Meridional Flow Observations: Implications for the current Flux Transport Models

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Abstract. Meridional circulation has become a key element in the solar dynamo flux transport models. Available helioseismic observations from several instruments, Taiwan Oscillation Network (TON), Global Oscillation Network Group (GONG) and Michelson Doppler Imager (MDI), have made possible a continuous monitoring of the solar meridional flow in the subphotospheric layers for the last solar cycle, including the recent extended minimum. Here we review some of the meridional circulation observations using local helioseismology techniques and relate them to magnetic flux transport models.

1. Introduction
The solar magnetic cycle is generally explained using magnetohydrodynamic dynamo theory. These models rely on two effects: the Ω effect (stretching of the poloidal field by differential rotation to produce the toroidal component) and the α effect (regeneration of the poloidal field). Solar meridional circulation is a key component of the regeneration of the poloidal field in the current Babcock-Leighton type models [1]. Traditional observations of the meridional circulation relied on the tracking of large or small magnetic elements or direct observation of photospheric Doppler shifts. These techniques are limited to measurements at the solar surface. Local helioseismology techniques have provided the opportunity to infer the meridional circulation profile with depth. In this paper we discuss some of the results obtained by the local helioseismology techniques, such as the temporal variation of the flows with the solar cycle, the extra circulation in the active latitudes and the preliminary inferences of the deep convection zone meridional circulation, and their relation to the flux transport models.

2. Polar Field Reversals
Two transport processes are believed to be involved in the polar field reversals: supergranular diffusion and meridional circulation [2]. While the leading polarity of tilted bipolar active regions cancels by diffusion, the trailing polarity is transported toward the poles canceling and inverting the previous cycle.

The polar field reversal during solar cycle 23 can be clearly seen in Figure 1 around 2001, at maximum activity. Figure 1 also shows that the polar fields during this solar minimum were weaker than the previous one. Wang et al. [2] demonstrated that this variation of the polar fields can be reproduced with a surface transport model that includes variation of the subsurface meridional flow from cycle to cycle. Long-term helioseismic observations from both
Figure 1. Magnetic field proxy calculated using Michelson Doppler Imager magnetograms obtained during the period 1996-2010 and covering the last solar cycle. The magnetic field is averaged in longitude for each Carrington rotation synoptic map and the sign is preserved. To see the pole reversal, the image is saturated at the active belts.

GONG and MDI provide the opportunity to compare the meridional flows in the previous and the current cycle. Basu and Antia [3], Kholikov et al. [4] and Komm et al. [5] show evidence of the subsurface meridional flow varying between the minimum of solar cycles 23 and 24, with a larger amplitude in this recent extended minimum. Surface observations confirm this behavior [6].

3. Meridional Circulation and Solar Cycle Prediction Models

Meridional circulation is believed to determine the solar dynamo cycle period as well as the Sun’s memory about its past magnetic fields [2,7]. Hence, the meridional flow is an essential component of the solar cycle predictions based on flux-transport dynamo models [7]. The assumption used by most modelers is that the meridional flow varies from cycle to cycle. However, it is well established by now that the meridional circulation also varies throughout a particular cycle, with a minimum amplitude at maximum activity and vice-versa [3,6,8,9]. Figure 2 presents the temporal variation of the meridional flow inferred by ring-diagram analysis of GONG data from 2001 to 2010 at 5.8 Mm under the solar surface. Recent work includes helioseismically inferred meridional flow in the subsurface layers that has been temporally averaged as input to their flux-transport model [10], but the variation within the cycle still needs to be considered.

3.1. Extra circulation (jets) of the meridional circulation

Superimposed meridional circulation in the active latitudes was first observed by applying local helioseismology techniques to the Taiwan Oscillation Network data in 2001 [11]. Since then, several studies have investigated the origin of such extra circulation. The recent prolonged solar minimum has provided the opportunity to investigate this behavior of the meridional circulation without contamination from surface activity [9]. In Figure 3, the formation of the bumps at medium latitudes precedes the onset of the activity, confirming the nature of this phenomenon as independent of the surface manifestation of active regions.
Figure 2. Temporal variation of the fitted polynomial to the meridional circulation observations at a depth of 5.8 Mm obtained from ring-diagram analysis of GONG data. A symmetrical plot averaging both hemispheres is shown. Positive velocities are taken toward each respective pole.

3.2. Meridional Flow deep in the convection zone
The return flow at or near the base of the convection zone is estimated to be of the order of 1-2m/s. To achieve that accuracy with helioseismic observations, time series that span at least one full solar cycle are needed [12]. Time distance analysis of spherical harmonic time series obtained from GONG observations that span from 1995 to 2009 have been used for this purpose [4]. Preliminary results show an increase of time differences at a depth of about 0.77R⊙. This can be an indication of large perturbations of the meridional flow or some other properties of the deep convective zone. The long series uses for the analysis reduce the uncertainties in the measurements to less than 0.02 seconds.

4. Summary and Future work
Proper determination of the meridional circulation at the surface and the solar interior is key for the current flux transport models. Local helioseismology has contributed substantially to the overall picture, but more work is needed to understand the details. The relationship between the extra circulation of the meridional circulation and the well established torsional oscillation of the zonal flows needs to be investigated. Gizon and Rempel [13] presented a model to account for independent observations of the meridional flow residuals at the surface and at a depth of 60 Mm., in which the flow at these two depths was anticorrelated. The meridional flow profile deep in the convection zone remains elusive. Preliminary results using data from a full solar cycle to infer the meridional flow profile until the base of the convection zone look promising.

The Solar Dynamics Observatory is expected to bring new insights into the meridional circulation, particularly in the subsurface behavior of the flow at higher latitudes (see preliminary results by Chakraborty et al. [14]).

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Figure 3. Temporal variation of the meridional circulation residuals at a depth of 5.8 Mm (bottom panel). Positive velocities are directed towards the poles. A symmetrical plot averaging both hemispheres is shown. The top panel presents the location and magnetic strength of the activity during the same period (calculated from MDI synoptic magnetograms).

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