Large-Scale Subsurface Flows during Solar Cycle 23 and 24

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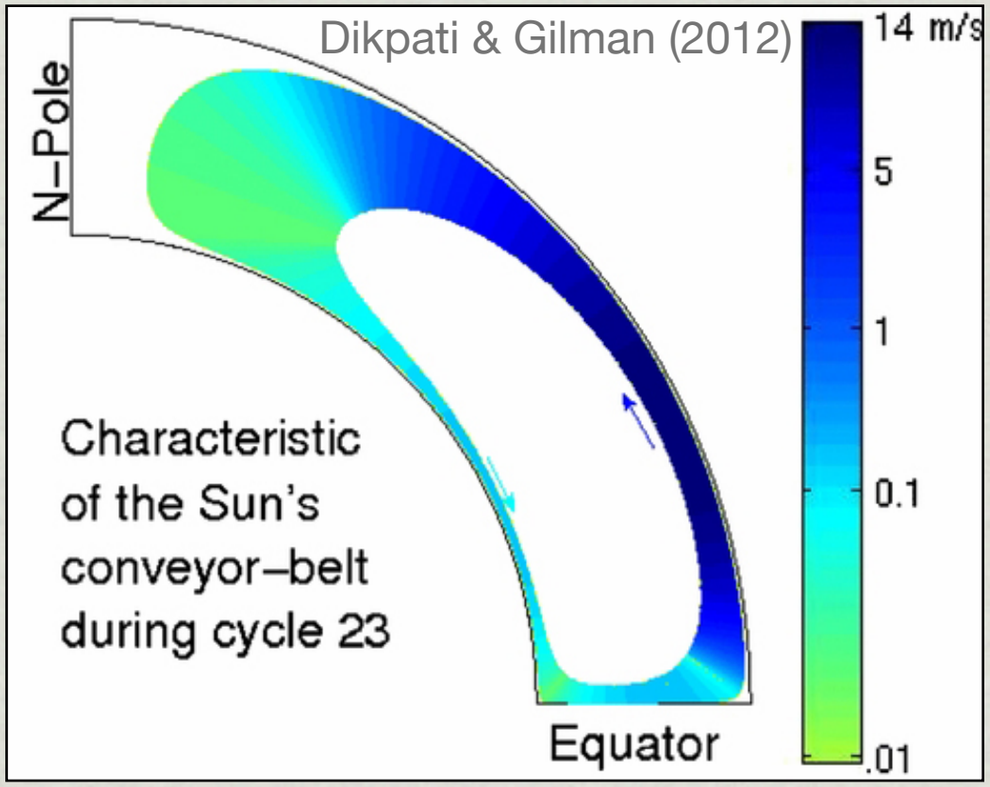
Introduction

- The zonal and meridional flow vary with the solar cycle. What does this tell us about magnetic activity?

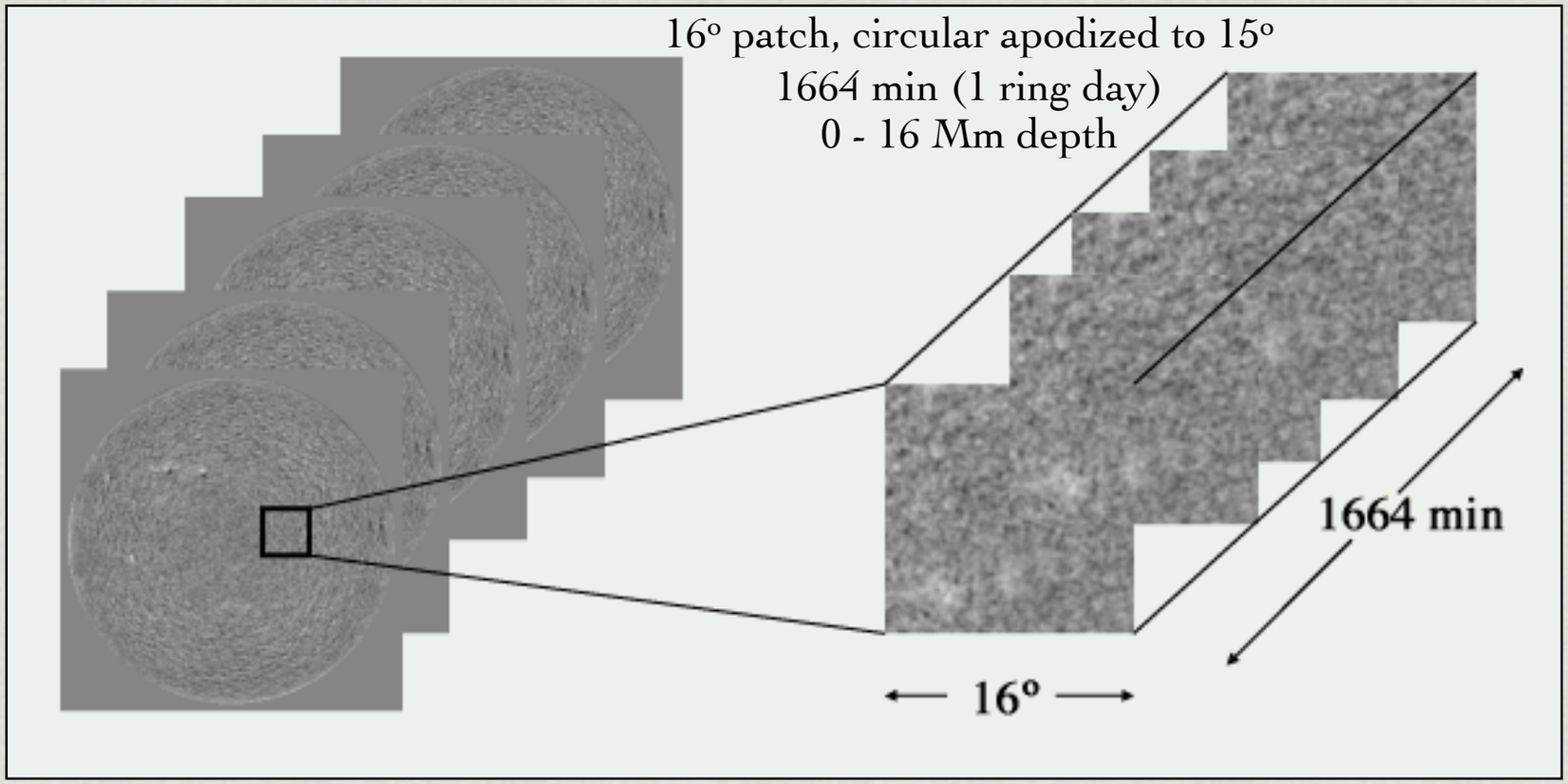
- The structure and strength of the meridional flow sets the timing of the solar cycle in flux-transport models.

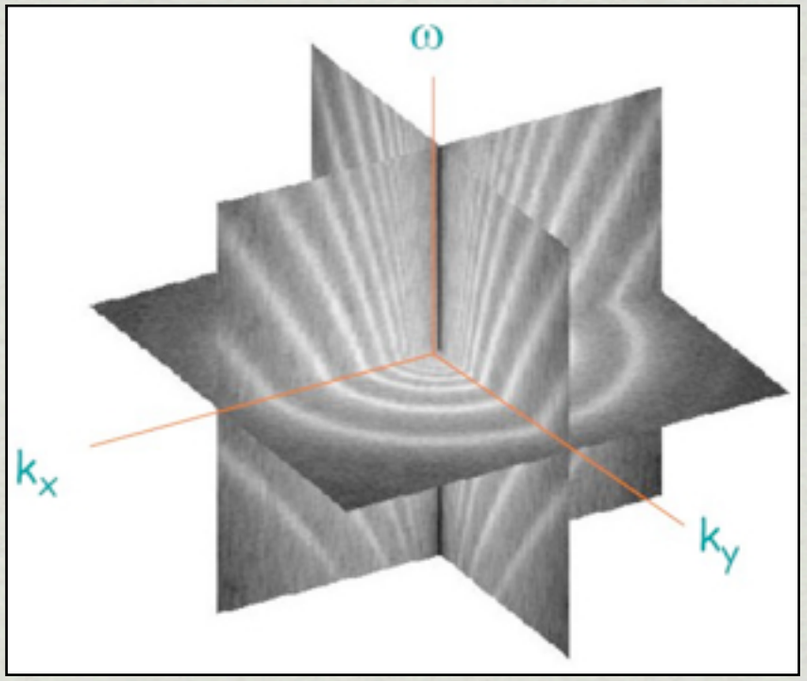


Introduction

- Subsurface flows from ring-diagram analysis (0-16 Mm) covering Solar Cycle 23 and 24:
  - SOHO/MDI (since May 1996)
  - GONG + (since July 2001)
  - SDO/HMI (since May 2010; up to 75° latitude).
- The rotation rate is about 2000 m/s (equator, surface), the meridional flow is about two orders of magnitude smaller. Their cycle variation is about 5-7 m/s.

Ring-Diagram Analysis

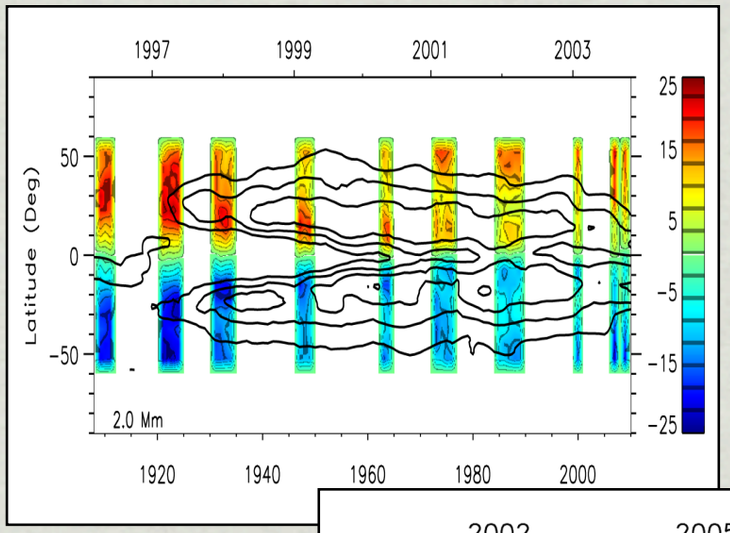




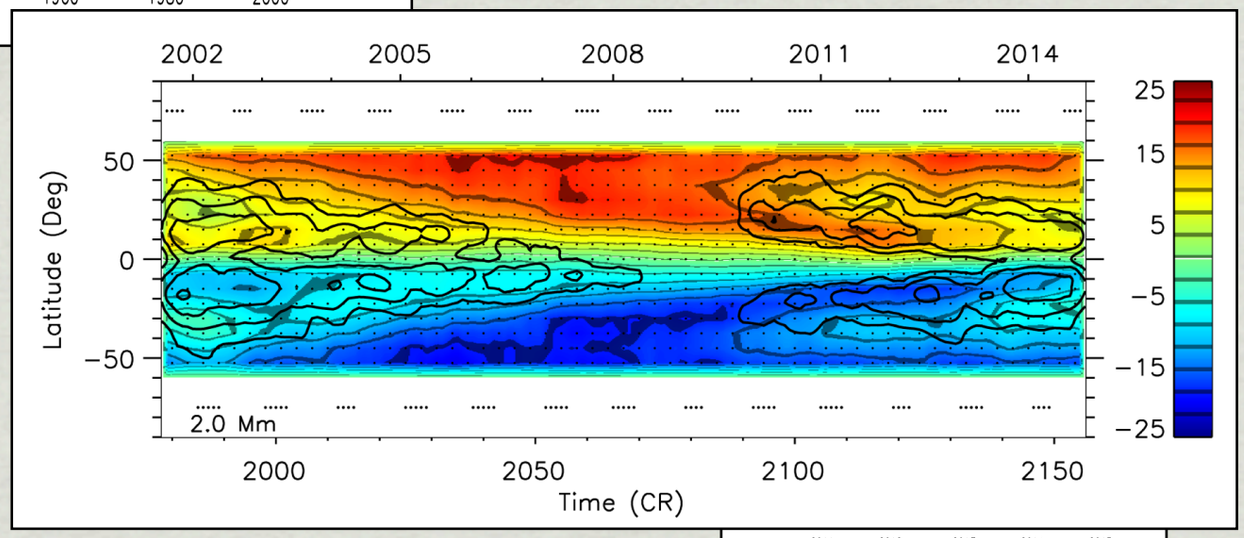
Patches are tracked in full-disk Dopplergrams (left). Ring displacements in power spectrum lead to estimates of horizontal velocities (right).

Solar cycle and meridional flow

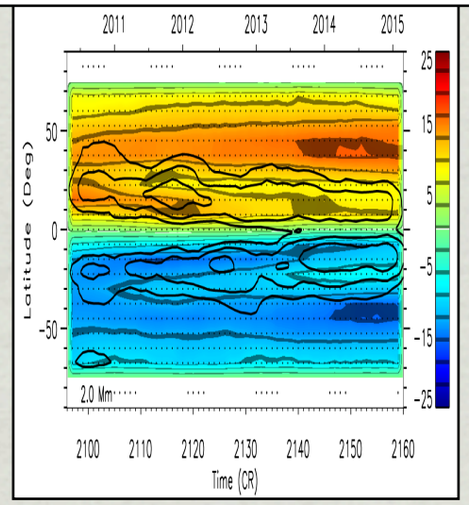
MDI



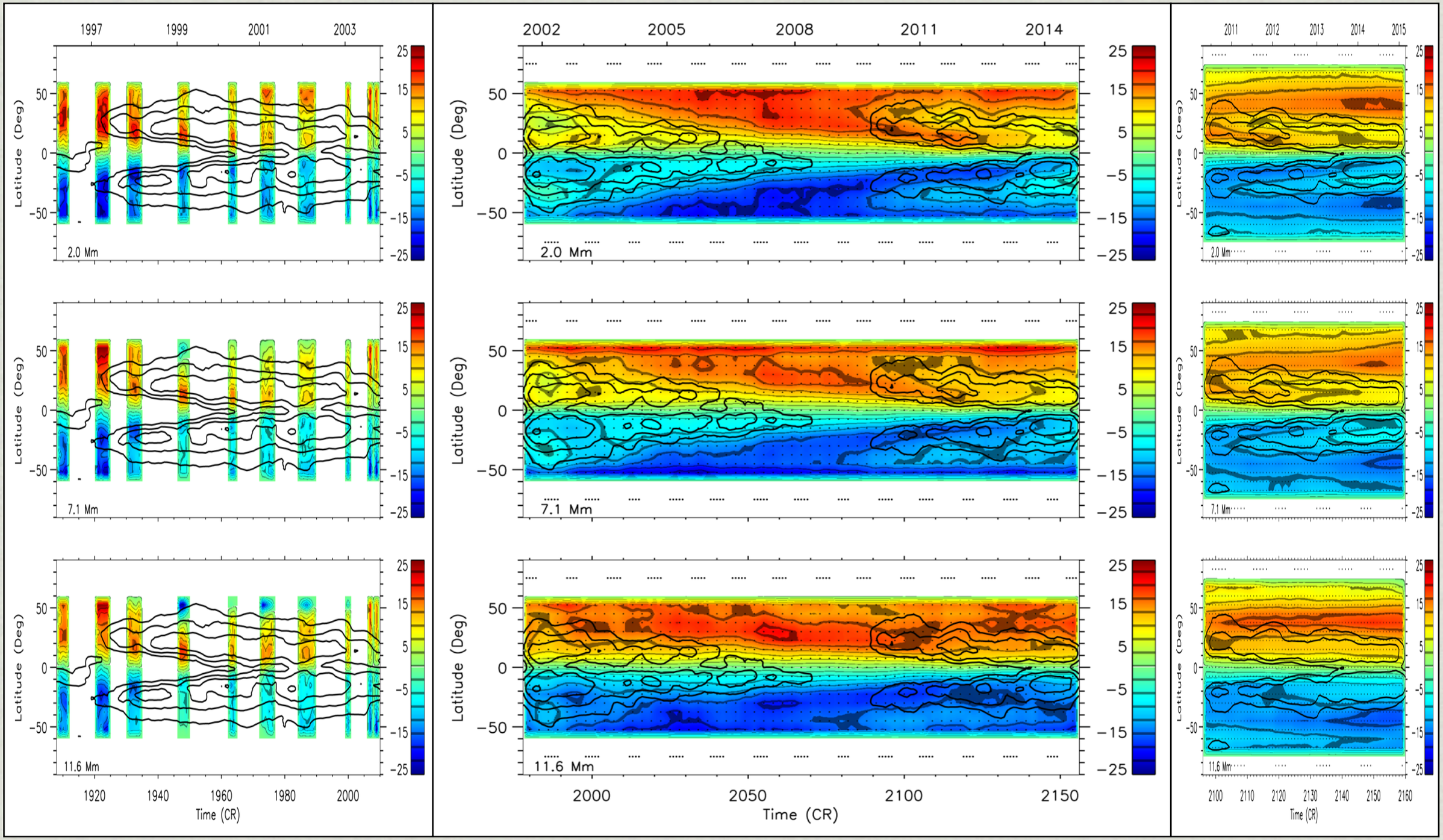
GONG



HMI

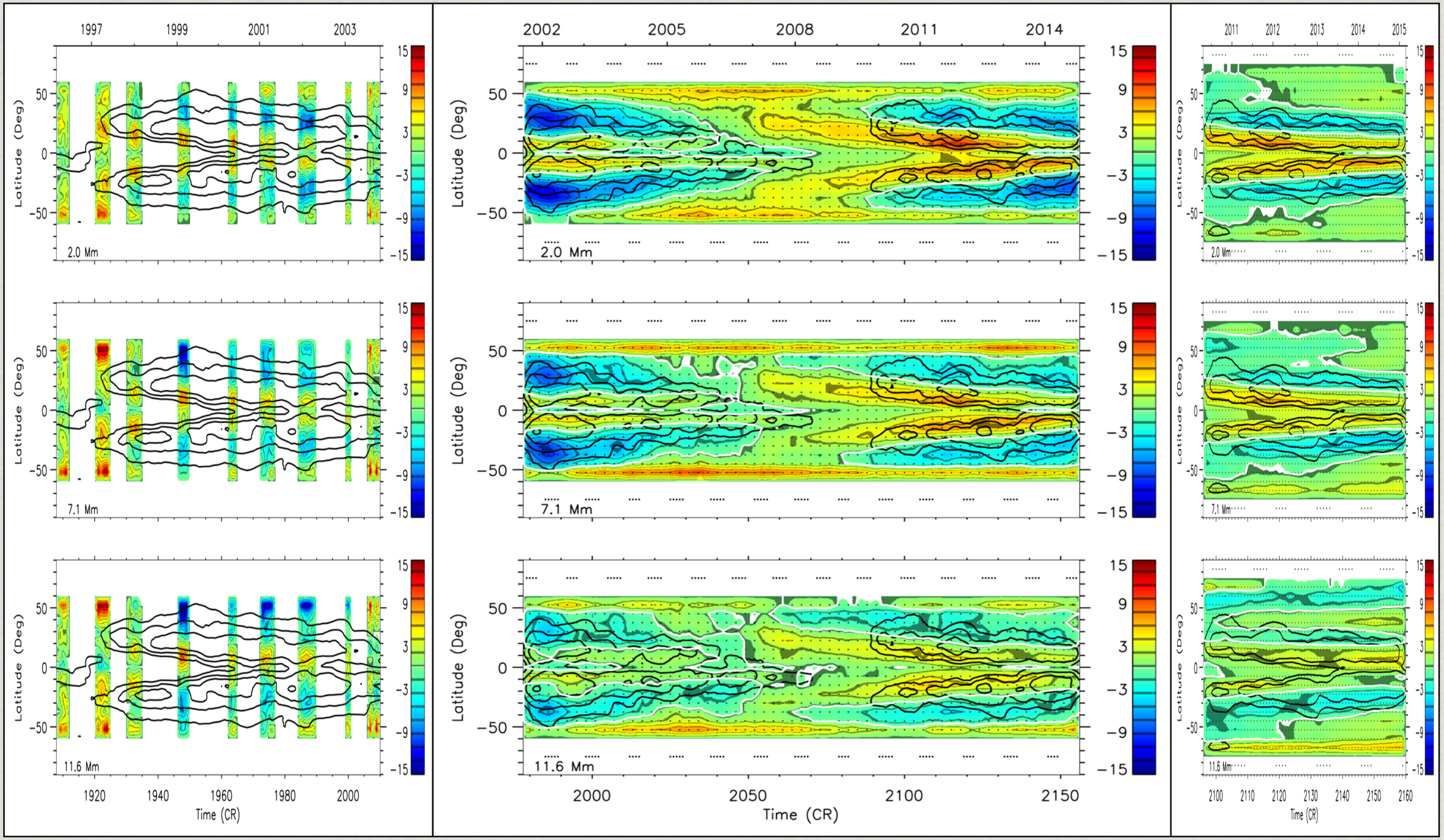


Solar cycle and meridional flow



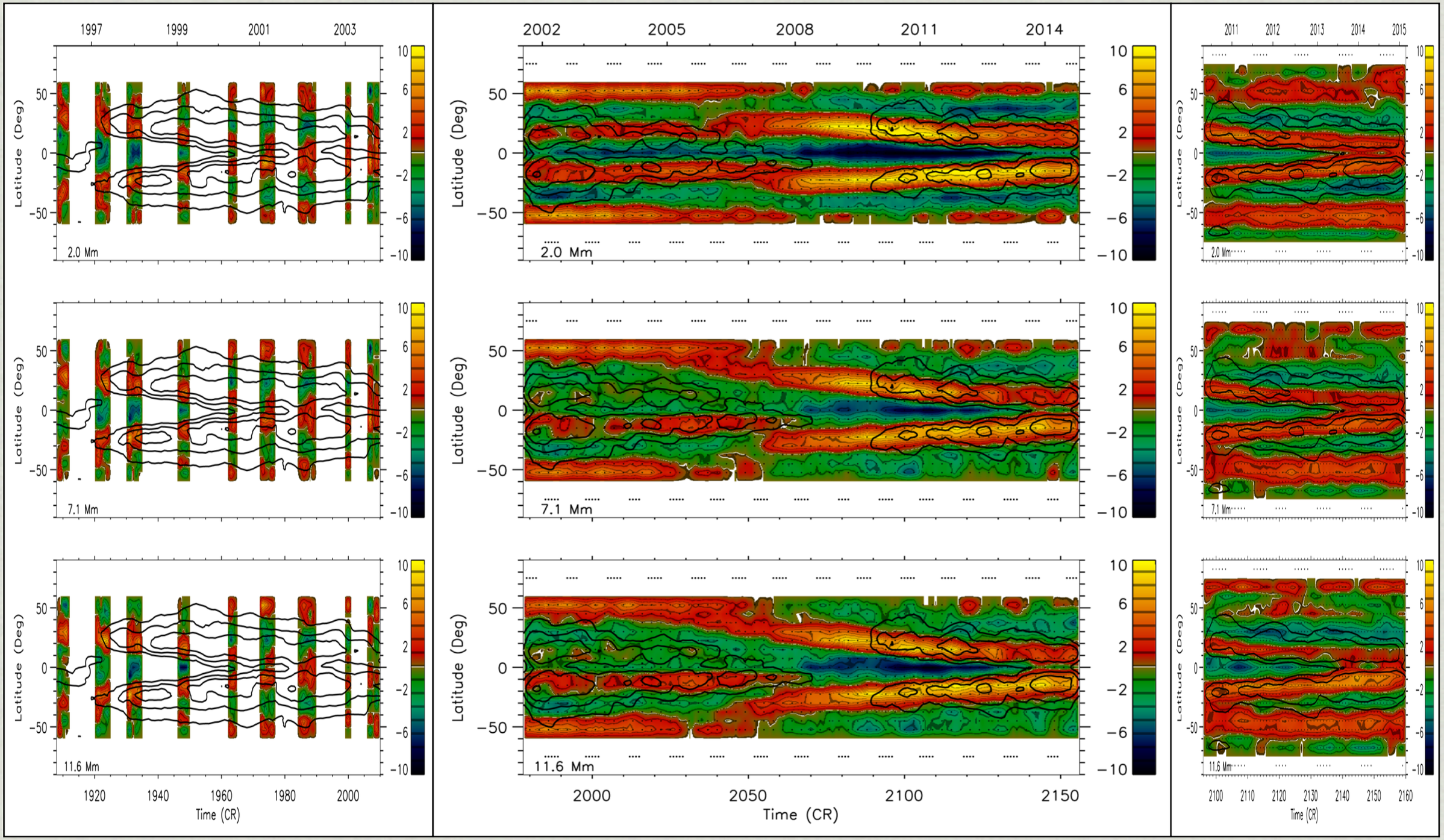
MDI GONG HMI

Residual meridional flow



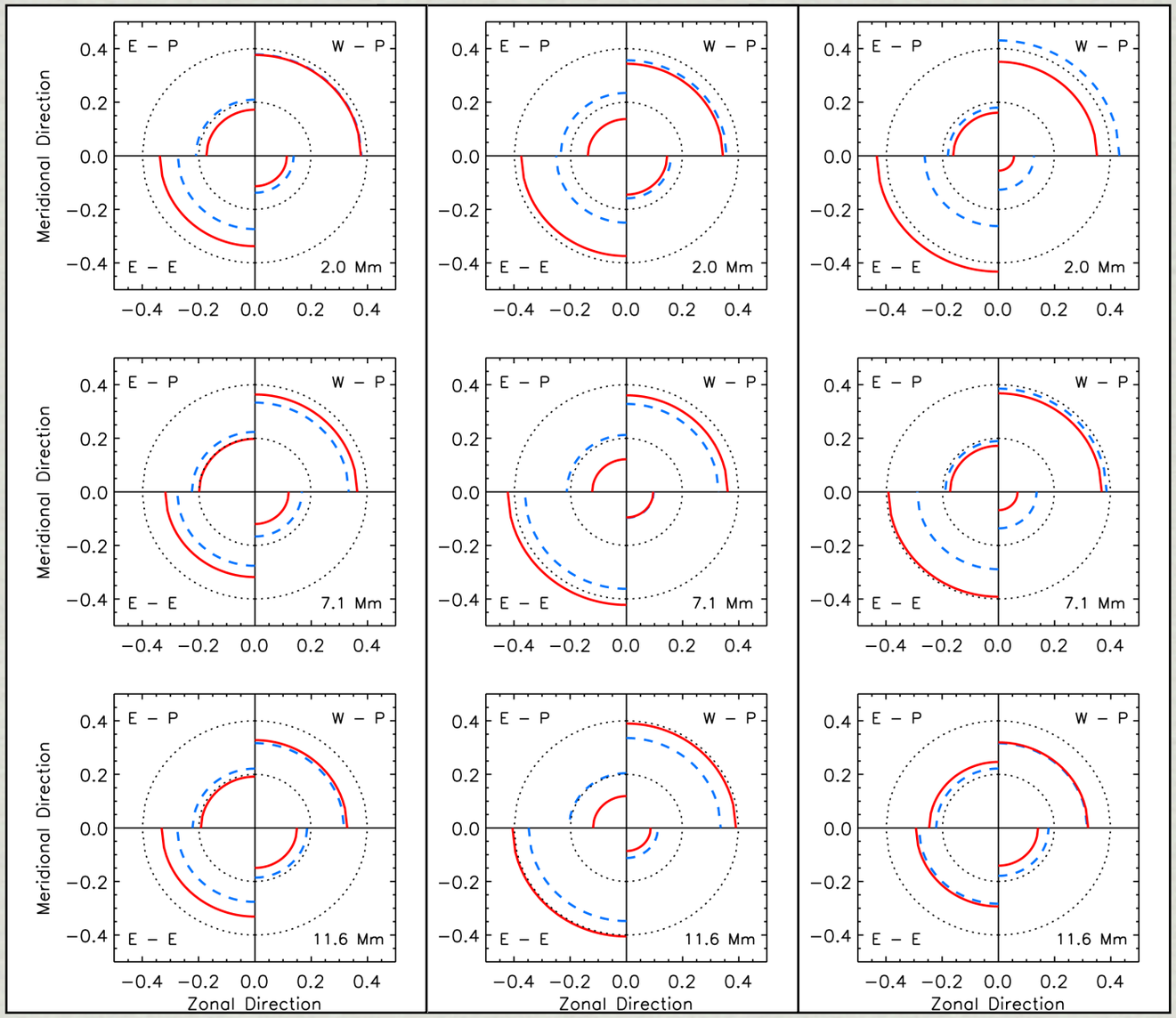
MDI GONG HMI

Solar cycle and zonal flow



MDI GONG HMI

Direction of residual flows



MDI GONG HMI

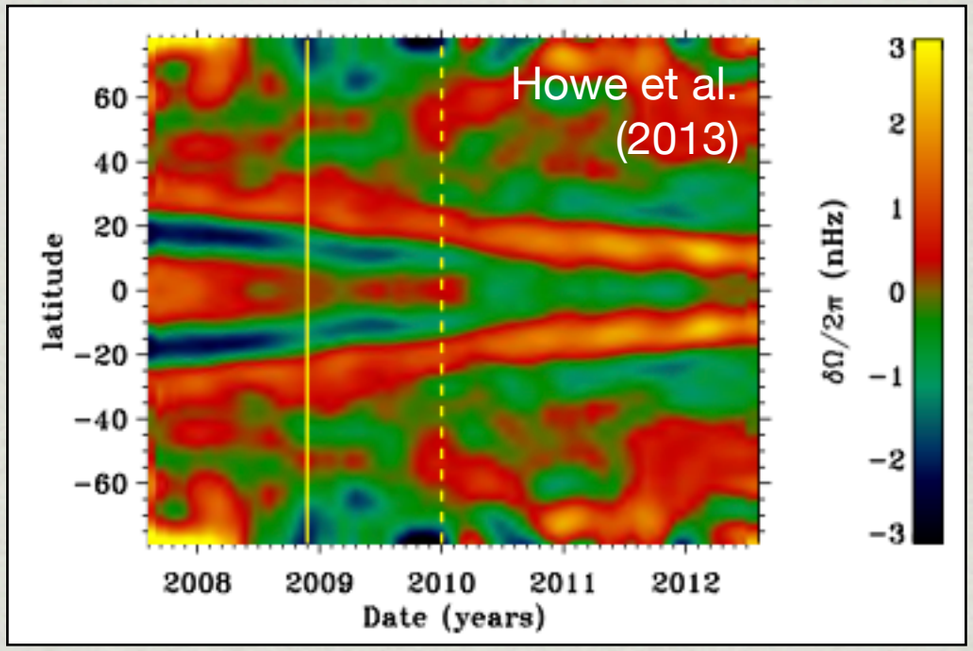
The majority of locations (70-80%) has either
(i) westward zonal flow with poleward residual meridional flow or
(ii) eastward zonal flow with equatorward residual meridional flow.

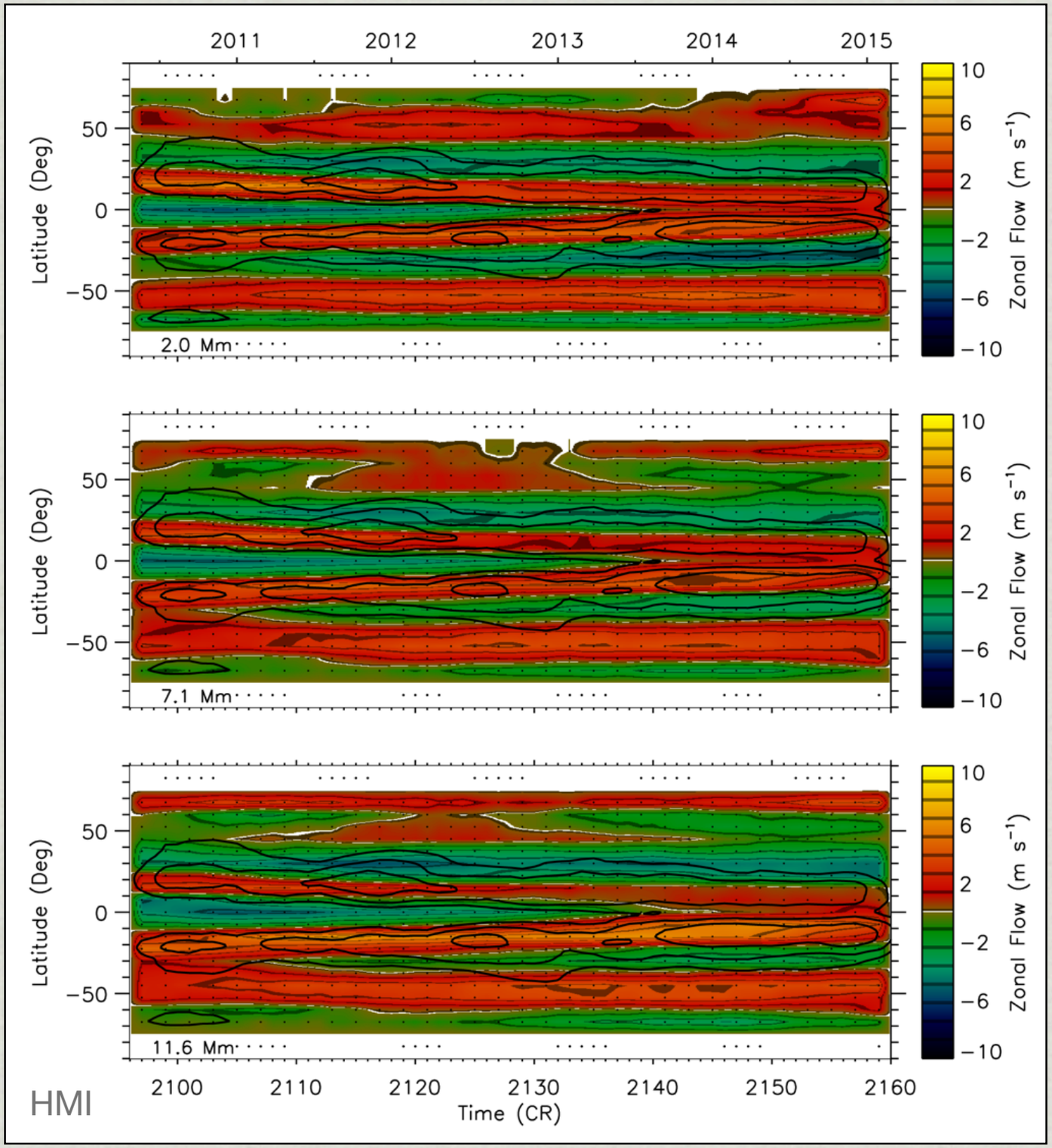
Residual flows pointing
(i) westward and poleward (W-P),
(ii) eastward and poleward (E-P),
(iii) eastward and equatorward (E-E),
(iv) westward and equatorward (W-E).

Summary (1)

- The amplitudes of the meridional flow are large during cycle minimum and small during cycle maximum.
- The residual meridional flow shows migrating bands of converging flows, while the zonal flow shows migrating bands of faster- and slower-than-average flows.
- Precursor of magnetic activity: the flow patterns appear about 3-4 years before magnetic activity is present.
- Are the flows due to surface cooling (Spruit, 2003) or the Lorentz force (Schüssler, 1981)?

Poleward branch: zonal flow



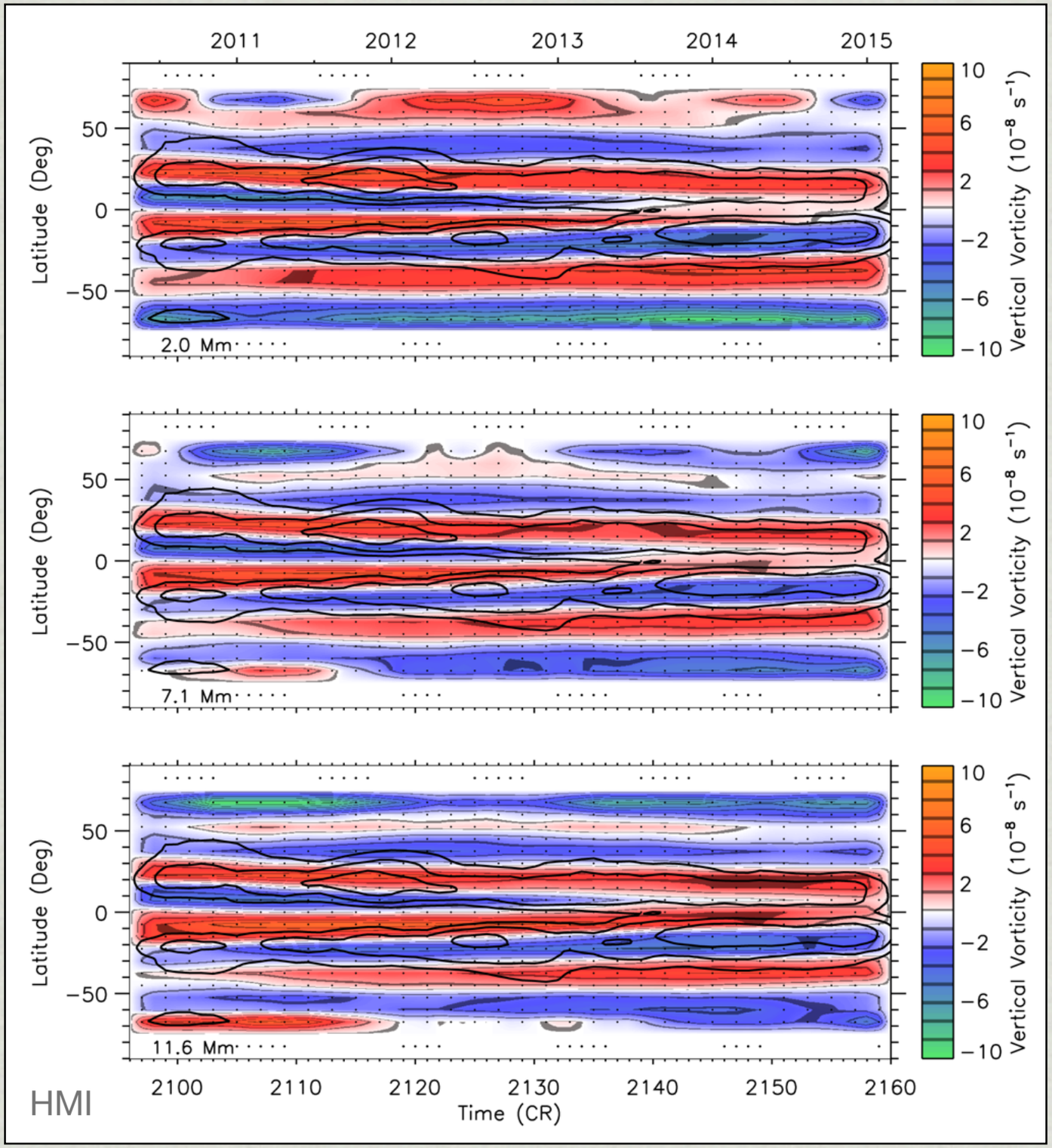


Fast zonal flows are seen at 50° latitude in global results (top-left).
The poleward branch is visible in ring-diagram flows especially in the southern hemisphere.

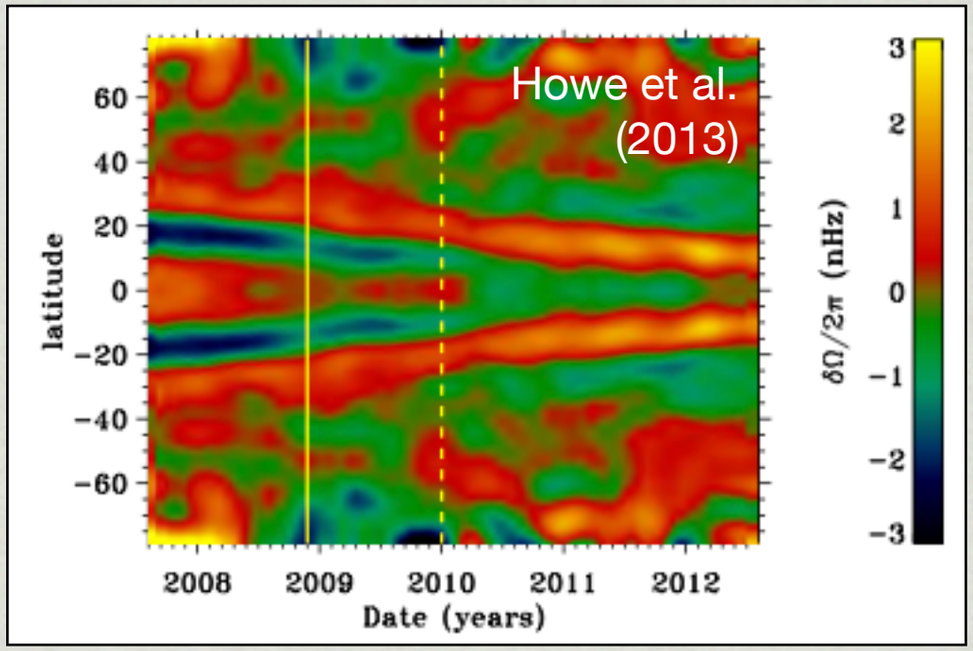
Poleward branch: zonal flow

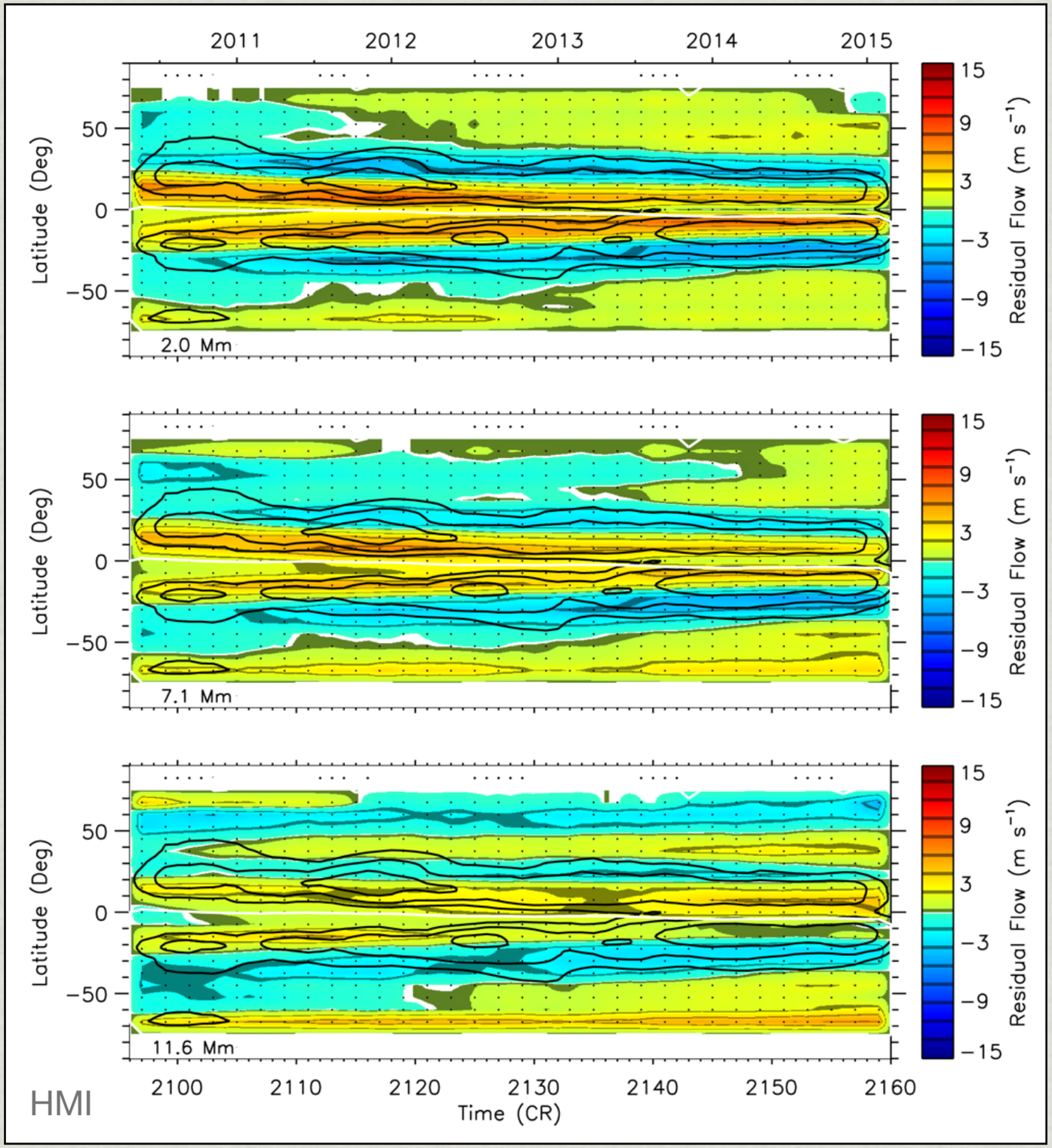
Vertical vorticity: derivative of zonal flows in latitude.

The poleward branch is visible as zero contour near 50° latitude in both hemispheres.



Poleward branch: meridional flow





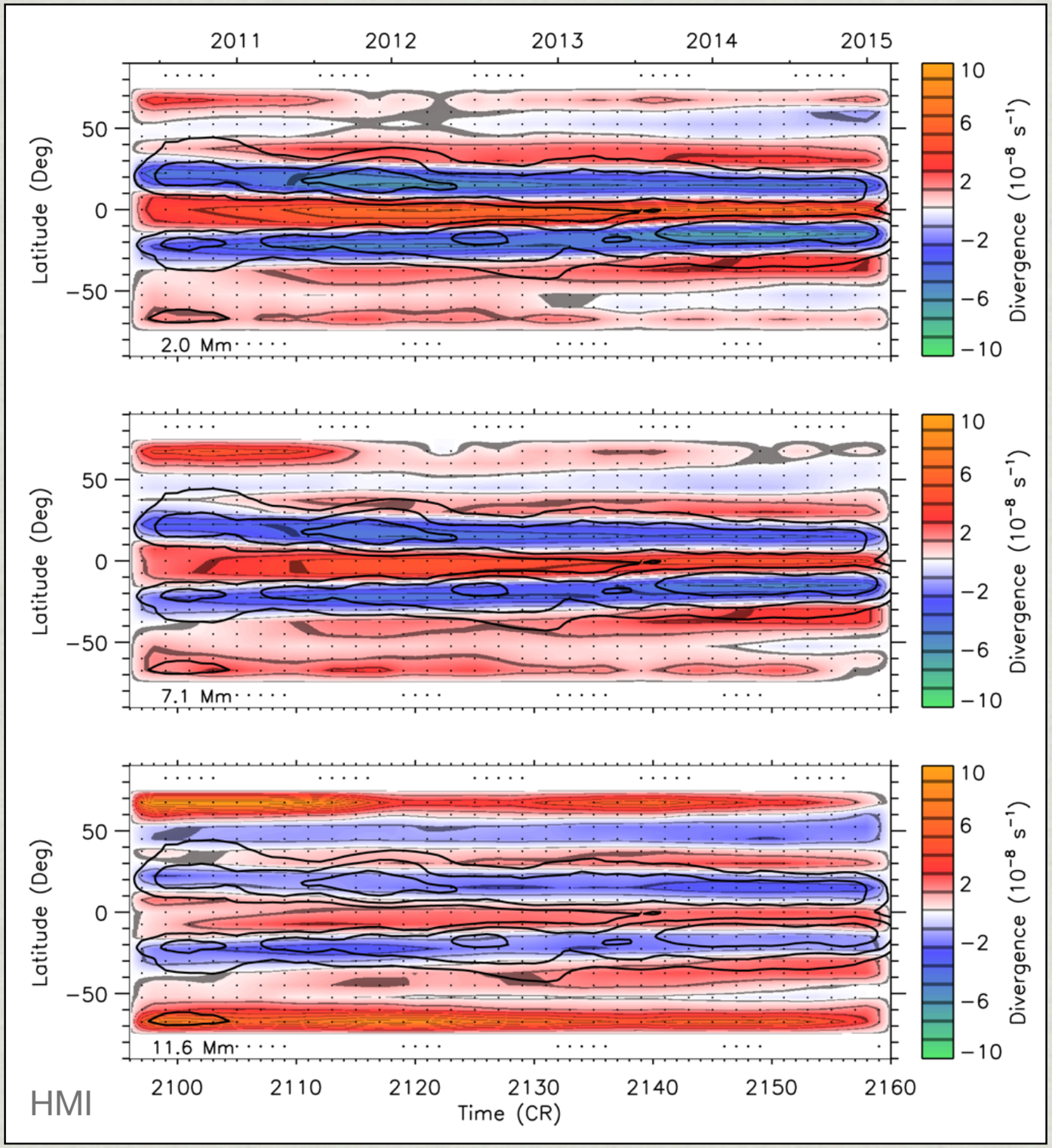
The residual meridional flows show nothing special at 50° latitude.

No poleward branch?

Poleward branch: meridional flow

Divergence: derivative of meridional flows in latitude.

There are converging flows near 50° especially in the north. Is this the poleward branch?



Summary (2)

- The poleward branch of the solar-cycle pattern is visible in zonal flows.
- The transition from faster- to slower-than-average zonal flow stands out as zero contour in the vorticity pattern.
- The meridional flow does not show an obvious pattern.
- The divergence pattern shows bands of convergence at latitudes where the poleward branch is present.
- Does the poleward branch have the same origin as the equatorward one?