Meridional Flow Observations: Implications for the current Flux Transport Models

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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 more than a solar cycle. Here we discuss the implications of some of these observations for the current flux transport models.

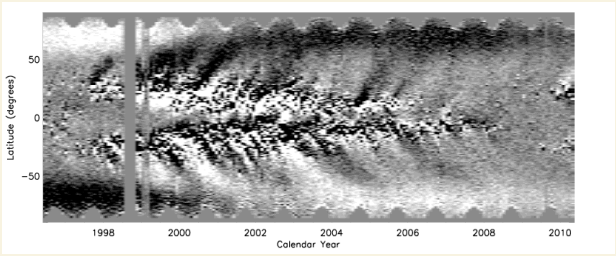
Introduction

The solar magnetic cycle is generally explained using magneto-hydrodynamic 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 [5].

Polar fields reversal

Perhaps the solar cycle characteristic that is most intuitively related with meridional circulation is the reversal of the polar fields. Two transport processes are believed to be involved: supergranular diffusion and meridional flow. While the leading polarity of tilted bypolar active regions cancels by diffusion, the trailing polarity is transported toward the poles cancelling and inverting the previous cycle.

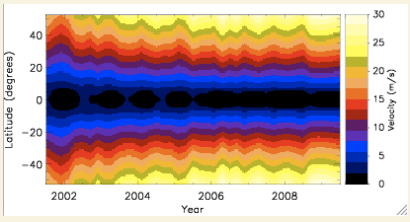
The polar field reversal during solar cycle 23 can be clearly seen in the figure below. It also shows that the polar fields during this solar minimum were weaker than the previous one. Wang et al. demonstrated that this can be reproduced with a surface transport model that include variation of the subsurface meridional flow from cycle to cycle [12]. Long-term observations from both GONG and MDI provide the opportunity to compare the meridional flows in the previous and the current cycle. Basu and Antia [1], Kholikov et al. [8] and Komm et al. [9] show helioseismic evidence of the subsurface meridional flow varying between the minimum of solar cycles 23 and 24.



Magnetic field proxy calculated using Michelson Doppler Imager magnetograms. *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.*

Predicting Solar Cycles

Meridional circulation is believed to determine the dynamo cycle period as well as the Sun's memory about its past magnetic fields. Hence, the meridional flow is an essential component of the simulation and prediction using flux-transport dynamo models [4]. Recent work includes observed temporal variations of the meridional flows through the solar cycle to further refine the models [11].

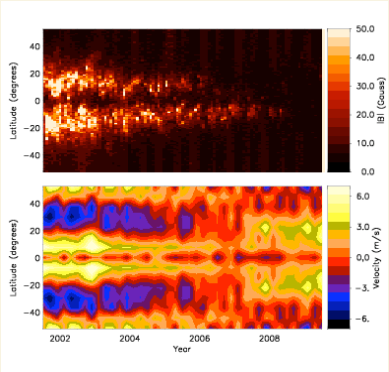


Temporal variation of the fitted polynomial to the meridional circulation observations at a depth of 5.8 Mm. *A symmetrical plot averaging ring-diagram analysis of GONG data for both hemispheres is shown. Positive velocities are taken toward each respective pole. The B0 effect is clearly seen superimposed in the results, however the long term trend of the amplitude increase is not associated with this artifact [7].*

New observational results and new challenges for the modelers

Extra circulation or '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 [3]. Since then, several studies have investigated the origin of such extra circulation.

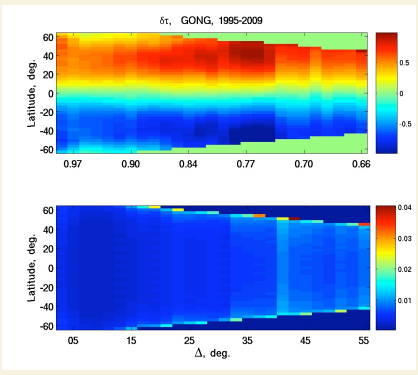


Temporal variation of the meridional circulation residuals (or jets) at a depth of 5.8 Mm (bottom panel). *Positive velocities are directed towards the poles. A symmetrical plot averaging both hemispheres is shown in the bottom panel [7]. The top panel shows the location and magnetic strength of the activity during the same period (calculated from MDI synoptic magnetograms). The existence of the residuals, or extra circulation, at medium-high latitudes before the onset of activity of solar cycle 24 confirmed previous results showing the persistence of such residuals after removing the contribution from active regions [6].*

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, very long time series are needed [2]. Time distance analysis of Spherical Harmonic time series obtained from GONG observations that span from 1995 to 2009 have been used for this purpose [10]. Preliminary results are shown in the figure below.

Zonal travel time differences as a function of latitude and propagation depth (top). *Measurements are averaged over the period 1995-2009. The increase of time differences at a depth of about $0.77R_{Sun}$ can be an indication of large perturbations of the meridional flow or some other properties of the deep convective zone. Inversions of these travel time differences are needed in order to get realistic estimations of the actual flows. The lower panel shows the precision of measurements. In this figure, the horizontal axis correspond to the same depths as the top panel, but has been labeled in units of separation distance for cross-correlation analysis. It should be noted that error bars for most measurements are smaller than 0.02 seconds [8].*



Meridional Circulation at High Latitudes

The recent successful launch of 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. Preliminary results obtained by analyzing Helioseismic and Magnetic Imager data are presented by Chakraborty et al. at this conference.

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