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# Solar large-scale flows obtained from the HMI time–distance data-analysis pipeline

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**Abstract**

Using the subsurface flow maps obtained from the HMI time–distance data-analysis pipeline, I examine the temporal evolution of torsional oscillation, meridional flow, and long-living large-scale structures in high-latitude areas. During the 5.5-year analysis period, both the torsional oscillation and meridional flow show strong hemispheric asymmetry while persisting the converging-flow patterns toward the activity belts. Meanwhile, for both hemispheres in the mid-latitude zone, the meridional-flow speed shows an anti-correlation with the magnetic flux being transported toward the pole, slowing down (speeding up) when following-polarity (leading-polarity) magnetic flux is transported. In the latitudinal band studied, the meridional-flow speed and magnetic field remained relatively unchanged from 2012 through 2015 in the northern hemisphere, but varied substantially during the same period in the southern hemisphere. Long-living large-scale structures, characterized by their low zonal speed, are observed in high-latitude areas, but the nature and cause of these structures are unknown.


*Keywords:* Helioseismology; Solar interior; Solar rotation; Meridional flow

## 1. Introduction

Large-scale flows inside the Sun play important roles in generating, amplifying, and transporting magnetic flux. Structures and temporal evolution of these large-scale flows have been intensively studied using different helioseismology analysis techniques. Global helioseismology provides a detailed profile of the solar differential rotation, with a rotational shear layer near the surface and a tachocline with substantial rotation gradient located near the bottom of the convection zone (e.g., Thompson et al., 1996; Kosovichev et al., 1997). These two locations are widely thought as where the solar dynamo operates (e.g., Choudhuri et al., 1995; Brandenburg, 2005). The global profile of the differential rotation does not stay the same through different phases of a solar cycle, but exhibits gradual changes that are closely related to the migration of the solar activity zones toward the equator. These faster and slower zonal-flow bands are known as the torsional oscillation (e.g., Howe et al., 2013). However, whether the activity belts cause the torsional oscillation or the torsional oscillation causes the activity belts is unclear.

Meridional flow inside the Sun is believed to play a role in transporting the internal magnetic flux and angular momentum. Its detailed structure is not yet as clearly known as the internal rotational profile, although substantial progress has been made in recent years. Hathaway (2012) reported an equatorward flow shallower than previously thought by analyzing supergranular features. Time–distance helioseismic analysis using HMI data agreed with the finding of shallow equatorward flow, and further suggested a double-cell circulation profile in each hemisphere (Zhao et al., 2013). A global helioseismic analysis reported the possibility of multiple circulation cells in both radial

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and latitudinal directions (Schad et al., 2013). Later time–distance travel-time measurements using GONG data agreed with the measurements using HMI (Kholikov et al., 2014), but the inversion results from these measurements did not show a flow profile systematically consistent with the HMI inversion results (Jackiewicz et al., 2015). A more recent time–distance analysis using HMI data claimed a single-cell circulation (Rajaguru and Antia, 2015). All these recent results suggest that an accurate determination of the Sun's meridional-flow profile still needs further improvements in analysis techniques and accumulation of more observations.

Due to the difficulty in probing the low-speed flow in the deeper interior, studies on temporal variation of the meridional flow mainly focus on the depths shallower than approximately 30 Mm. It was reported that the residual meridional flow, obtained after subtracting a quiet-period meridional-flow profile, converges toward the activity belts (e.g., Zhao and Kosovichev, 2004; Gizon, 2005; Komm, 2015), and this converging flow pattern extends to solar minimum years when there are no activity belts (González Hernández et al., 2010). More recently, based on the HMI time–distance data-analysis pipeline results (Zhao et al., 2012), Zhao et al. (2014) confirmed that the shallow converging flow trend continues during the rising phase of cycle 24. Moreover, they reported that above latitude 35° for both hemispheres, the meridional-flow speed shows an anti-correlation with the local net magnetic flux, i.e., the flux-transport speed slows down when the magnetic flux being transported has opposite sign to the polar region. In this paper, with more data accumulated, we examine the further evolution of the torsional oscillation and shallow meridional-flow profiles.

Giant cells are thought of as large-scale convective cells inside the Sun, although their existence and reliable detection are often controversial. Recently, Hathaway et al. (2013) reported a detection of long-living large-scale structures in the Sun's high-latitude areas, which were speculated by these authors as giant cells. Later ring-diagram analyses using HMI data found structures consistent with the earlier report (Bogart et al., 2015; Howe et al., 2015). In this paper, we report on a similar detection of long-living large-scale structures using the HMI time–distance pipeline results.

## 2. Torsional oscillation and meridional flow

Results presented in this section use the data produced by the HMI time–distance data-analysis pipeline (Zhao et al., 2012), and are an update of the results reported earlier by Zhao et al. (2014). Nearly two years has passed since these results were published and the Sun already passed its activity maximum of cycle 24 and entered its decaying phase; therefore it would be interesting to examine whether the phenomena reported previously have changed or still persist. For the description of data reduction and analysis procedure, please refer to the two articles mentioned above.

### 2.1. Torsional oscillation

Fig. 1 shows a magnetic butterfly diagram, i.e., evolution of the magnetic field from 2010 through the end of 2015 observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012; Schou et al., 2012) onboard the *Solar Dynamics Observatory* (*SDO*; Pesnell et al., 2012). In the following, these magnetic structures will be used to compare with the zonal- and meridional-flow structures.

Fig. 2 shows the torsional oscillation during the analyzed period. The torsional oscillation manifests as faster and slower zonal bands residing on both sides of the activity belts. Zhao et al. (2014) reported that during the rising phase of cycle 24, the torsional oscillation shows clear hemispheric asymmetry, with the faster branch in the northern hemisphere about 4° (1° represents 1 heliographic degree) closer to the equator than the faster branch in the southern hemisphere. They also reported that near the end of their analysis period, in January 2014, it seemed that the faster branch in the northern hemisphere crossed the equator into the southern hemisphere. With two more years observations available, it becomes clear that the faster branch of the northern hemisphere did not cross the equator near January 2014. It briefly arrived at the equator and then bent back. Since then, that branch stayed relatively flat, mostly in parallel with the equator. In contrast, the faster branch in the southern hemisphere grew stronger, migrated closer to the equator, and eventually met its counterpart of the northern hemisphere.

The torsional oscillation patterns in Fig. 2 are in general agreement with the patterns derived using global helioseismology and ring-diagram analysis (see Komm and Howe, 2014). One main difference between our results and theirs may be that the faster branches in the time–distance results are closer to the equator than those in the ring-diagram results (Komm and Howe, 2014) near the middle of 2013.

### 2.2. Meridional flow

As introduced in Section 1, temporal evolution of solar meridional flow has been studied by many authors. Fig. 3 shows the evolution of the residual meridional flow, obtained after a mean meridional-flow profile is subtracted. The residual flow exhibits a converging flow pattern toward the activity belts in both hemispheres, and this is consistent with previous reports. Moreover, there are two points that need to be emphasized regarding this converging-flow pattern:

1. Although the residual meridional flow also shows faster and slower patterns on either side the activity belts, the patterns do not resemble those of the torsional oscillation. Apparently, at the depth of 0–1 Mm, the faster branch in the northern hemisphere ended around the middle of 2013, although its counterpart in the southern