Solar-Cycle Variations of Meridional Flows
and
Magnetic Fields at the Base of Convection Zone

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Measure solar-cycle variations of travel time difference $\delta\tau$ on meridional planes using 15-year MDI data.

Two Systematic Effects in Measured $\delta\tau$

- surface magnetic effect
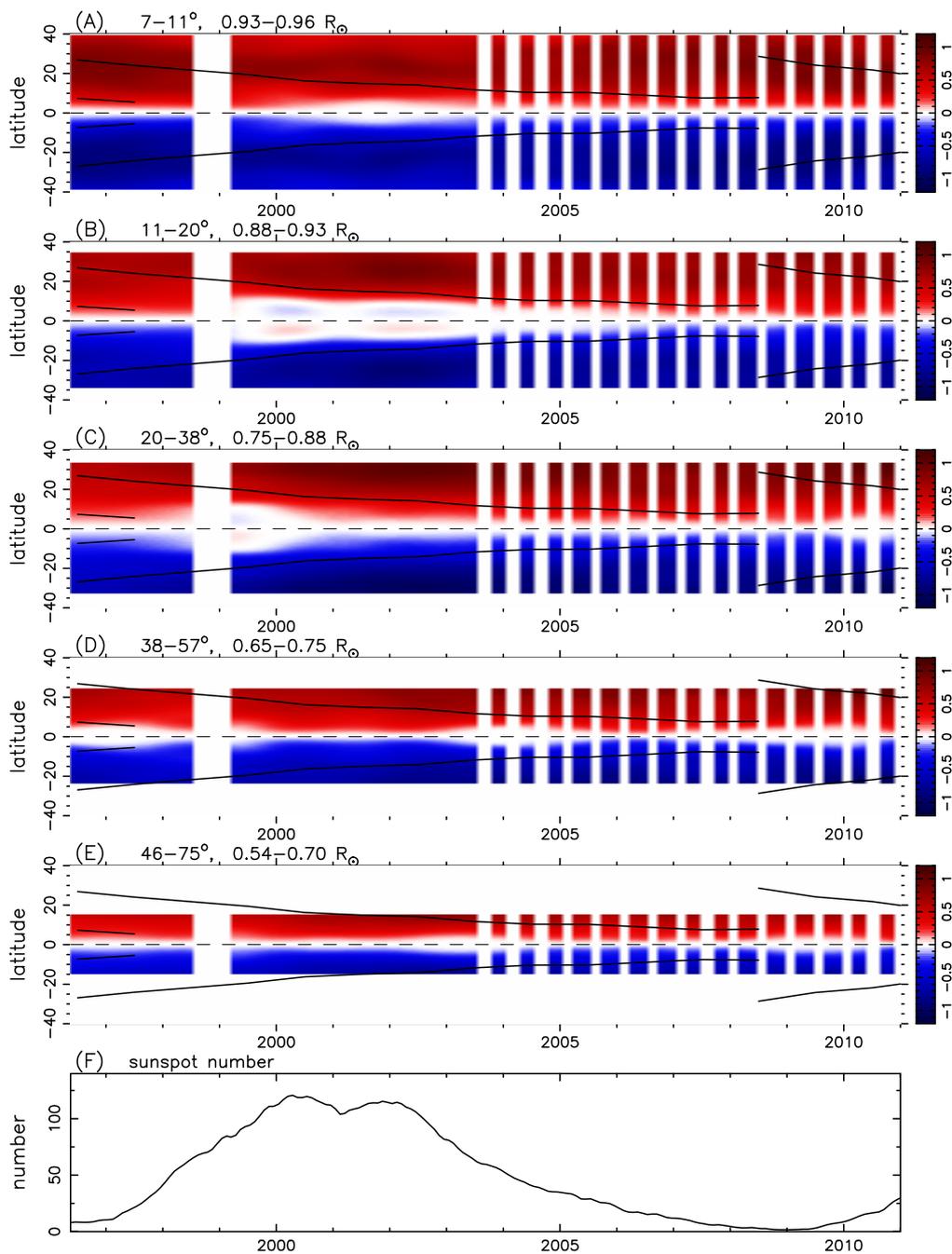- center-to-limb effect

Surface Magnetic Effect

- Surface magnetic fields introduce additional signals in $\delta\tau$, which are unrelated to global meridional flows. (Liang & Chou 2015)

- If one of paired points is inside a magnetic region greater than a threshold (50G), the CCF is removed from averaging.
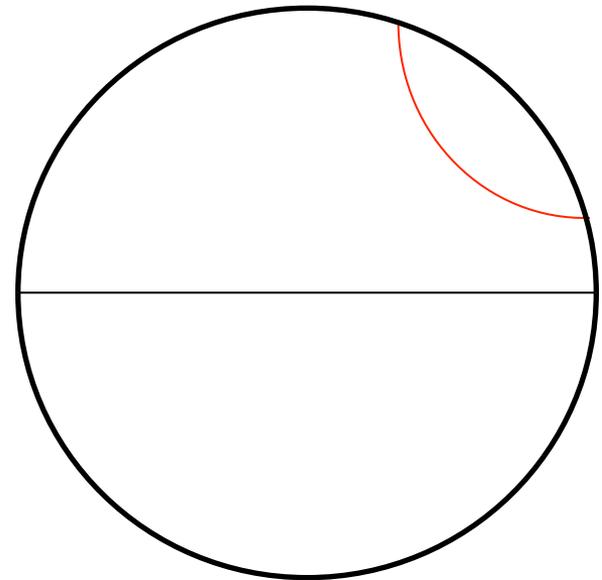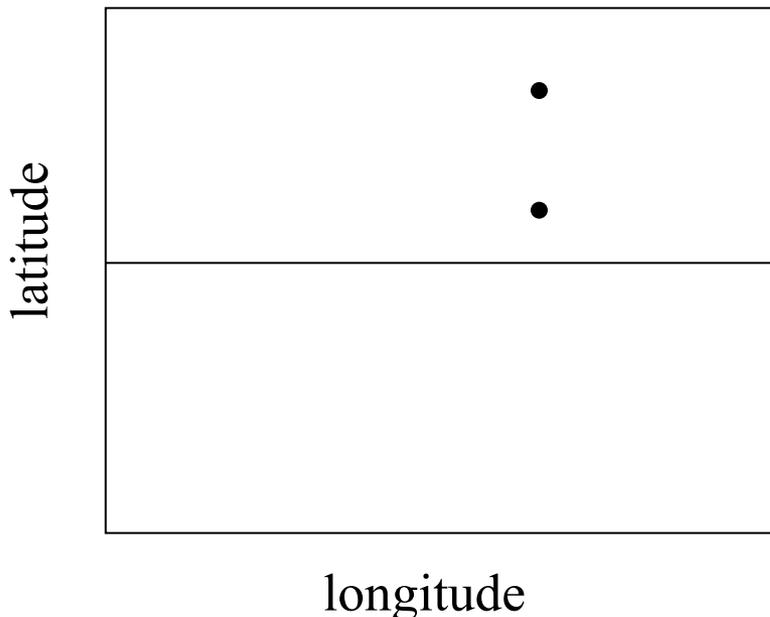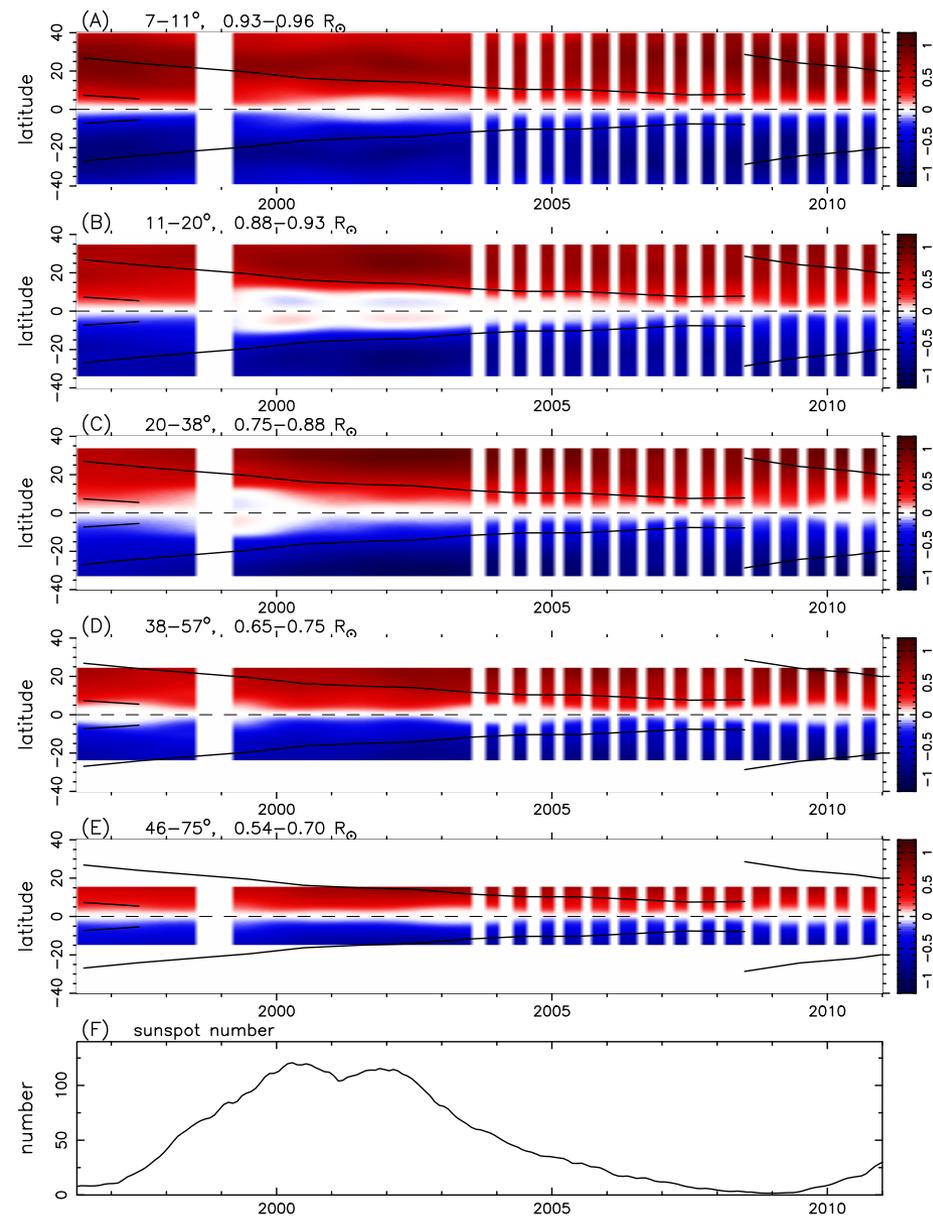
Center-to-Limb Effect

- First noticed by Duvall & Hanasoge (2009):
  $\delta\tau$ in the E-W direction depends on longitude.

- Suggested by Zhao et al. (2012):
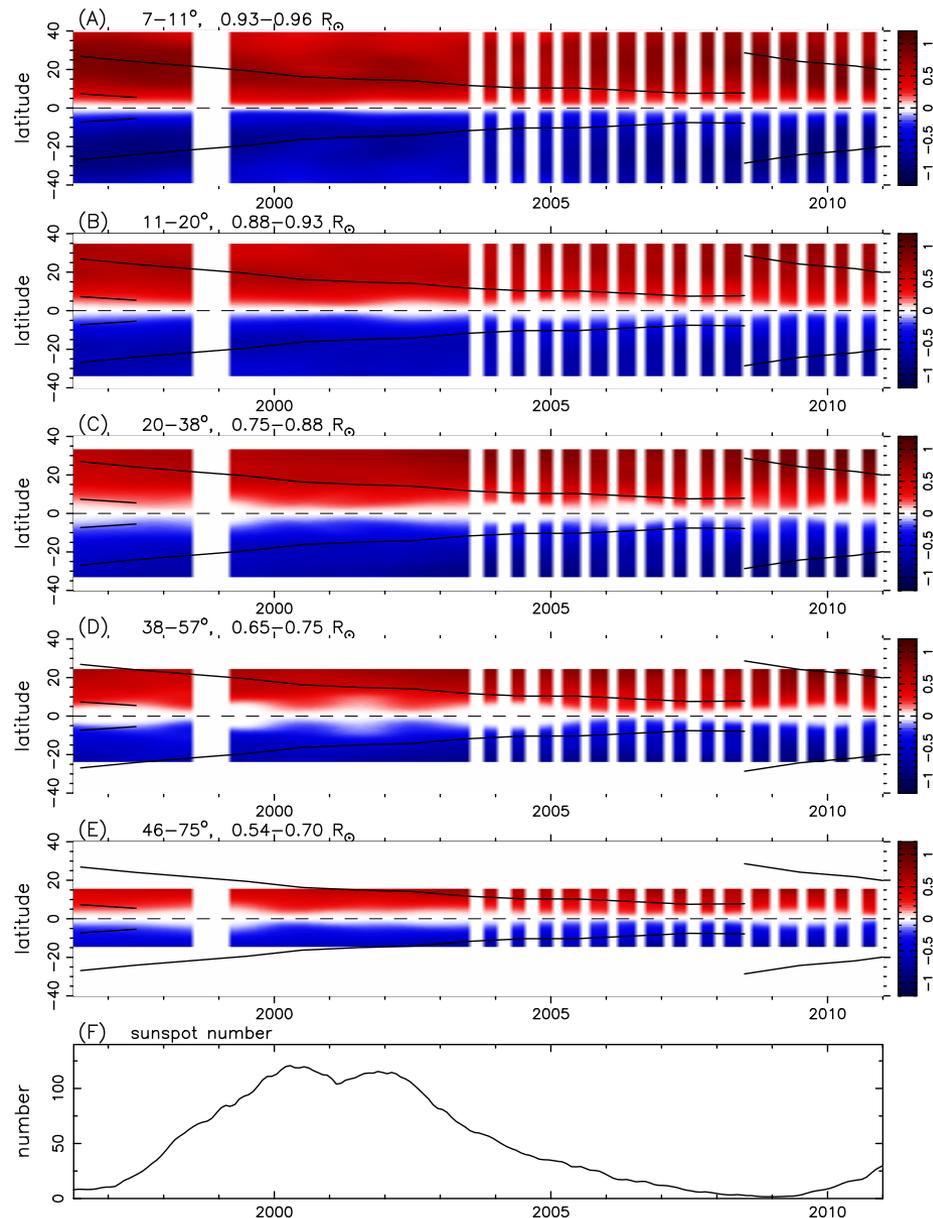 Using $\delta\tau$ of E-W to remove the center-to-limb effect in $\delta\tau$ of N-S.
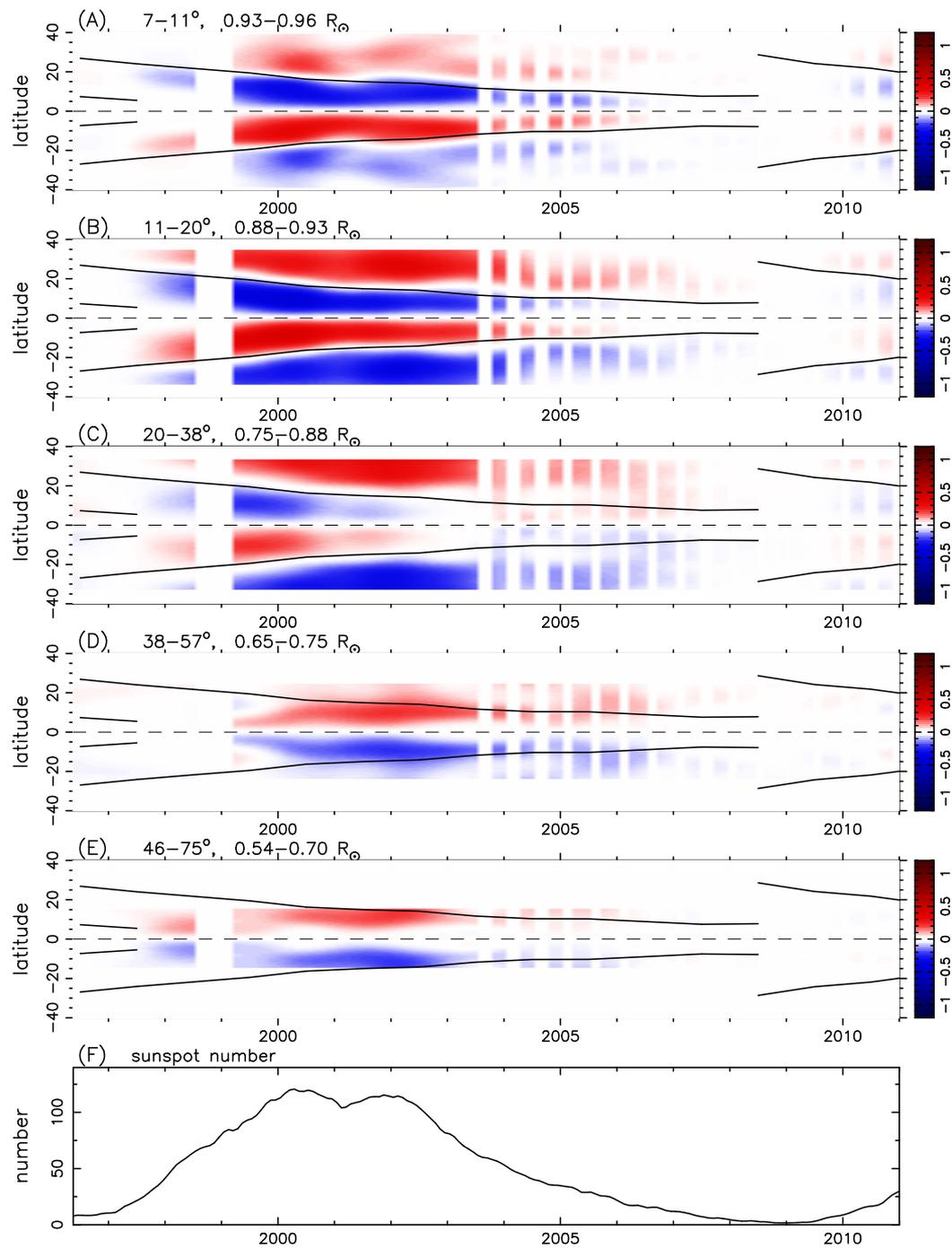
15-year SOHO/MDI data
(1996.06 – 2010.08)

(A) 7–11°, 0.93–0.96 R⊙

(B) 11–20°, 0.88–0.93 R⊙

(C) 20–38°, 0.75–0.88 R⊙

(D) 38–57°, 0.65–0.75 R⊙

(E) 46–75°, 0.54–0.70 R⊙

(F) sunspot number

original   surface magnetic effect removed

(A)   7–11°,   0.93–0.96 $R_\odot$

(B)   11–20°,   0.88–0.93 $R_\odot$

(C)   20–38°,   0.75–0.88 $R_\odot$

(D)   38–57°,   0.65–0.75 $R_\odot$

(E)   46–75°,   0.54–0.70 $R_\odot$

(F)   sunspot number

original – 50G

(A) 7–11°, 0.93–0.96 $R_\odot$

(B) 11–20°, 0.88–0.93 $R_\odot$

(C) 20–38°, 0.75–0.88 $R_\odot$

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(E) 46–75°, 0.54–0.70 $R_\odot$

(F) sunspot number
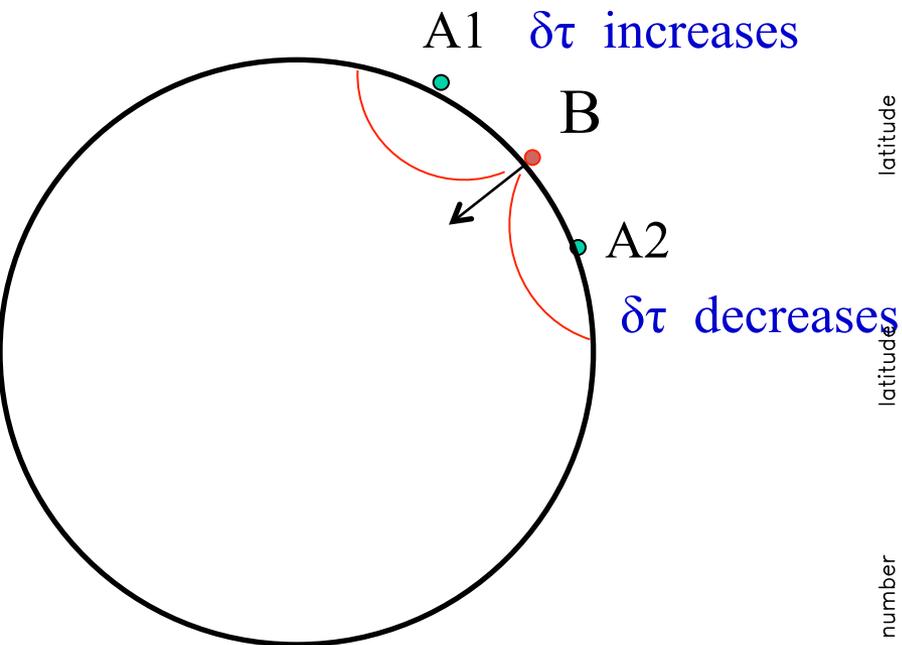
original – 50G

Effects of downflow on $\delta\tau$

A1 $\delta\tau$ increases

B

A2

$\delta\tau$ decreases

(A)   7–11°, 0.93–0.96 $R_\odot$

(B)   11–20°, 0.88–0.93 $R_\odot$

(C)   20–38°, 0.75–0.88 $R_\odot$

(D)   38–57°, 0.65–0.75 $R_\odot$

(E)   46–75°, 0.54–0.70 $R_\odot$

(F)   sunspot number
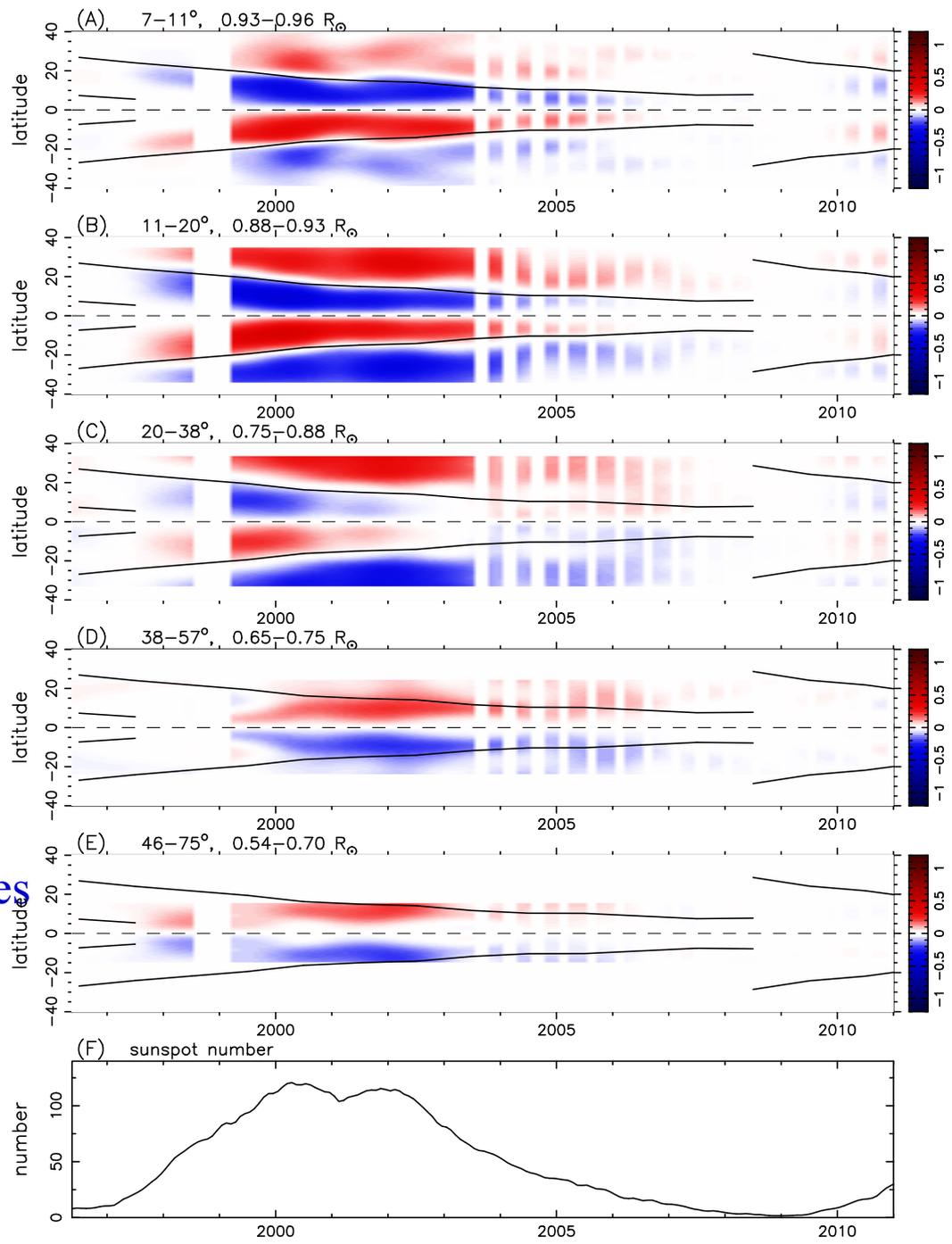
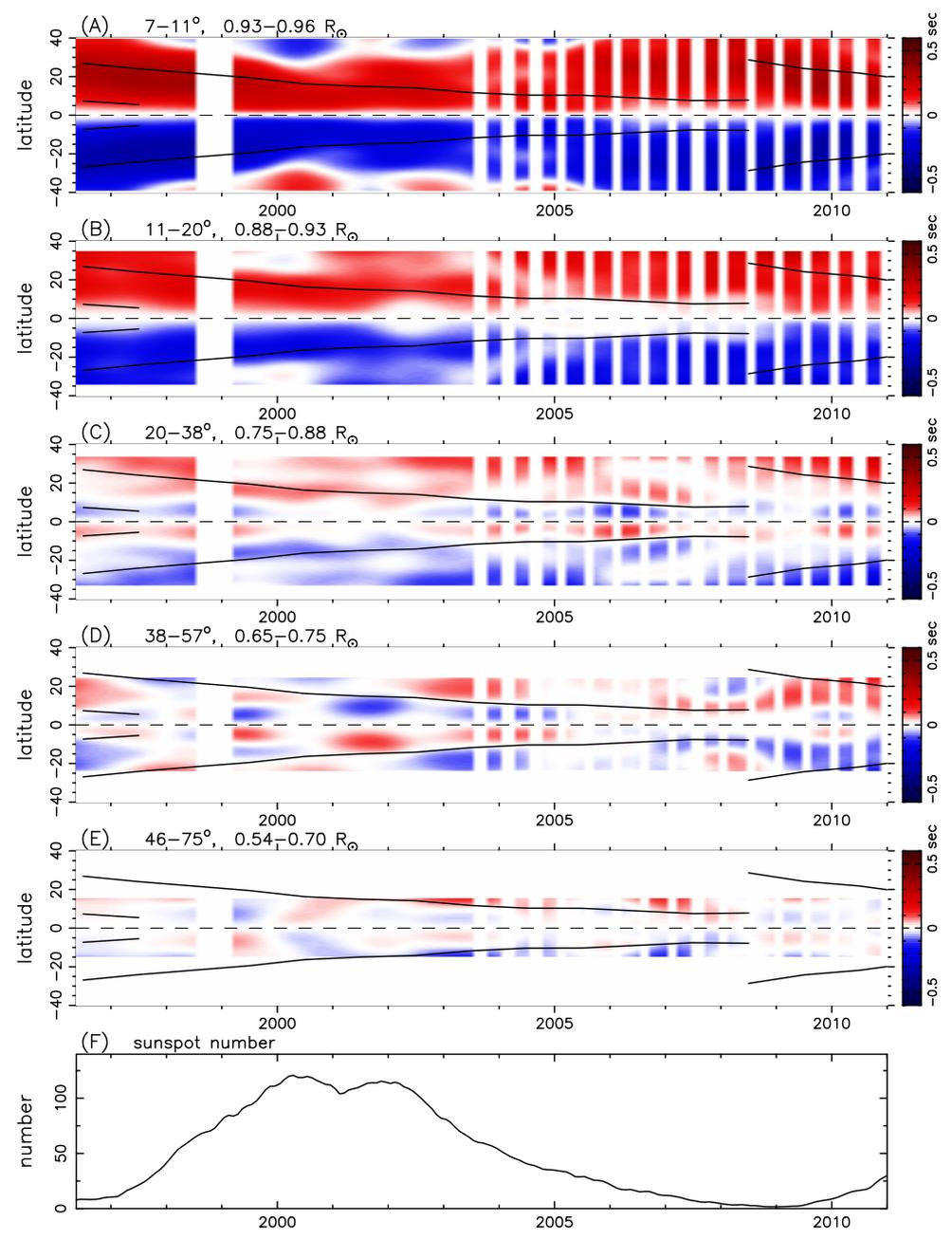# δτ with surface magnetic field removed

NS (50G)

EW (50G)
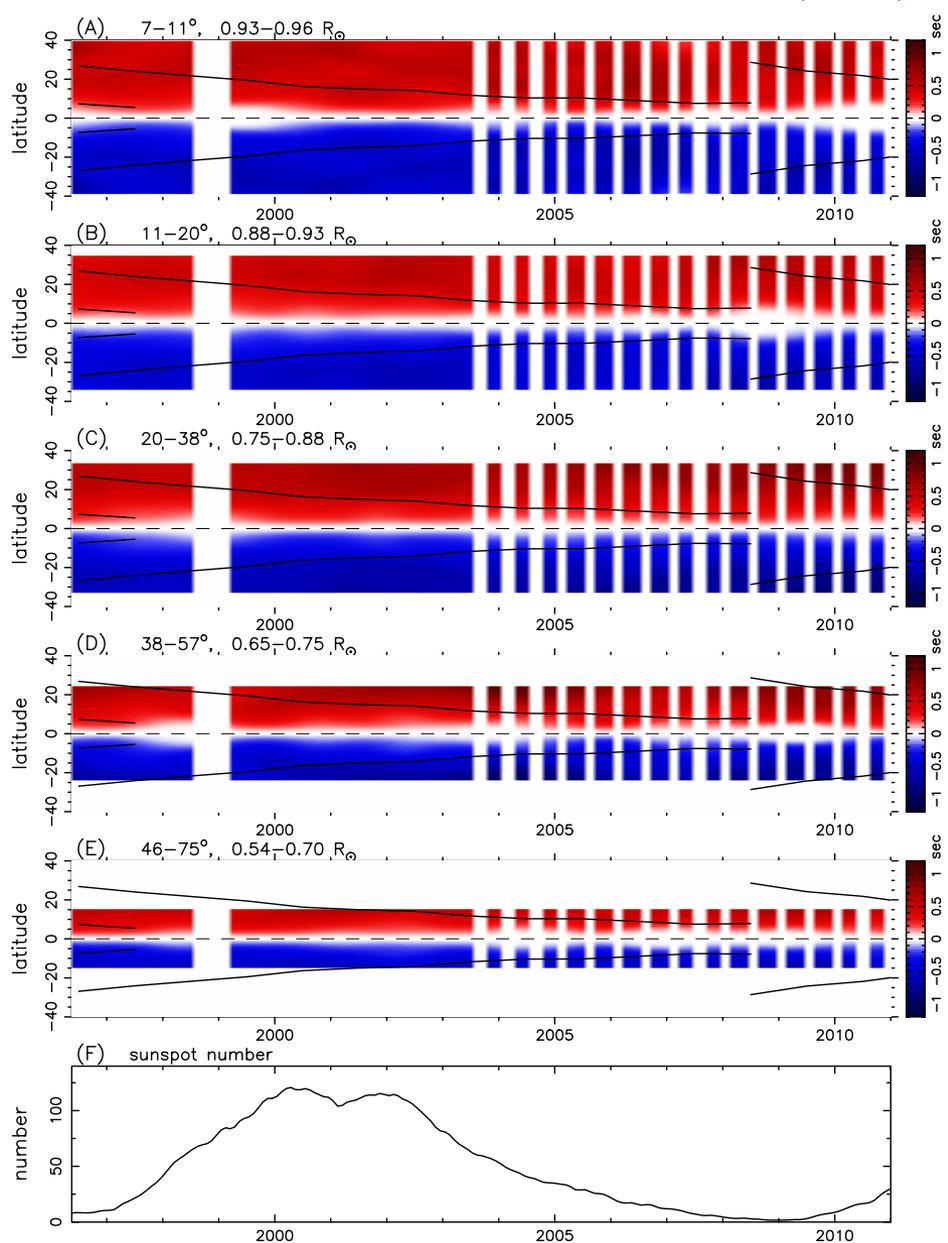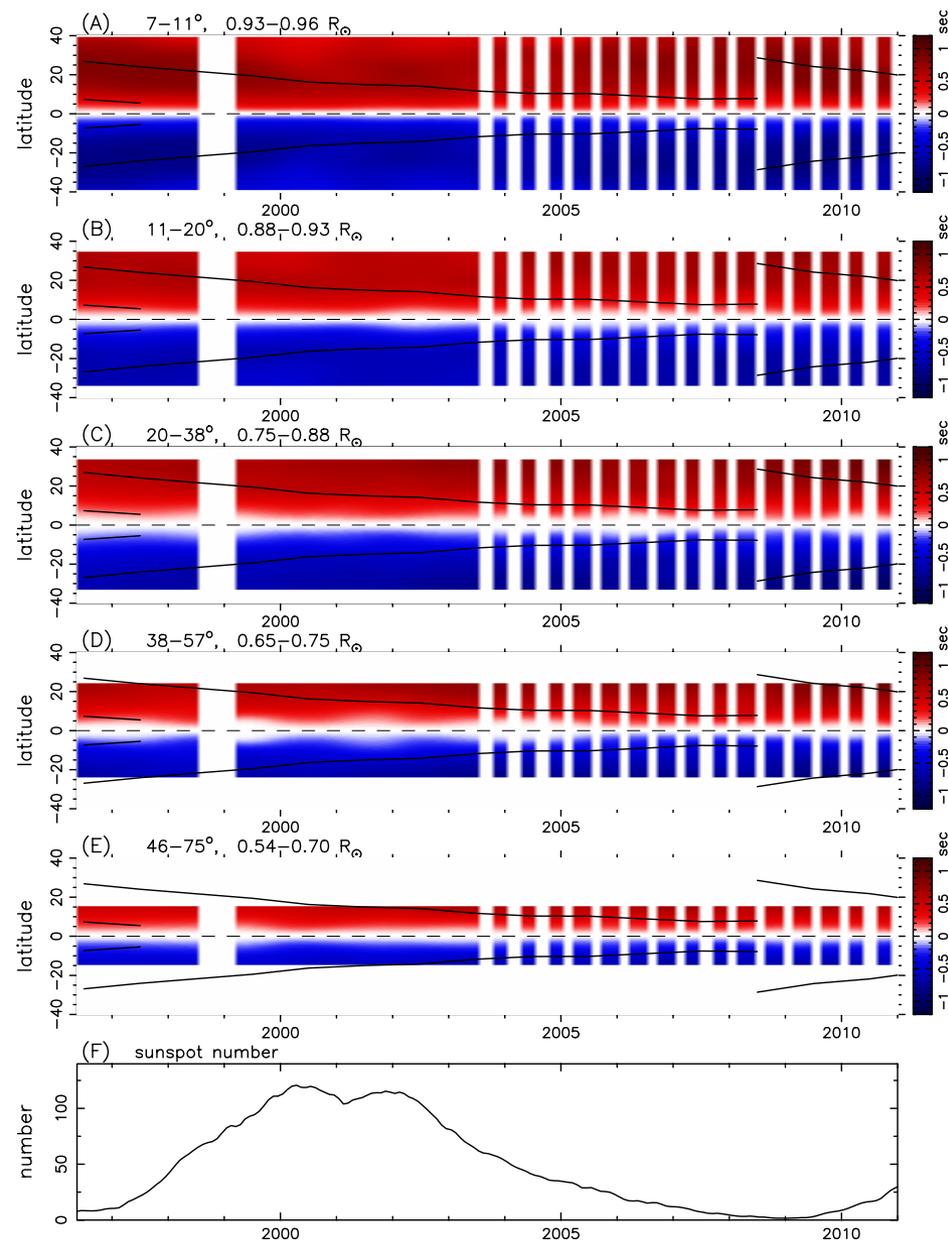
surface magnetic effect & center-to-limb effect removed

Comparison of Maximum and Minimum vs. Latitude

- δτ's at two minima are similar, but different from the maximum.
- A, B show inflows toward active latitudes (consistent with previous study).
- Above BCZ (A-C), δτ at maximum is greater than minimum below active latitudes.
- Around BCZ (D), δτ at maximum is smaller than minimum below active altitudes.
- Below BCZ (E), δτ is close to zero for maximum and minima.
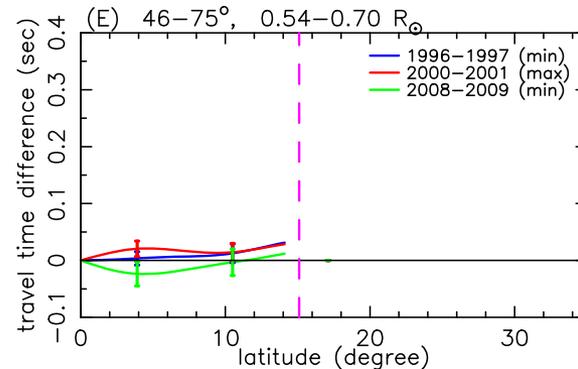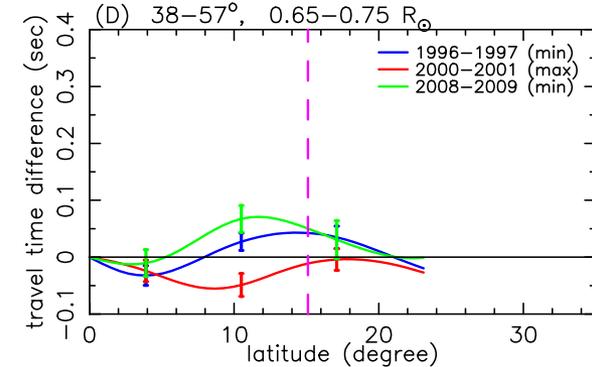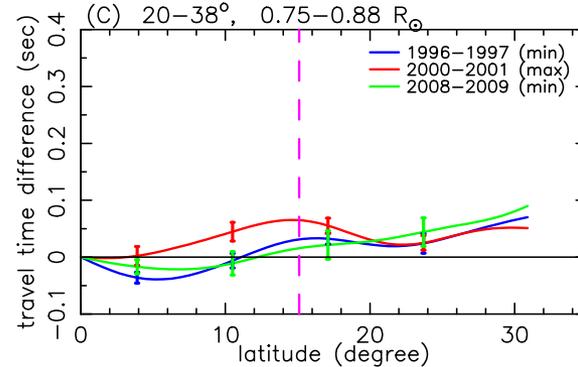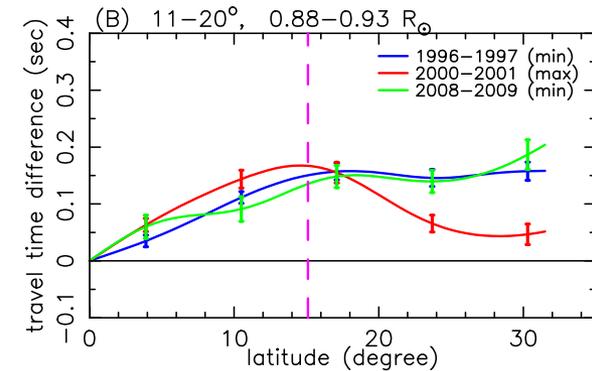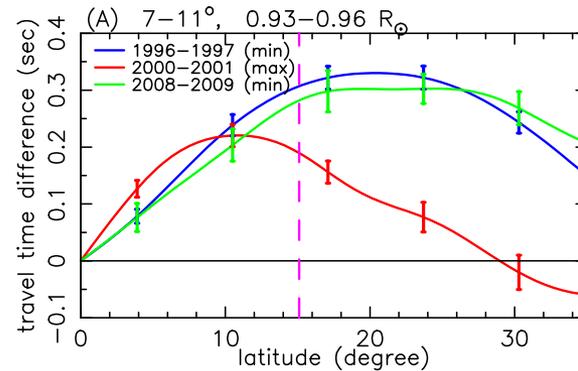
Comparison of Maximum and Minimum vs. Depth
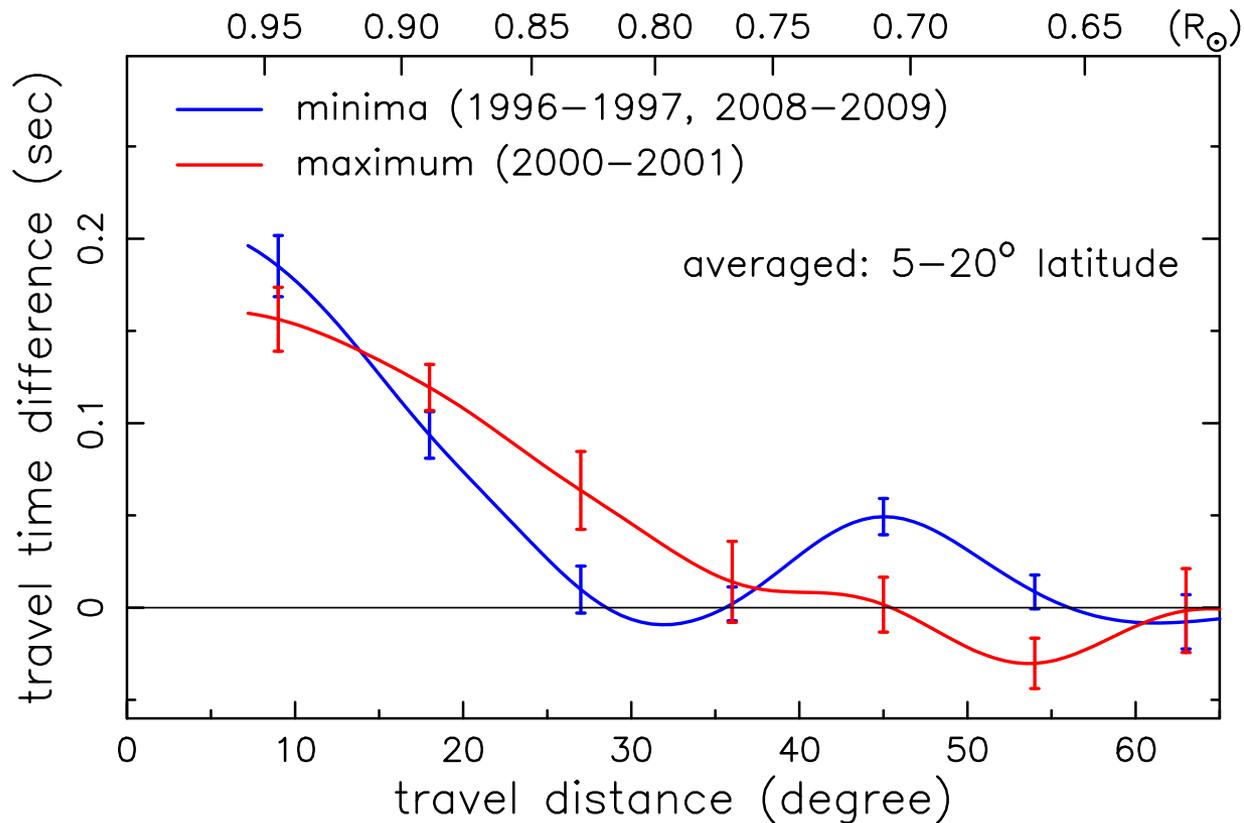
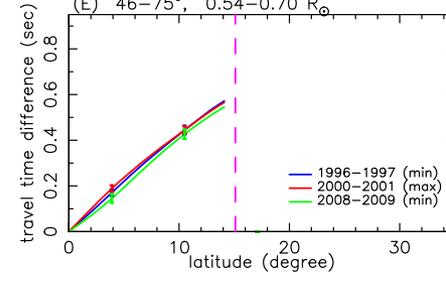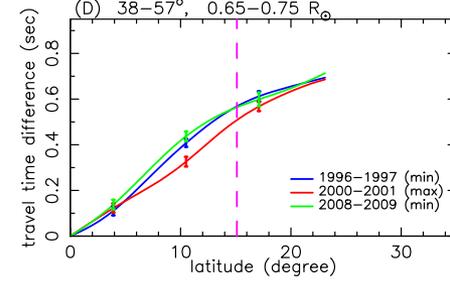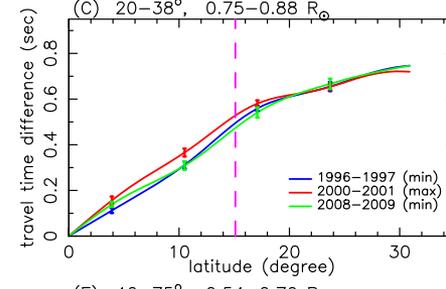- above BCZ: $\delta\tau$ at maximum $>$ $\delta\tau$ at minimum
- around BCZ: $\delta\tau$ at maximum $<$ $\delta\tau$ at minimum
- below BCZ: $\delta\tau$ at maximum $\approx$ $\delta\tau$ at minimum ≈ 0

Does these solar-cycle variations depend on the center-to-limb correction?

Comparison of Maximum and Minimum vs. Latitude

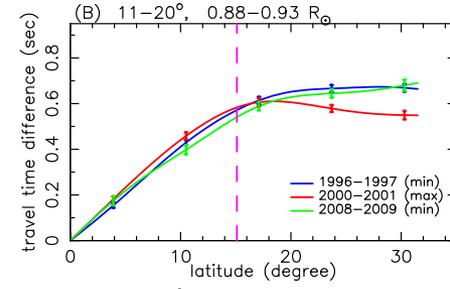center-to-limb effect removed   center-to-limb effect not removed
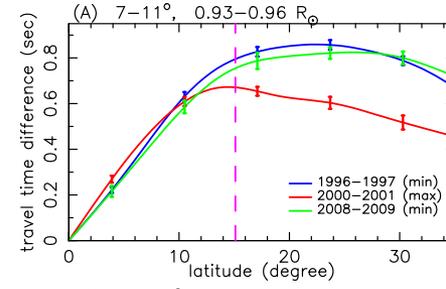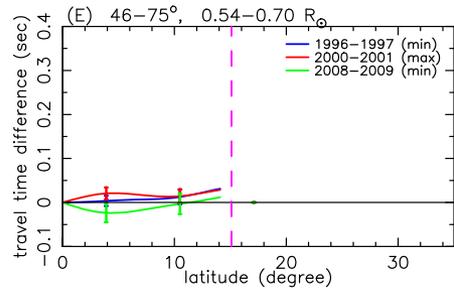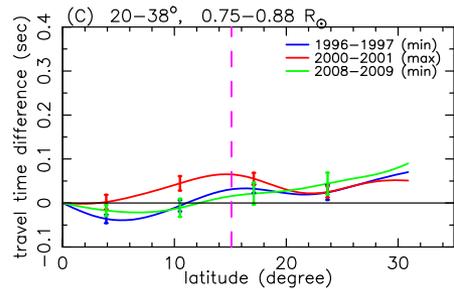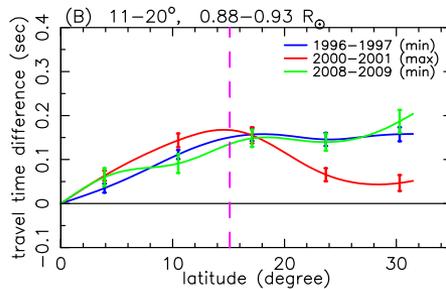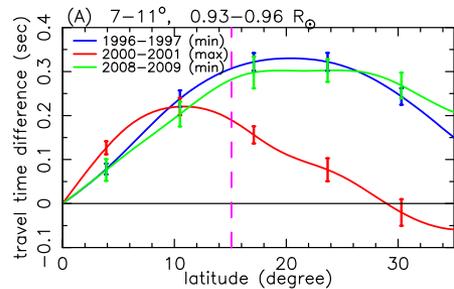
Comparison of Maximum and Minimum vs. Depth

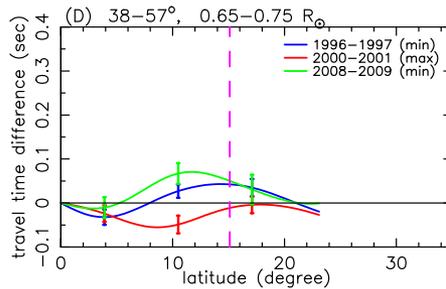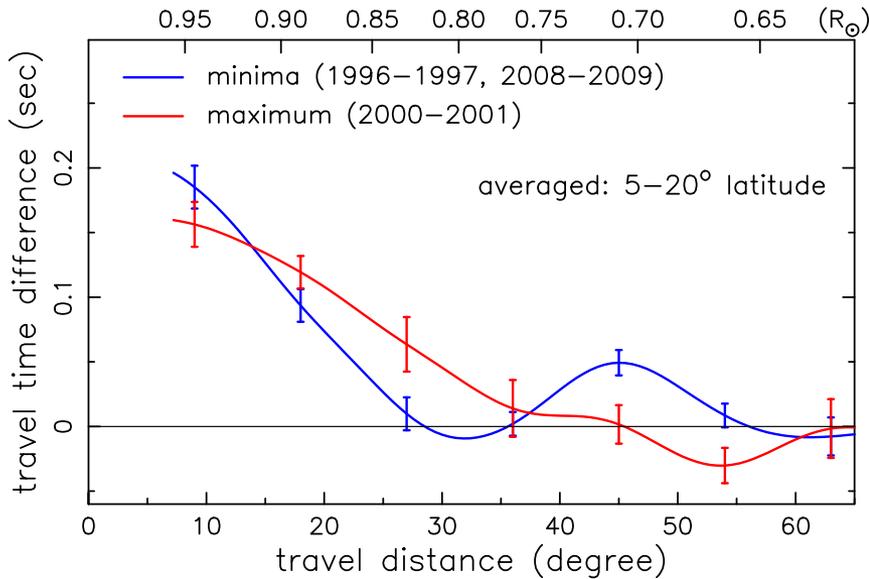center-to-limb effect removed   center-to-limb effect not removed
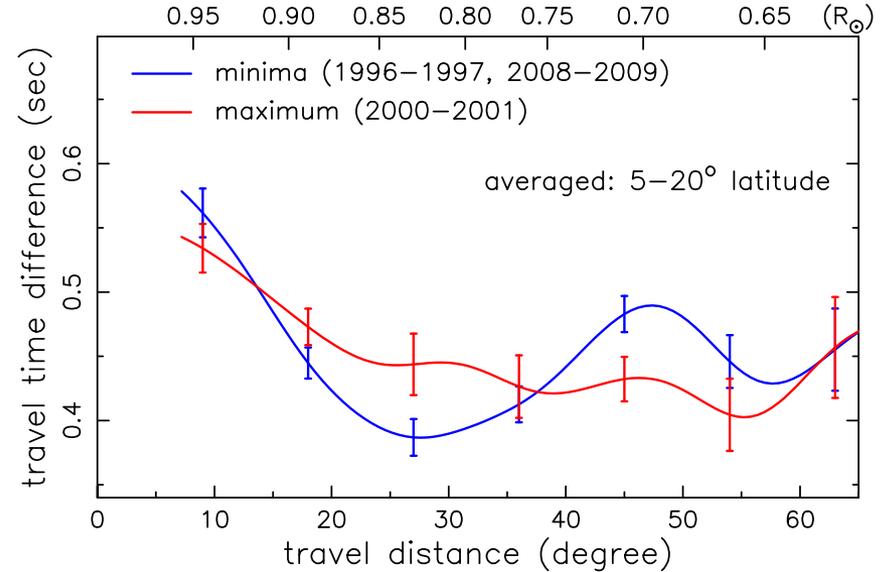
The center-to-limb correction does not modify the variation between minimum to maximum around the BCZ.

Does these solar-cycle variations depend on
the residual signal of surface magnetic fields?

Comparison of Maximum and Minimum vs. Depth
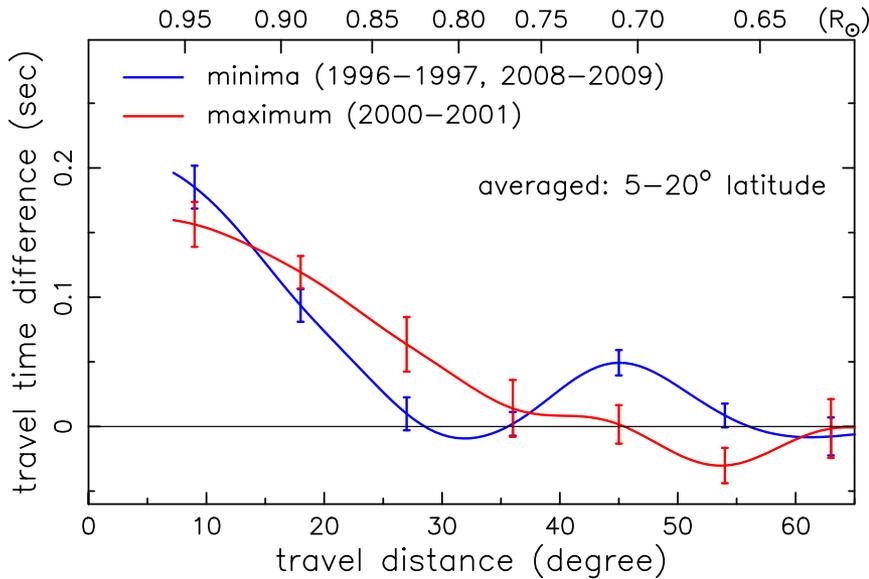
surface-magnetic effect removed   surface-magnetic effect not removed

The residual signal from magnetic regions below 50G would further increase the variation between minimum and maximum around the BCZ.

Summary of Measurements of $\delta\tau$

- Two systematic effects (surface magnetic effect and center-to-limb effect) are corrected.
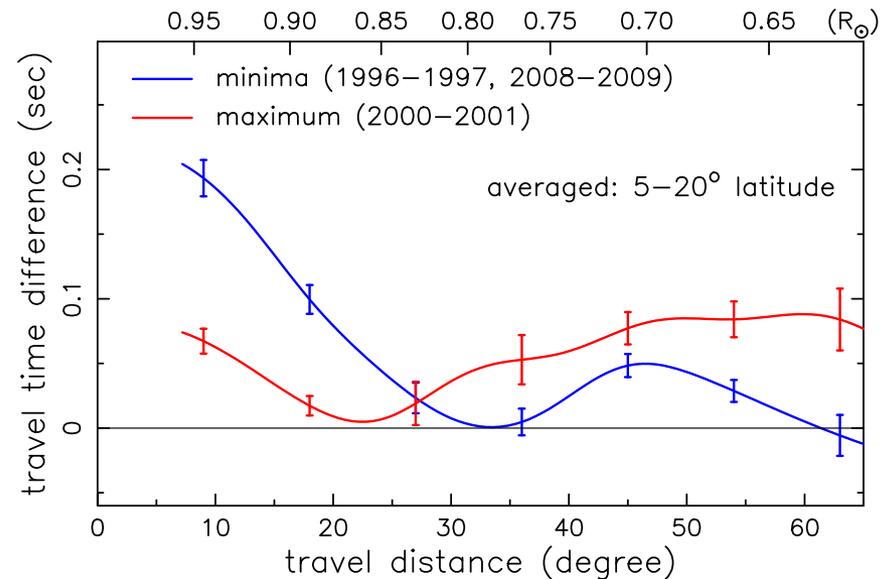
- The latitudinal dependences of $\delta\tau$ at two minima are similar at all depths, but they differ from that at the maximum. The difference changes the sign near the BCZ.

- The depth dependences of $\delta\tau$ (averaged over 5-20°) at the minima and maximum are different. The difference changes the sign near the BCZ.

- The variation in $\delta\tau$ between minimum and maximum $\Delta\delta\tau \sim 0.05$-$0.1$ sec.

- The difference of $\delta\tau$ between the depth above the BCZ and near the BCZ is unlikely caused by other unknown systematic effects, if they are time-independent.

- The variation between minimum and maximum around the BCZ is not caused by the center-to-limb correction and the residual surface magnetic effect.

- If we attribute this change in $\delta\tau$ around the BCZ to the change in magnetic field at the BCZ, we may derive the magnetic field change at the BCZ.

But it needs:

- Correct flow distribution at the minimum and the maximum from inversion of measured $\delta\tau$.

- A theory relating the change in flow distribution to the change in field distribution.

An Estimate for the Lower Limit of B field at the BCZ.

$$\Delta\delta\tau = 2\int \frac{\Delta\vec{v}\cdot d\vec{s}}{c^2} \sim 2\frac{\Delta v}{c^2}\Delta s \sim 2\frac{\Delta v}{c^2}R\Delta\theta$$

- If $\Delta\delta\tau \sim 0.05\text{-}0.1$ sec, $\Delta\vartheta \sim 20^o$ (R=0.7 Rsun, c=2.3x10^7), $\Delta v \sim 10$ m/s.

- Equivalent to B ~ 2x10^3 G.

- Since the flow kinetic energy density is much less than the magnetic energy density, this value is the lower limit for B near the BCZ.

The End