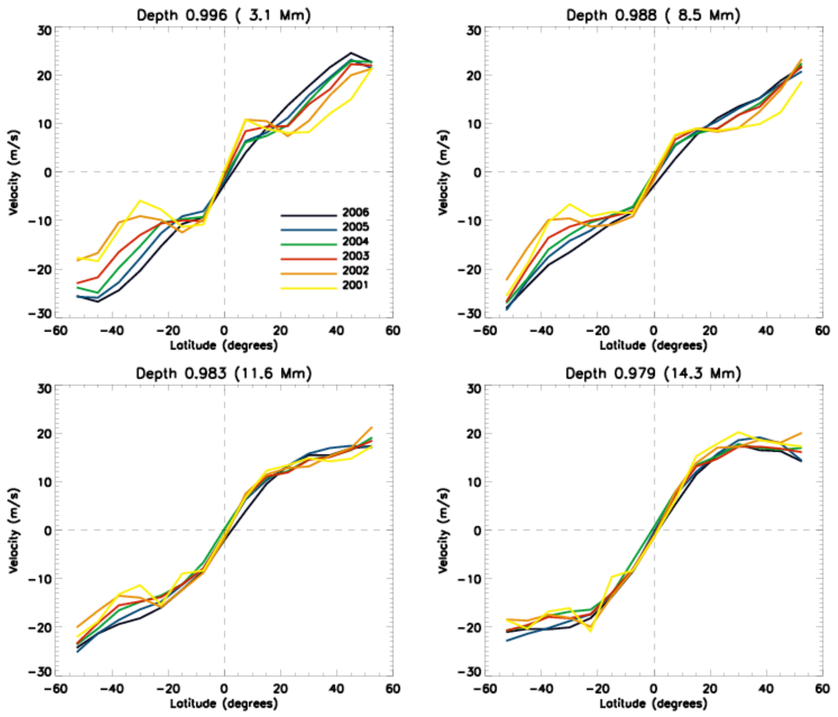
I. González Hernández, S. Kholikov, R. Howe, F. Hill and R. Komm

National Solar Observatory, Tucson, AZ

The temporal variation of the subsurface meridional flow with the solar cycle have been reported by several authors. This work examines the possible contamination of these measurements by the extra velocity fields associated with active regions as well as the uncertainties in the data obtained where strong magnetic fields are present. We study the variation of the meridional circulation in the declining phase of cycle 23 after the contribution of surface activity has been removed. The divergent flow towards the active belts in the upper layers of the convection zone is also investigated.

Introduction

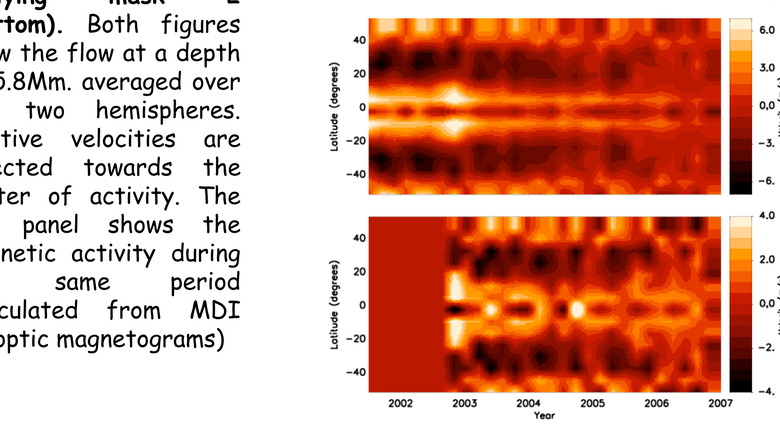
Meridional circulation is a major focus of solar studies as it has become a key component of solar dynamo models. Its temporal variation has been shown to influence the upcoming solar cycle features. Thus, accurately describing the meridional flow both in latitude and depth as well as understanding its variation with the solar cycle has become a focus of local helioseismology observations. Several studies during solar cycle 22 and 23 have shown an anticorrelation between the amplitude of the meridional flow and the surface magnetic activity. We focus here on the effects of the surface activity in the temporal variation of the meridional flow as well as in the divergent flow in the active belt. We apply ring diagrams, a local helioseismology technique, to 5.5 continuous years of GONG observations and obtain the meridional circulation both before and after removal of the surface activity.



Yearly averages of the meridional flow obtained by ring-diagram analysis of GONG continuous set of data at four different depths. The variation with the solar cycle, clearly observed at high latitudes at the superficial layers, is less pronounced at deeper layers. The extra circulation in the active belts seems to be confined to the upper layers of the convection zone.

Results

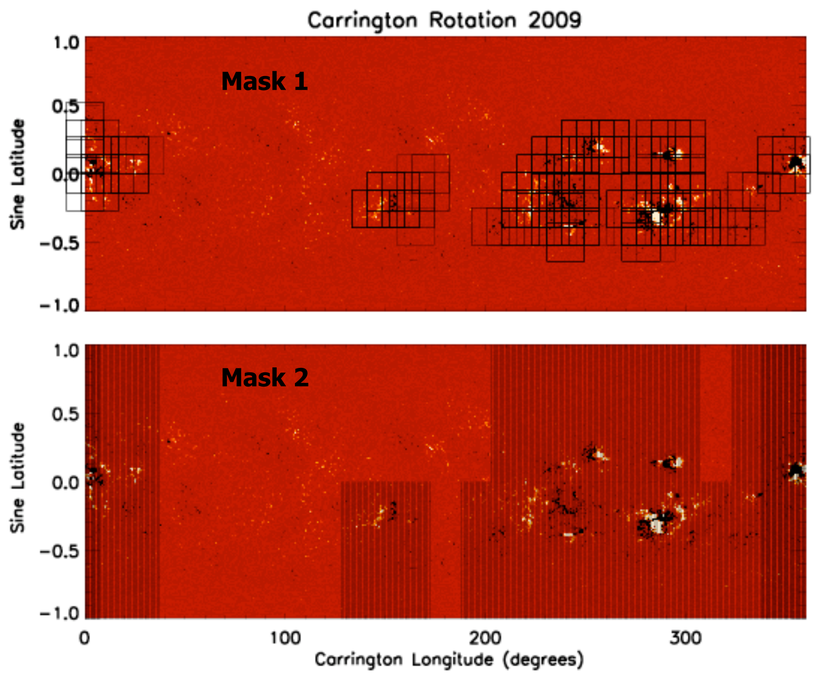
Yearly average meridional flow after removing surface activity. The flow is presented at two different depth after applying **mask 1** (left) and **mask 2** (right).



The variation with the solar cycle at high latitudes, as well as the extra circulation in the active belts, is attenuated after applying the more aggressive masking procedure, especially in the shallow layers of the convection zone, but they don't disappear completely.

Excluding data from areas of surface magnetic activity

With the spatial resolution of the standard ring-diagram analysis, removing areas of surface magnetic activity to measure meridional circulation in the quiet Sun is complicated, especially in periods of high activity. However the period from 2003 to 2006 of the complete data set presents areas of high activity combined with large areas of very low activity, allowing for statistically significant comparison between meridional flows averaged over all areas versus those obtained only from quiet regions.



Two different approaches were taken to eliminate data associated to surface magnetic activity.

Mask 1: Removing all the ring-diagram patches with an averaged magnetic field strength above a certain threshold. For our purposes, 10 Gauss seemed to account for most of the surface activity.

Maks 2: Removing the patches with average magnetic field strength above 10 Gauss and all the patches at the same longitude and in the same hemisphere as the masked one. In this way, flows associated with surface activity that extend for long distances will be completely removed.

An extra component in the meridional circulation

Temporal variation of the meridional circulation residuals obtained by averaging all available data (center) and after applying mask 2 (bottom). Both figures show the flow at a depth of 5.8Mm. averaged over the two hemispheres. Positive velocities are directed towards the center of activity. The top panel shows the magnetic activity during the same period (calculated from MDI synoptic magnetograms)

The observed extra circulation in the active latitudes varies with the solar cycle, decreasing towards solar minimum, when all the available data is averaged in longitude. These inflows towards the center of activity do not disappear when the contribution of superficial activity is removed, although the amplitude is reduced and the center of confluence seems to move toward higher latitudes. We find that the flows are more affected by surface activity in very shallow layers.

Conclusions

- **The overall trend of the meridional flows at high latitudes, once the active regions have been eliminated, confirms previous results obtained by local helioseismology: larger amplitude flows towards solar minimum. However the variation is attenuated. The temporal variation is less pronounced with depth.**
- **A second component of the meridional flow towards the centre of activity is present in the final results even after aggressively removing the magnetic activity at the surface. This suggest the existence of a global pattern of extra meridional circulation in the main active latitudes or longitudinally persistent cells where dynamics persist for long time during the decay of active regions.**
- **When using only quiet Sun areas to calculate the meridional flow, the mean latitudinal position of the extra circulation in the active belts does not change significantly during the studied period of 2001-2006.**

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