Abstract. We present updated observations of the pattern of migrating solar zonal flows known as the torsional oscillation, covering 15 years of helioseismic measurements with GONG and MDI and 30 years of surface Doppler observations from Mount Wilson. We compare the behavior of the flows during the extended solar minimum following Cycle 23 with that in earlier minima. We demonstrate that the timing of the migration of the zonal flow belts may be of some use in predicting the start of the new cycle. We also note that the behavior of the high-latitude part of the pattern currently differs from that seen early in the previous cycle, with the high-latitude poleward-migrating branch still not established.

1. Introduction
The migration of zonal flow bands from mid-latitudes to the equator and poles over the course of the solar cycle, first reported and dubbed the “torsional oscillation” by Howard and LaBonte [1] has been observed for 15 years [2; 3] by the Global Oscillation Network Group [GONG] and Michelson Doppler Imager [MDI] [4], and for over 30 years in surface Doppler measurements at the Mount Wilson Observatory [5; 6]. In recent years there has been a revival of interest in the relationship between these flows and the solar cycle, due to the extended solar minimum following cycle 23 [7].

2. Data and analysis
The helioseismic data consist of medium-degree rotational splitting coefficients derived from 145 overlapping 108-day intervals of GONG observations and 69 non-overlapping 72-day intervals of MDI observations, covering the period from May 1995 to April 2010. The rotation profile was inferred using 2-dimensional regularized least-squares inversions, and a temporal mean was subtracted from each set of inversions at each location in depth and radius to reveal the temporal variation in the rotation.

The Mount Wilson Doppler data, taken with the Babcock Magnetograph at the 150 foot tower, cover the period 1976 – 2009. The data are sampled at 34 points equidistant in the sine of the latitude, giving a separation of approximately 4° at low latitudes. Each Carrington rotation is divided into 18 pixels, giving a temporal resolution of about 1.5 days. For this study, the data
Figure 1. Rotation-rate residuals from RLS inversions at 0.99R⊙, for combined GONG and MDI data. The vertical white line at left (right) indicates the time at which the flow profile at latitudes below 45° best matches the most recent (earliest) observations; black contours represent unsigned magnetic field strength from KPVT and SOLIS.

Figure 2. RLS Rotation-rate residuals as a function of depth at latitudes 0° (a) to 60° (e) at 15° intervals. The grayscale is in nHz, and is non-linear (varying most rapidly across the zero contour).

were further averaged in time to give a sampling interval of approximately 2 months, similar to the time period used for the MDI global inversions.

3. Results

3.1. Helioseismic observations

Figure 1 shows the combined MDI and GONG zonal-flow residuals at 0.99R⊙ as a function of latitude and time. Clearly, as we reported in Howe et al. [7], the time for the flows to migrate from the 1995 position to the current position was longer in the declining phase of Cycle 23 than in the previous cycle, by 1.5 to 2 years. As in the previous cycle, significant magnetic activity started to appear once the flows reached a latitude of about 20°. The other noticeable feature of this plot is that the rotation rate poleward of the faster-rotating belts is still slower than it was in 1995, and there is little sign of the appearance of the new poleward branch, which was already starting to be visible in 1997.

Figure 2 shows the combined RLS rotation-rate residuals as a function of time and depth at selected latitudes. For clarity, the data have been smoothed with a one-year running mean. As
in the previous cycle, at lower latitudes we can see hints that for a given latitude the rotation speeds up in the middle of the convection zone a couple of years earlier than at the surface.

3.2. High-Latitude Residuals
Figure 3 shows the GONG and MDI RLS rotation-rate residuals for selected higher latitudes at a depth of $0.99 R_\odot$. At $52.5^\circ$ we can see that the rotation rate was increasing in 1997, whereas in 2009–10 it is still trending down or just starting to increase again. At $67.5^\circ$ the 1997.6 epoch seems to mark a minimum in the rotation rate, and it appears that this may be true in the recent data also. Finally, at higher latitudes the rotation rate was decreasing through 1997 to a minimum in 1999, whereas in the 2009–2010 observations it appears to have either reached a (higher) minimum after decreasing during the declining phase of Cycle 23, or to be still decreasing.

The “double peak” seen in the rotation rate at $0.99 R_\odot, 78.8^\circ$ is curious. Could it reflect different behavior in the northern and southern hemispheres? The new magnetic activity cycle in the southern hemisphere does seem to be more delayed than in the northern one.

![Figure 3](image)

Figure 3. Rotation-rate residuals at latitudes $52.5^\circ$ (a), $67.5^\circ$ (b), and $78.8^\circ$ (c), for GONG (open symbols) and MDI (closed symbols).

3.3. Doppler Observations
For historical context, in Figure 4 we show the Mount Wilson observations since 1975. The data have been symmetrized about the equator. The black contours show unsigned magnetic field strength. For each cycle, we see that the epoch most closely matching the current low-latitude flow pattern — when the equatorial branch of the pattern reaches about $20^\circ$ — corresponds to a time when significant and widespread activity had begun. In the previous two cycles the first hint of high-latitude zonal flow enhancement is also visible around this epoch, at least in the southern hemisphere, whereas in Cycle 24 it seems to be delayed.

4. Discussion
The torsional oscillation signal may provide some indication of the timing of the solar cycle in advance of the appearance of surface activity. At the current time, though the low-latitude branch for Cycle 24 is well established and the cycle is (finally) underway, the high-latitude branch has yet to appear. It will be interesting to see how the zonal flow pattern evolves with the new cycle, both in continuing observations from GONG and in new data from HMI.

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Figure 4. Rotation-rate residuals from Mt. Wilson data. The vertical light lines indicate the epochs where the zonal flow profile below 45° best matches the most recent helioseismic measurements; black contours show the unsigned magnetic field strength. The horizontal line at 20° North indicates the latitude of the flow belts at these epochs.

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