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The Effect of Latitudinal Averaging of Surface Tracers on Patterns of Torsional Oscillations

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Abstract. Latitudinal bands of faster/slower (relative to average) rate of rotation of solar plasma (also known as the solar torsional oscillations) are considered to be a fundamental property of the Sun, and are believed to be important for the solar dynamo. Torsional oscillations are derived from the measurements of the solar rotation at the photosphere and (indirectly, via methods of helioseismology) in the convection zone. Here, we raise a possibility that the pattern of the torsional oscillations could be a spurious feature resulting from a combination of the differential rotation, the latitudinal drift of tracers, and a weighted contribution of tracers within an averaging window used to determine the solar rotation rate. This spurious feature may have an effect on both the observations taken in the solar photosphere (e.g., Doppler velocity measurements and feature tracking techniques) and the helioseismic measurements.

1. Introduction

Studies of solar rotation revealed the presence of the latitudinal bands (or zonal flows), in which the rotation rate is heightened or reduced by a few meters per second relative to an average rotation rate for a given latitude. The latitude of these bands changes with the phase of the solar cycle: they start in mid-latitudes, and as the cycle progresses, gradually drift towards the equator mimicking closely the sunspots butterfly diagram. The pattern was discovered by Howard & Labonte (1980), who dabbed the phenomenon the torsional oscillations (TOs) of the Sun. Since then, the TOs have been observed in the photosphere using Doppler velocity measurements (Howard & Labonte 1980) and by employing the magnetic fields as tracers (Komm et al. 1993; Snodgrass & Dailey 1996), in the chromosphere and corona (Makarov & Tlatov 1997), and later, in the helioseismic measurements of subsurface velocity (e.g., Schou et al. 1998; Howe et al. 2000). Torsional oscillation-like pattern was also reported in observations of the current helicity of the large-scale magnetic fields (Pevtsov & Balasubramaniam 2003). Godoli & Mazzucconi (1982) raised the possibility that the signature of the torsional oscillations may be present in the sunspot position data. However, Gilman & Howard (1984) did not find such a pattern. Polar branches of TOs were found to be co-spatial with the pattern of the enhanced coronal activity that starts at the descending phase of a previous cycle and propagates poleward reaching both poles at about the maximum of the following cycle (so-called, “rush to the poles”, Altrock et al. 2008). The fact that the torsional oscillations’ pattern of a cycle develops well before the cycle starts drew a renewed attention to this phenomenon, both as a potentially fundamental feature of the solar dynamo, and as a possible forecasting tool. Thus, for example, the absence of polar branches of TOs at the beginning of Cycle 24 raised questions about the future of the Cycle 25 (Howe et al. 2011).

Residual velocities associated with the torsional oscillations pattern are extremely small, and may be a subject of various distortions. In this article we raise a possibility that the pattern can be significantly affected by a combination of the differential rotation, the latitudinal drift of tracers used to derive the solar rotation, and the weighting function for the traces within the averaging window used to derive the solar rotation. We argue that a care should be taken to separate the effects of this spurious pattern from the real pattern of the torsional oscillations.

2. Torsional Oscillations-like Pattern as an Artifact of the Latitudinal Averaging

The solar rotation can be derived by measuring the displacement of a selected feature (e.g., a sunspot) over a known period of time. To minimize the effects of noise and the proper motions, the displacements derived from tracking many features of the same class are averaged over a fixed range of latitudes. This latitudinal averaging is the key for understanding a development of a spurious pattern, which is reminiscent of pattern of zonal flows (torsional oscillations).

Let's imagine that there is a band of solar features in the Northern hemisphere gradually migrating through the averaging window from its top (higher latitudes, Figure 1a) to the bottom (lower latitudes, Figure 1c). All features in this band rotate with the same rate as the surrounding plasma, and their drift from higher to lower latitudes mimics the equatorward drift observed, e.g., in sunspots and many other solar features associated with the magnetic fields. When the features we track are at the top (bottom) of an averaging window (Figures 1a and 1c), average rotation rate will be determined mostly by the contribution of features located at higher (lower) latitudes. When the features are present everywhere inside the averaging window, the average rotation rate will represent a rotation rate characteristic to an average latitude inside the window. Thus, passage of a band of solar features across an averaging window will create an appearance of two bands (first, slower than average, and later, faster than average) drifting from high to low latitudes even though all features follow the rotation rate of a mean solar rotation profile.

To verify the above qualitative inferences, we run a simple model, in which a band of "activity" (15° wide in latitude and 30° in longitude) was created using a random number generator. The tracers represented by small circles were placed at random latitudes and longitudes within the band, and they were assigned the rotation rate according to their latitude. At the beginning of the experiment, two bands of "activity" were placed in two solar hemispheres at high latitudes. Next, the latitudinal rotation profile was computed by sampling all solar latitudes (± 90°) by 5° × 5° averaging window. For this exercise we employed the solar rotation profile as in Komm et al. (1993):

$$W(lat) = 14.38 - 1.95 \cdot \cos^2(lat) - 2.17 \cdot \cos^4(lat) \tag{1}$$

At the subsequent iterations, the band of tracers was gradually shifted in latitude to imitate the equatorward drift as in the solar butterfly diagram. The difference between the latitudinal profiles derived as above and the profile represented by the Equation 1, exhibits the pattern of a slower-than-average and faster-than-average rotation bands

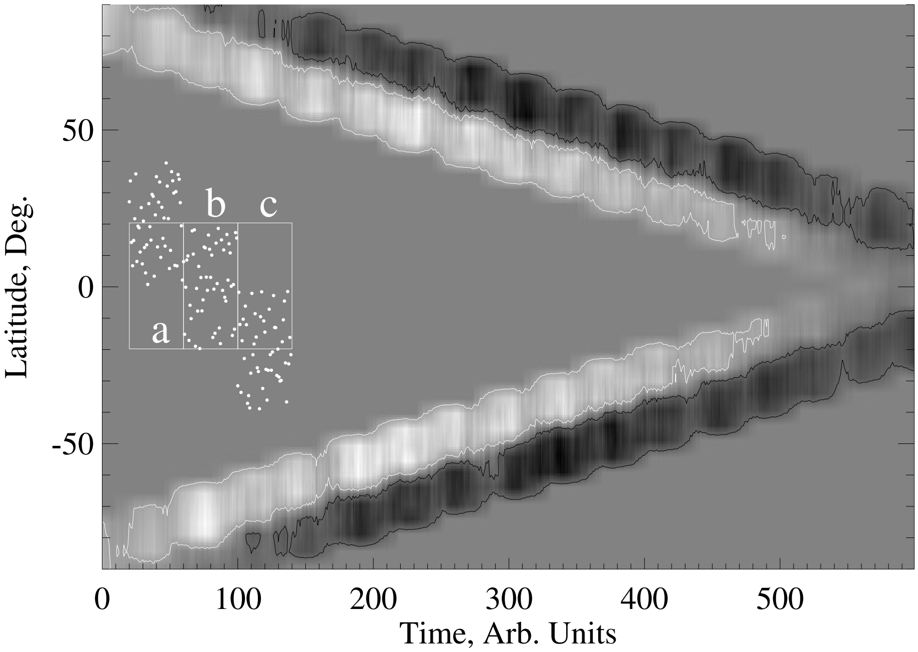

Figure 1. Pattern reminiscent of zonal flows with slower (dark) and faster (bright) rotation rate than the mean solar rotation represented by Equation 1, which develops when a band of features (small white circles) moves across of the averaging window (white rectangles).

consistent with the conclusions of our mental experiment. Thus, a combination of the differential rotation, latitudinal drift of tracers, and the weighting function of traces within the averaging window creates a pattern of the rotation bands reminiscent of the torsional oscillations (Figure 1). Deviations from the mean rotation profile from this model correspond to ±20 m/s, which is in a quantitative agreement with the observations of the torsional oscillations (Miesch 2005).

Next, we used a subset of the data set of magnetic bipoles studied by Tlatov et al. (2010). Only bipoles with magnetic flux larger than 100 Gauss were used for this test. Figure 9 in Tlatov et al. (2010) shows the latitudinal distribution of bipoles and their polarity orientation over about 35 years of observations. One can see a clear presence of the equatorward drifting branches (corresponding to a regular butterfly diagram) as well as the poleward moving arms. For the present article, we have extended the Tlatov et al. (2010) data through February 2011 using SOHO/MDI full disk magnetograms. For the purpose of our test, we only consider data from the period of Solar Cycle 23 (1996 – 2008) and the beginning of Cycle 24 (2009 – 2011). Butterfly (latitude vs. time) diagram corresponding to this dataset is shown in Figure 2. Strong equatorward and a weak poleward drifting branches in the latitudinal distribution of bipoles are readily identifiable.

Next, we applied the same rotation rate to all bipoles based on their latitude. For simplicity, all bipoles were assigned equal weights, and the final rotation rate was determined using 5° × 5° averaging windows centered at fixed latitudes for each day of observations with the latitudinal distribution of bipoles corresponding to that day.

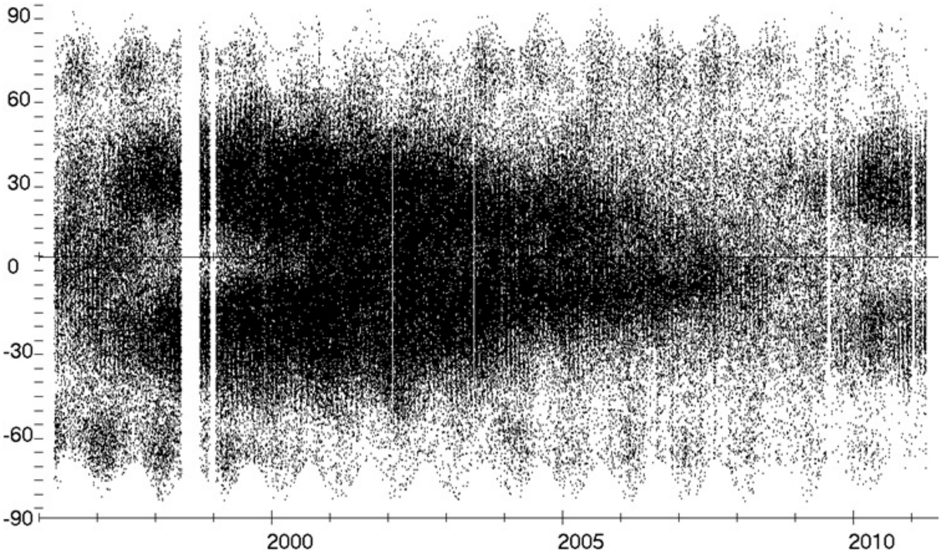

Figure 2. Latitude-time distribution of magnetic elements from SOHO/MDI magnetograms. In addition to strong equatorward drifting arms, weak poleward drifting branches can be identified as a slight increase in density of bipoles starting at about ± 60 degrees of latitude and drifting to higher latitudes through during 1996 – 1999, and again from 2003 – 2007. Only bipoles observed near the central meridian area of the solar disk were used for this plot. Vertical white bands correspond to missing data. "Wavy" edges at high latitudes are the result of the annual variation in B-angle (the latitude of the solar disk center).

Figure 3 depicts a difference between the mean profile from the Equation 1 and the average profiles derived as described above. One can see the bands of slower-/faster-then-average rotation drifting from the mid-latitudes to the equator and similar bands drifting towards the solar poles. Qualitative comparison with pattern of the torsional oscillations, e.g., from Howe et al. (2011) indicates their close similarities both in the overall time-latitude distribution and the amplitude.

3. Discussion

In Section 2, we used a "feature-tracking" method to demonstrate that the torsional oscillation-like patterns can appear as a combination of the differential rotation, the latitudinal drift of tracers, and the distribution of tracers inside the averaging window. However, our conclusions are equally applied to the measurements of the solar rotation using the Doppler observations of spectral lines and the helioseismic inversions.

As the features moving across the averaging window have different intensity, their contribution of the average profile of a spectral line used to derive the Doppler shift will be weighted in a similar way as in "feature-tracking" method resulting in a similar effect. Furthermore, in the case of the helioseismic inversions, the sound speed is affected by the presence of the magnetic fields within averaging pixel. If there is a band of magnetic features inside the averaging window, their contribution to the mean velocity

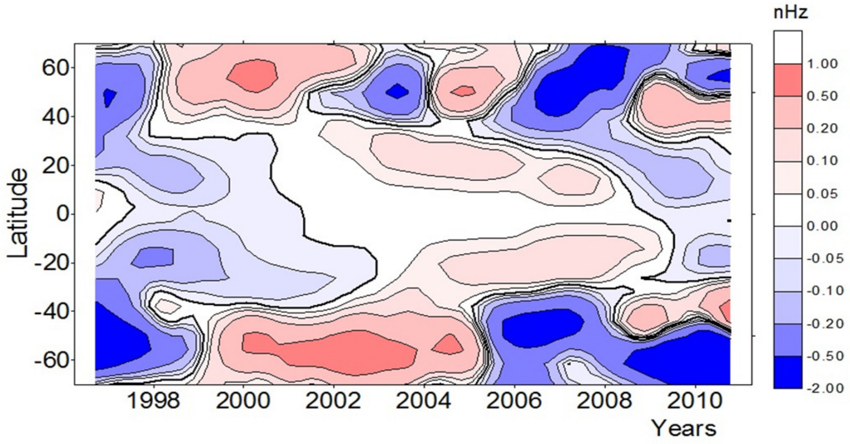

Figure 3. Time–latitude distribution of differences between the computed and the average profile of solar rotation (from Equation 1) showing torsional oscillation-like patterns of artificial zonal flows.

will be unequally weighted as compared with the pixels without the magnetic field. The latter can result in development of a similar pattern as in the "feature tracking" method. Howe (2009) found that the torsional oscillations are restricted to the upper portion of the convection zone, which could indicate that even if the magnetic bipoles are a near surface (photospheric) phenomenon, their effect on the helioseismic signal may "leak" to the sub-photospheric layers.

Several previous studies (e.g., Wilson et al. 1988; Tlatov et al. 2010) had demonstrated the presence of the extended solar cycle, with the magnetic activity of Cycle n appearing sometimes at the declining phase of Cycle $n - 1$, or well before the sunspots of Cycle n emerge at the solar surface. There also appear to be both the equatorward and the poleward drifting arms in the time–latitude distribution of the solar magnetic features (e.g., Tlatov et al. 2010). Thus, it is conceivable that the pattern of the torsional oscillations might be affected by the latitudinal averaging when these near surface magnetic features drift through the averaging window.

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