

Meridional Motion and the Slope of Isorotation Contours

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Abstract

As helioseismic inversions have continued to improve in precision, it has become apparent that in the bulk of the solar convection zone the contours of rotation, while certainly not parallel to the rotation axis as predicted in earlier global convection simulations, are also not radial, as has often been stated based on earlier inversions. Instead, between 15 and about 55 degrees latitude (measured at $r=0.8R_{\text{SUN}}$) the rotation contours make an angle with the rotation axis of about 25 degrees, which does not appear to vary systematically with latitude in this latitude range. What then determines this angle? By use of an extremely simple dynamical equilibrium model, we show that coriolis forces from the observed meridional circulation could be responsible for this angle if, without this effect, the contours of rotation would be radial.

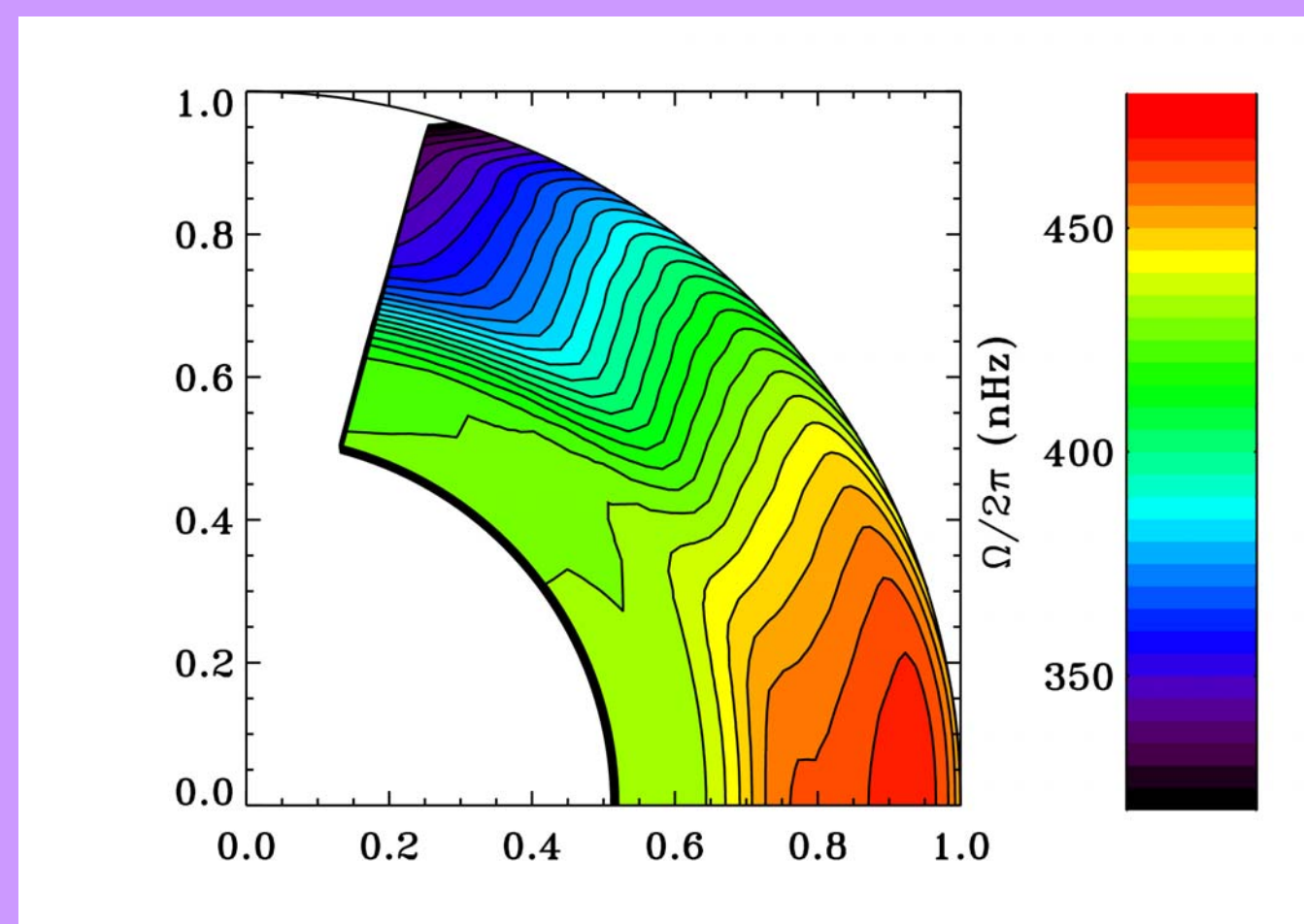
Introduction

Global compressible convection models for the solar convection zone have yet to reproduce well the radial gradient of rotation within the convection zone, though they appear to be getting somewhat better (Brun & Toomre 2002). Since helioseismically determined profiles of solar rotation have become plentiful, it has been common to characterize the bulk of the convection zone as having very little radial rotation gradient, with sharp radial gradients confined to near the photosphere on the top, and in the tachocline on the bottom. In reality this appears to be a slight oversimplification, in that the latest helioseismic profiles are refined enough to see that in low and mid-latitudes, the rotation contours instead seem to be oriented at an approximately constant angle to the solar rotation axis, of about 25 degrees (e.g., Schou et al. 1998, 2002).

At the same time, helioseismic measures of meridional flow show it is usually toward the poles through the bulk of the convection zone, as far down as can be measured (Haber et al. 2002).

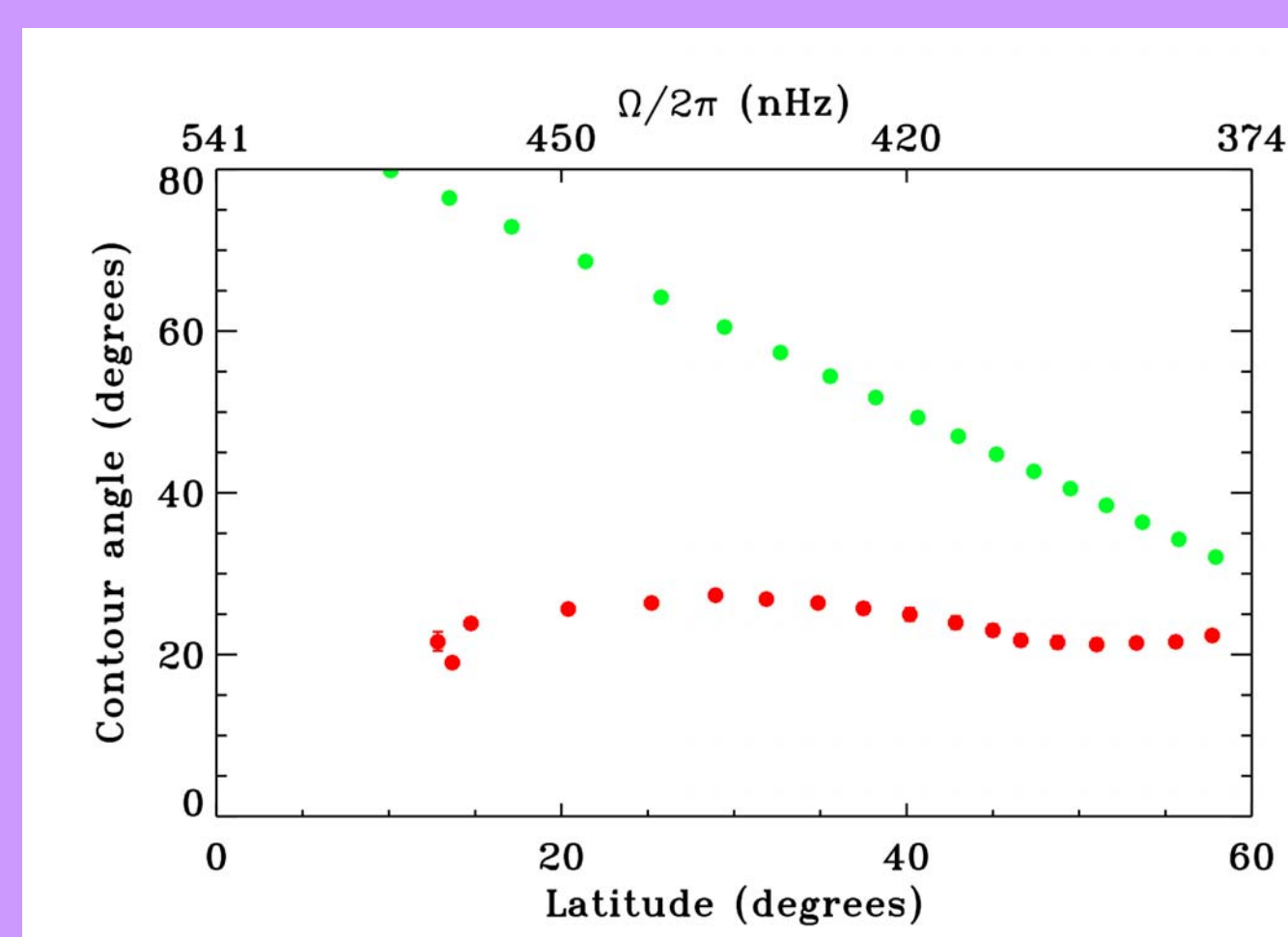
Leaving aside the detailed complexity of full-blown 3D spherical shell convection models, we show here that taking into account only the influence of coriolis forces from the meridional circulation, and a simple drag on the differential rotation, we can reproduce rather well the angle the rotation contours make with the rotation axis, if we assume that in the absence of meridional circulation, the rotation contours would indeed have been radial, as has been previously inferred from helioseismic measurements.

Mean Rotation Profile



The figure at left shows the mean rotation profile derived from 66 overlapping 108-day periods of GONG data starting in May 1995 and continuing through December 2001. The isorotation contours are spaced at 5nHz. The contours in the bulk of the convection zone, below the subsurface shear layer and above the tachocline, maintain almost the same angle to the vertical over a wide range of latitudes.

The figure at right shows the angle between the rotation contours and the rotation axis for the observations (red) and for the notional radial rotation profile (green). Notice that the observed contours are always steeper than the radial picture would suggest. The latitudes were measured about the middle of the convection zone, and the angles were measured over the interval $0.8 < r/R_{\text{SUN}} < 0.95$.



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The Model

The rotation field $\Omega(r, \theta)$, where r is the radial co-ordinate and θ is co-latitude, is described as the combination of the radially-independent component, $\Omega_0(\theta)$, with the component arising from the meridional motion, as

$$\Omega(r, \theta) = \Omega_0(\theta) - 2 \frac{R}{r\nu \sin \theta} (v_{e,\theta} \cos \theta + v_{e,r} \sin \theta)$$

where R is the solar radius, ν is a combination drag term and scaling coefficient, and $v_{e,r}$, $v_{e,\theta}$ are the radial and latitudinal components of the meridional flow field.

In the absence of well-established measurements of the meridional circulation in the bulk of the Convection Zone, we use a simple model due to van Ballegoijen and Choudhuri (1988). In this model, the density profile is approximated by $\rho(r) \propto (R/r - 1)^n$, with $n = 1.5$, and a flow field satisfying the continuity equation is given by

$$v_{e,r}(r, \theta) = u_0 \left(\frac{R}{r}\right)^2 \left(\frac{-1}{n+1} + \frac{c_1}{2n+1} \xi^n + \frac{c_2}{2n+k+1} \xi^{n+k} \right) \xi \sin^m \theta [(m+2) \cos^2 \theta - \sin^2 \theta],$$

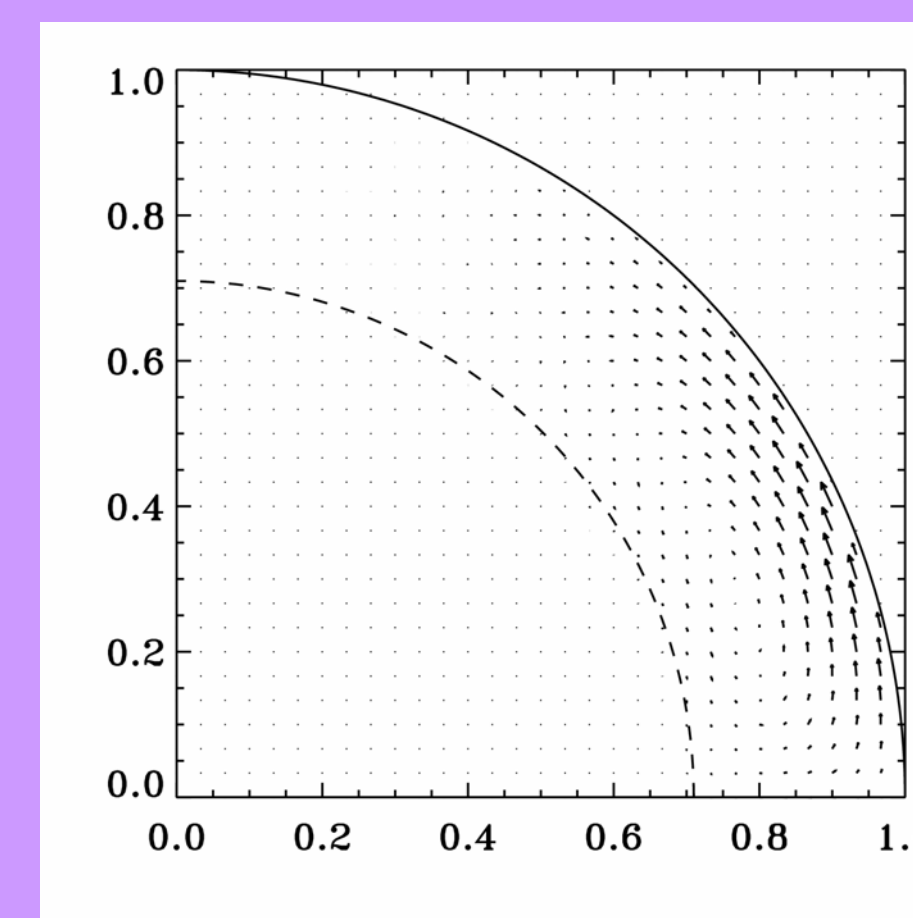
$$v_{e,\theta}(r, \theta) = u_0 \left(\frac{R}{r}\right)^3 (-1 + c_1 \xi^n - c_2 \xi^{n+k}) \sin^{m+1} \theta \cos \theta,$$

where $\xi = (R/r - 1)$, u_0 gives the scale of the flow field and $k > 0$ and $m \geq 0$ are adjustable parameters governing the radial and latitudinal dependence of the flow field. The constants c_1 and c_2 are defined as

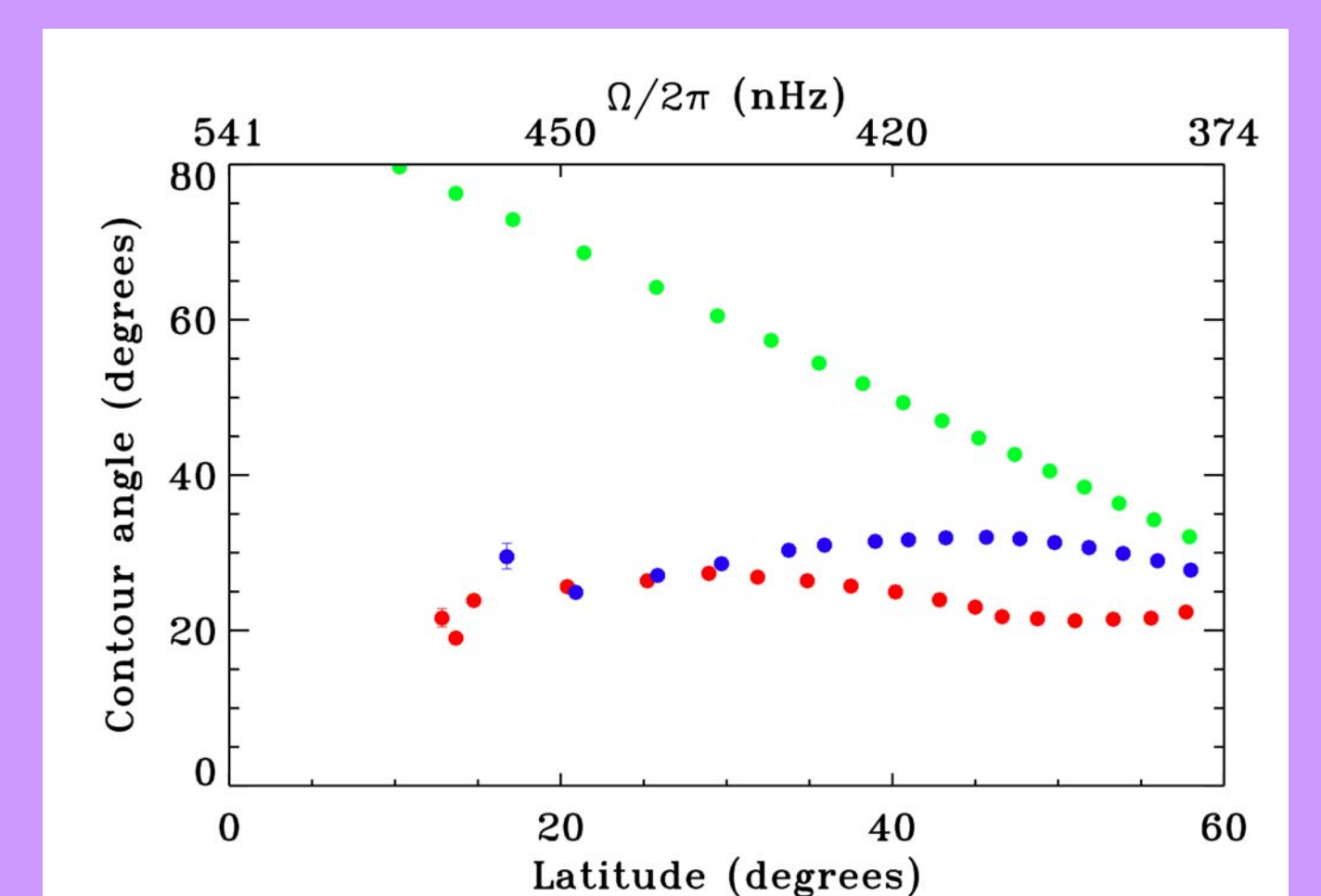
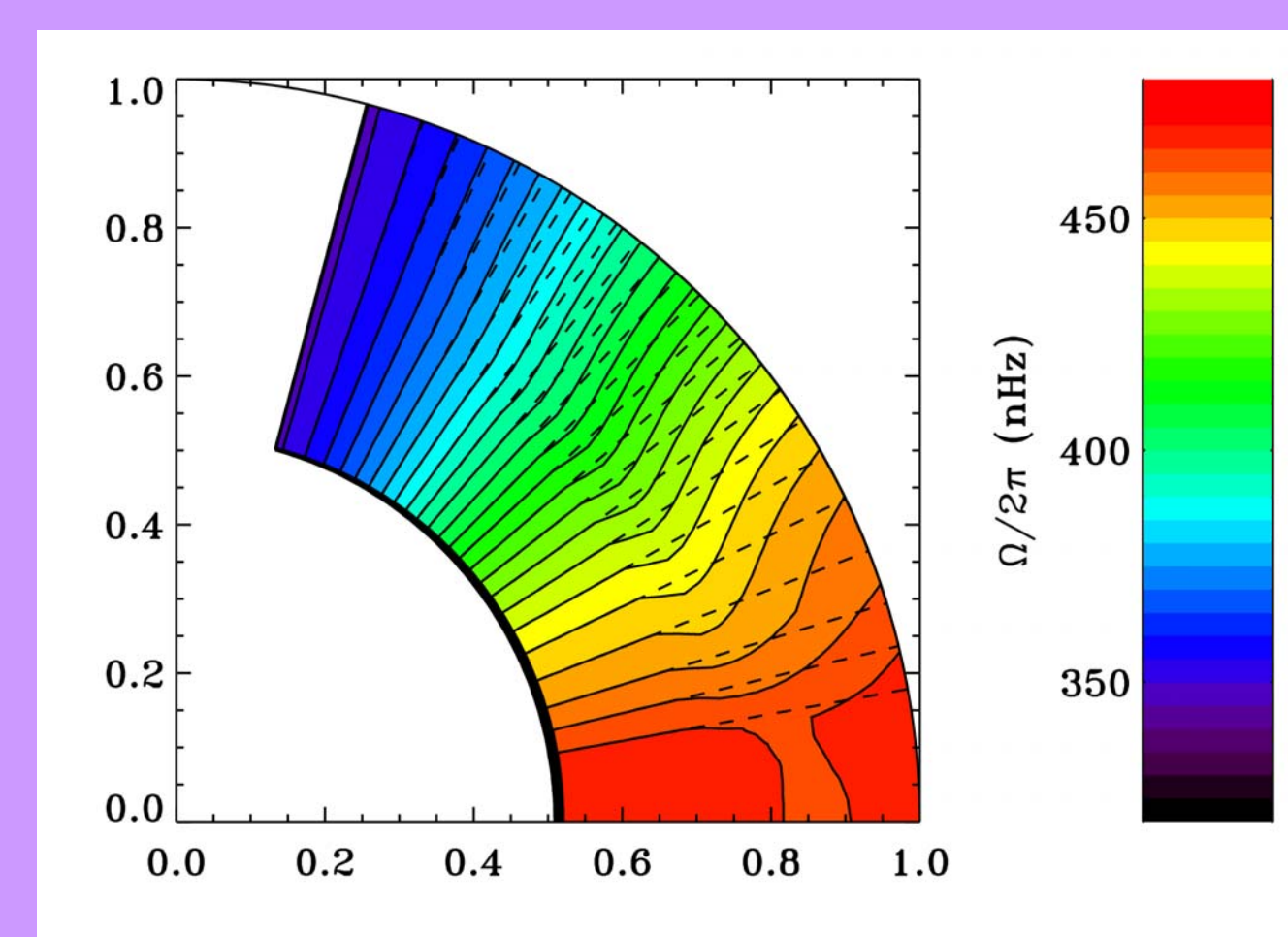
$$c_1 = \frac{(2n+1)(n+k)}{(n+1)k} \xi_b^{-n}, c_2 = \frac{(2n+k+1)n}{(n+1)k} \xi_b^{-(n+k)}$$

where ξ_b is the value of ξ at the base of the Convection Zone.

Results



The best fit of the model to the data was found by exploring the (u_0, k, m) parameter space to minimize the χ^2 value (the sum of squares of the difference between the observations and the model, weighted by the inverse squares of the formal errors on the inversion results) over the range $0.8R < r < 0.95R$ and $\theta > 15$ degrees. Under this criterion the best fit was found with $k=-0.5$ and $m=5.6$, and a u_0 value that, given the observed peak flow of about 15ms^{-1} near the surface, corresponds to a drag time scale around 0.3nHz . The figures show (left) the meridional flow field, (below left) the perturbed radial-pattern flow field, (below right) the contours of the unperturbed radial field as dashed lines, and (below right) the angles of the contour lines in the unperturbed (green) and perturbed (blue) radial patterns, with the observed values shown in red.



Discussion

The coupling of convection, meridional circulation and differential rotation in the solar convection zone is inherently complex, so understanding their interplay invites a variety of approaches, including some that do not rely exclusively on full 3D numerical simulations. We offer the above modest diagnostic analysis as an example of what might be done, now that the details of differential rotation and meridional circulation below the solar surface are becoming better known from helioseismic inferences.

The possible relationship between meridional circulation and differential rotation we have defined suggests that it would be worth while to determine, with a 3D global convection simulation, under what conditions our starting assumption (no radial rotation gradient when meridional flow absent) would be true. It would also be useful to see whether imposing on such a model a meridional circulation like that observed would result in differential rotation contours closer to the observed profile than are now generated without this constraint. If this latter test were successful, it could mean that the weak spot in global convection models for the solar convection zone is to be found in the calculation of meridional circulation.