Removal of Active Region Inflows Reveals Solar Cycle Scale Trends in Meridional Flow

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Abstract/Take home message

Using time-distance local helioseismology[1] flow maps within 1 Mm of the solar photosphere, we detect inflows toward activity belts that contribute to solar cycle scale variations in near-surface meridional flow. These inflows stretch out as far as 30 degrees away from active region centroids. If active region neighborhoods are excluded, the solar cycle scale variation in background meridional flow diminishes to below 2 m/s but still shows systematic variations in the absence of active regions between sunspot cycles 24 and 25. We, therefore, propose that the near-surface meridional flow is a three component flow made up of: a constant baseline flow profile that can be derived from quiet Sun regions, variations due to inflows around active regions, and solar cycle scale variation of the order of < 2 m/s. Torsional oscillation, on the other hand, is found to be a global phenomenon i.e. exclusion of active region neighborhoods does not affect its magnitude or phase significantly. This non-variation of torsional oscillation with distance away from active regions and the three-component breakdown of the near-surface meridional flow serve as vital inputs for solar dynamo models and surface flux transport simulations.

Data & Methodology

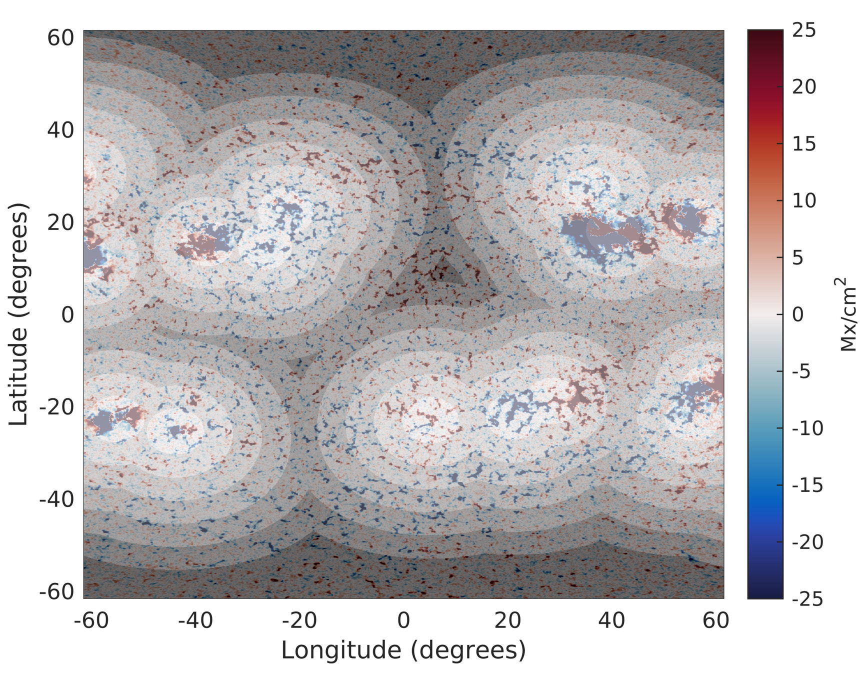

Figure 1: A magnetogram (magnetic field values represented by the color bar) from 2012 March 12 04:00:00 TAI with annuli around active regions depicted by translucent gray areas. Darker shades represent larger distances in steps of 5° away from active region centroids up to 30°. We look for the variation of meridional flow and torsional oscillation as a function of distance away from active regions by averaging the velocity maps in each of the shaded regions.

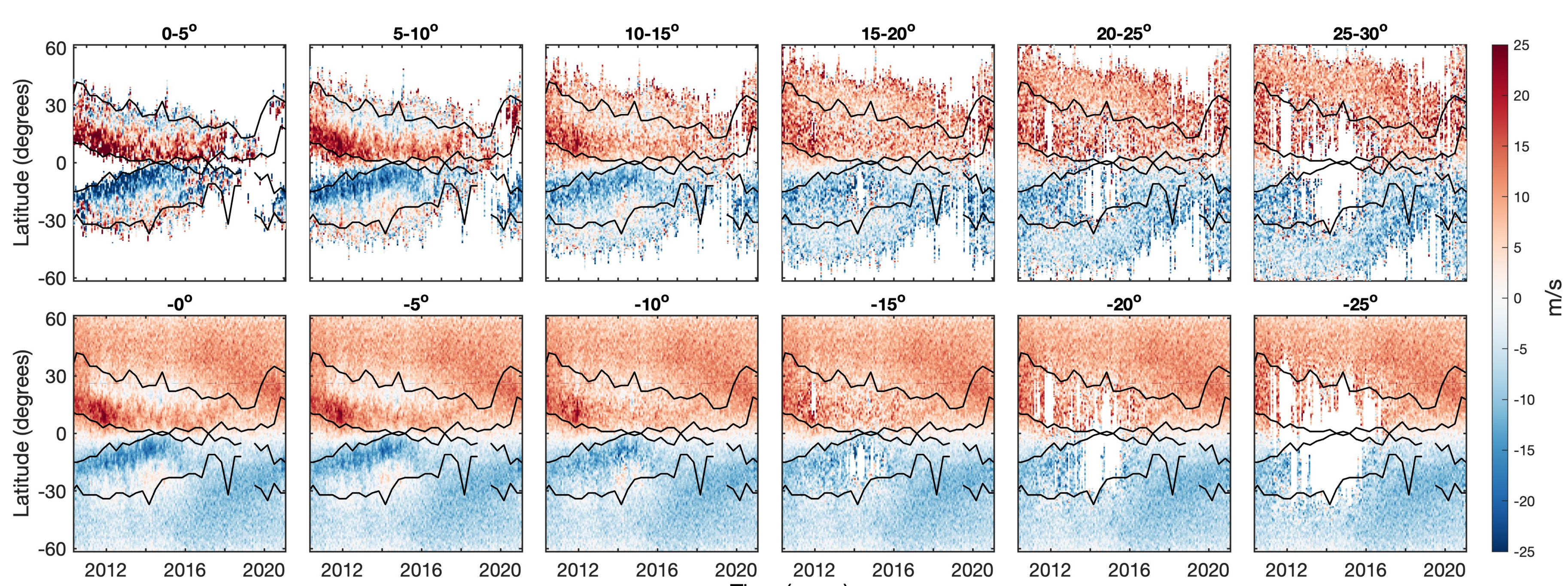

Figure 2: *Top row:* Meridional flow (MF) derived only from active region neighborhoods, within the annuli marked above each panel, averaged every Carrington rotation. All neighborhood sizes are in heliographic angular distance and measured with respect to the unsigned flux weighted centroid of the active regions reported in SHARP[2] metadata. *Bottom row*: Background MF derived after removing active region neighborhoods from velocity maps with their sizes marked above (negative sign represents exclusion of these areas). The annuli around active regions show less solar cycle scale variation in MF as the annulus size increases, as does the background MF with larger active region neighborhoods excluded. Here and throughout this poster, the black curves denote the active latitudes.

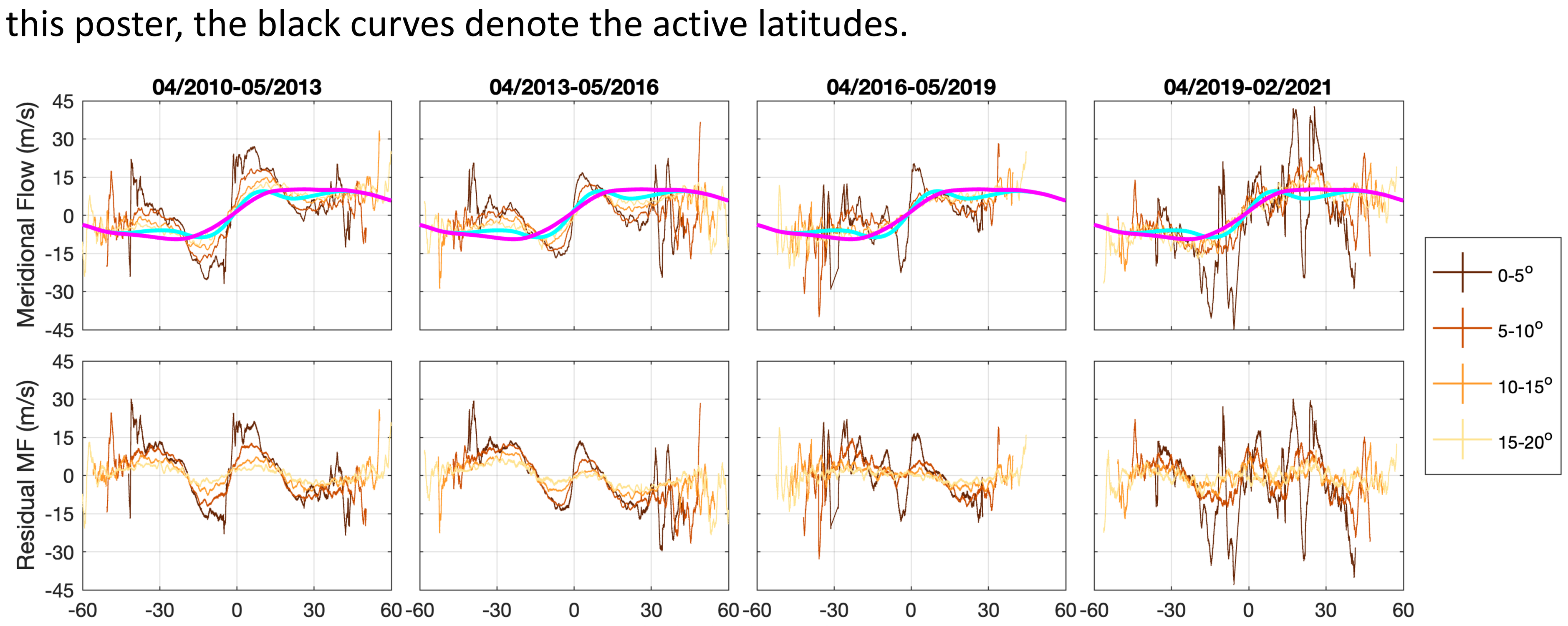

Figure 3: *Top row:* Temporally averaged meridional flow profiles obtained in different annuli around active regions. The baseline meridional flow is shown in magenta whereas the meridional flow averaged over all data is shown in cyan for reference. Meridional flow in different annuli bins are shown in yellow/orange colors. The thickness of the lines depict typical uncertainties. *Bottom row:* Same as top row, showing residuals after removal of baseline (magenta) meridional flow profile.

References

[1] Zhao, J., Couvidat, S., Bogart, R. S., et al. 2012b, SoPh, 275, 375, doi: 10.1007/s11207-011-9757-y
[2] Bobra, M. G., Sun, X., Hoeksema, J. T., et al. 2014, SoPh, 289, 3549, doi: 10.1007/s11207-014-0529-3

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Baseline Meridional Flow

Baseline Meridional Flow is calculated as the mean flow (averaged over cycle 24) obtained from more than 30° (heliographic) and 48 hours away from all active regions. It is further smoothed with a 15° FWHM Gaussian running mean. As indicated by the second row of Fig. 2, this profile is heavily reliant on meridional flow close to sunspot minima due to missing data during the sunspot maximum.

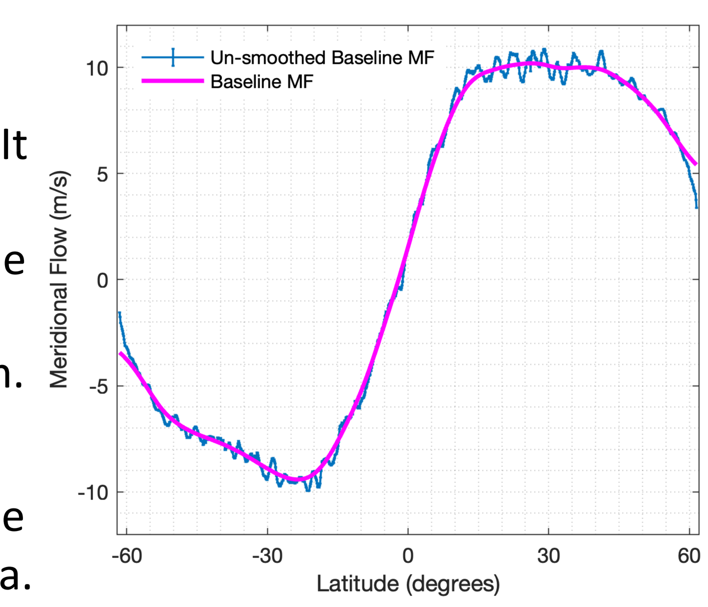


Figure 4: Measured baseline meridional flow is shown in blue. Statistical errors are included in thickness of the blue curve. The smoothed baseline profile is shown in magenta.

Solar-Cycle-Scale Trend in Meridional Flow

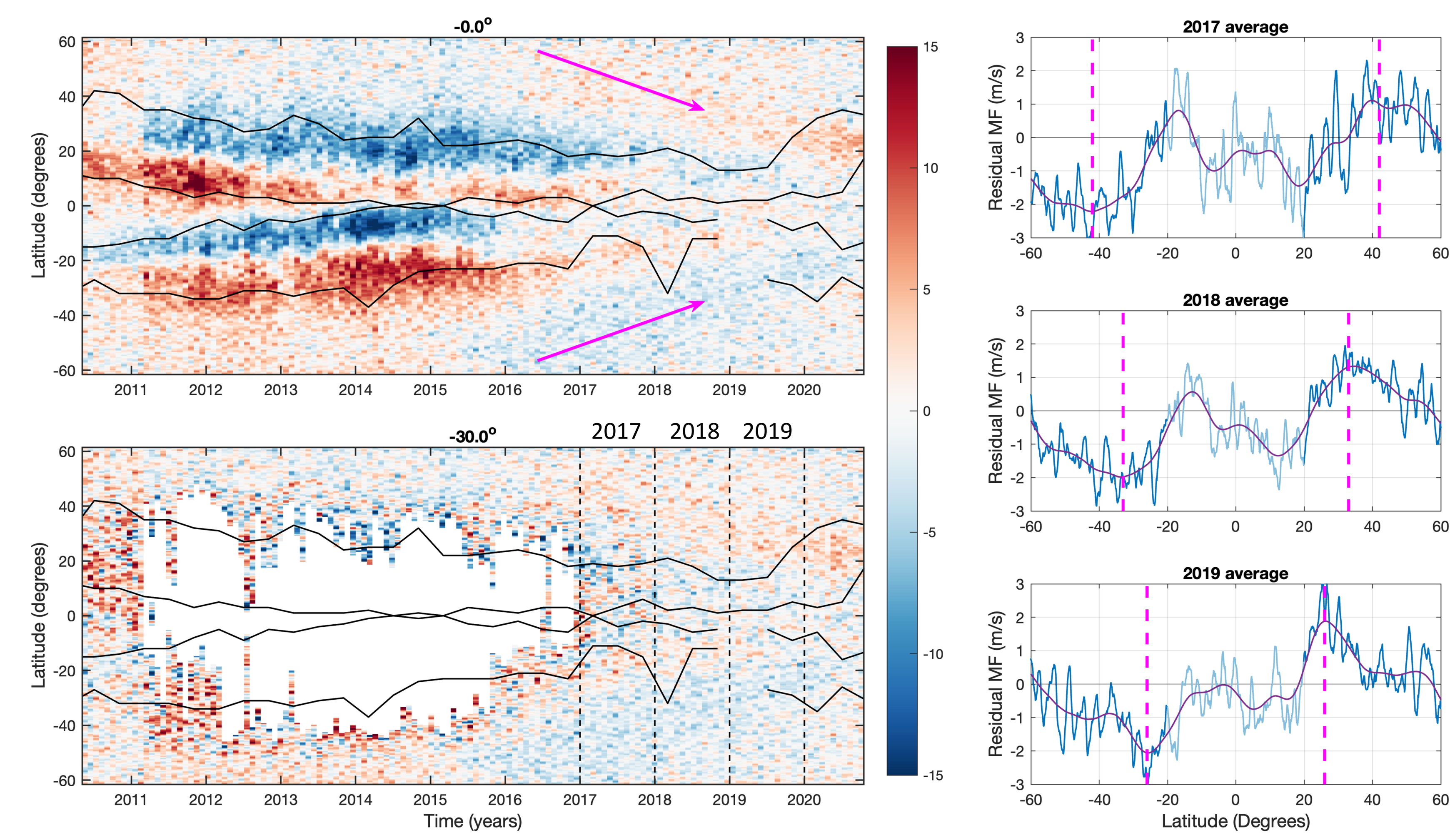


Figure 5: *Top left:* Residual meridional flow (after baseline flow subtraction) measured everywhere averaged over all Carrington rotations shows strong inflows into activity belts and weak bands of faster meridional flow migrating toward the equator near the end of solar cycle 24 (marked by magenta arrows). *Bottom left:* Residual meridional flow farther than 30° around active regions still shows weak equatorward migrating bands. *Right:* Meridional flow farther than 30° from active regions averaged over the years 2017 (top), 2018 (middle) and 2019 (bottom) shows that the amplitude of these bands is ~2 m s−1. The locations of the equatorward propagating bands in each year are marked by dashed magenta lines.

Torsional Oscillation

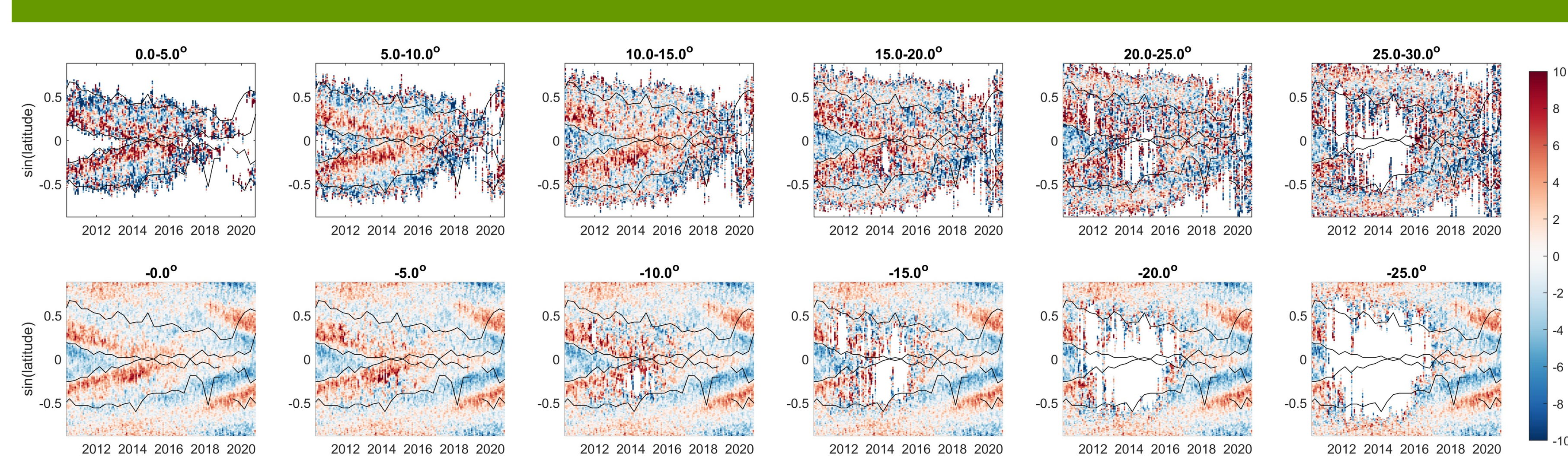
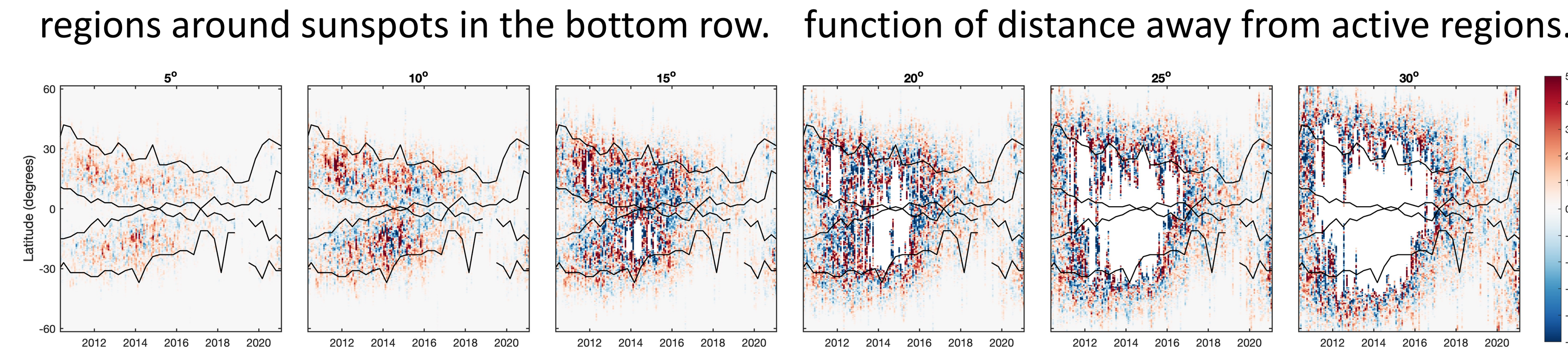


Figure 6 (above): Similar to Fig. 2, but for torsional oscillation within several annuli around active regions in the top row and torsional oscillation outside excluded regions around sunspots in the bottom row.

Figure 7(below): The difference between each panel in the bottom row of Fig. 6 and torsional oscillation measured everywhere shows no clear trend in torsional oscillation as a function of distance away from active regions.



Physical Insights for the Solar Dynamo

1. Removal of active region neighborhoods removes most variation in meridional flow, but a solar-cycle-scale trend in meridional flow of the amplitude of ~2 m/s remains (Fig. 5)
2. This solar-cycle-scale trend of faster than average meridional flow appears between solar cycles 24 and 25 and is disparate from active regions (see magenta arrows in Fig. 5)
3. Inflows around active regions stretch as far as 30 degrees (heliographic) away (Figs. 2 & 3)
4. However, torsional oscillation is omnipresent and does not change significantly with distance away from active regions (Figs. 6 & 7)
5. Thus, the active region inflows in East-West direction cancel out and do not contribute to torsional oscillation