Inferring Tropical Cyclone Boundary Layer Roll Circulations from SAR

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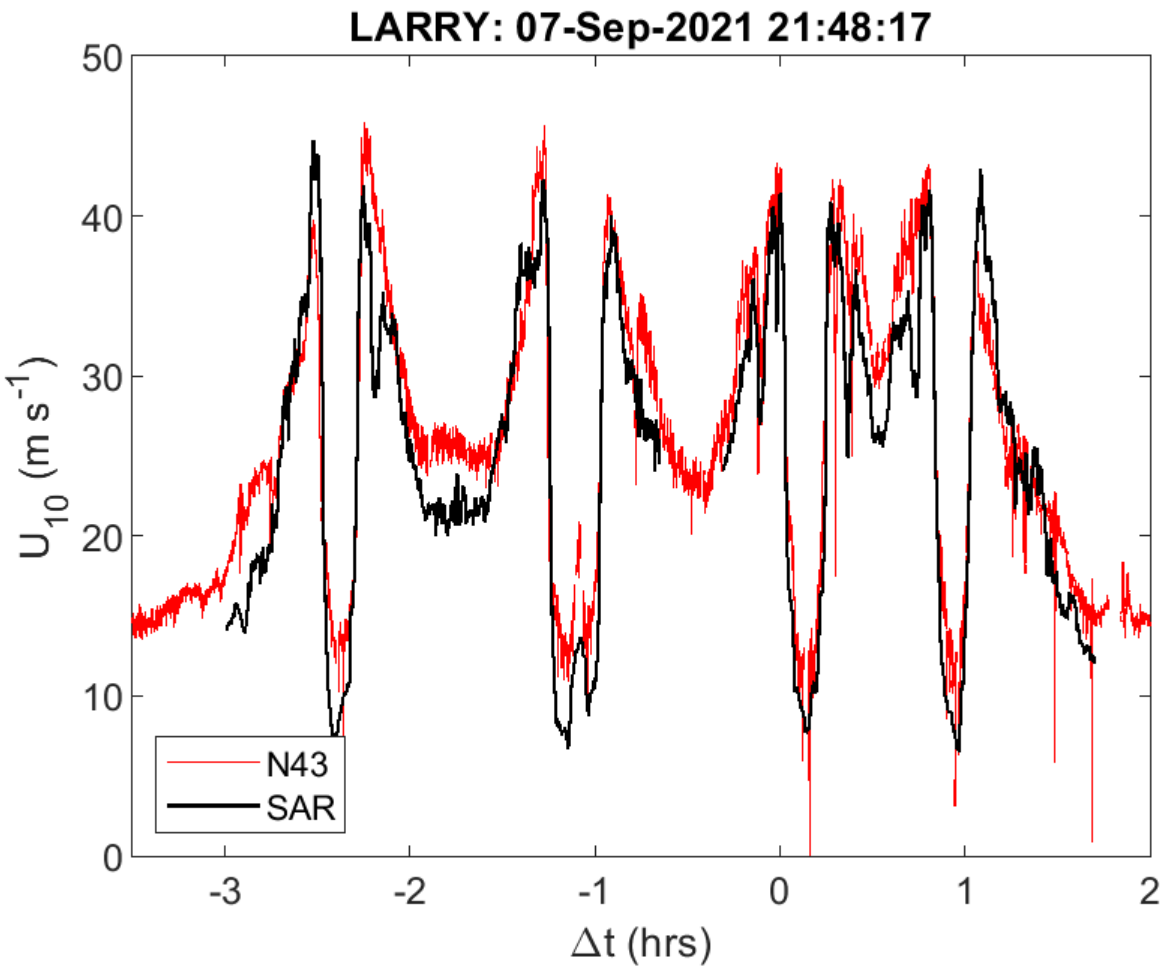
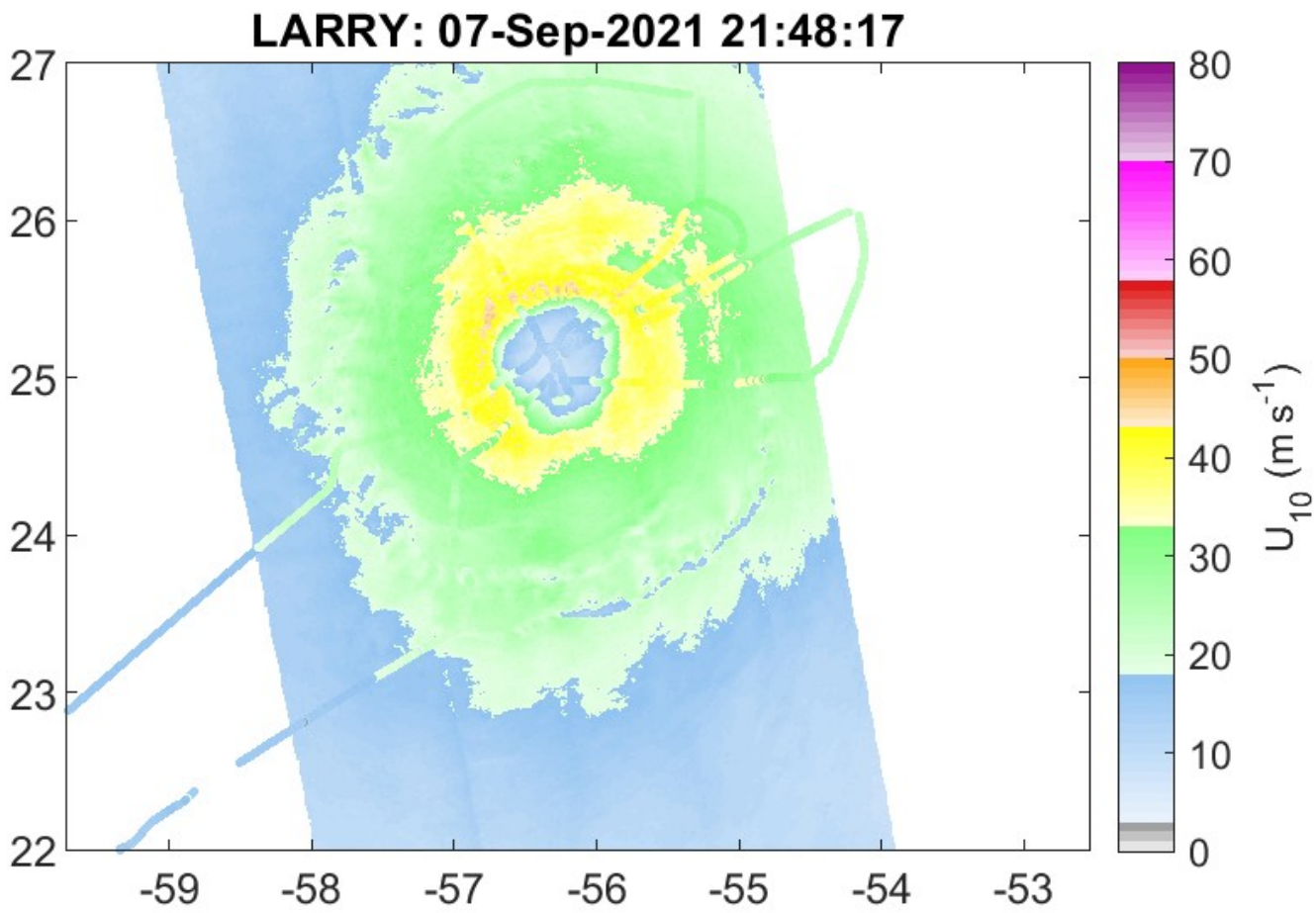
Take-Home Messages

- Ocean SAR images of Tropical Cyclones (TC) provide:
  - Surface wind (U_{10}^N, V_{10}^N) & stress (τ_x, τ_y) in 1 km wind vector cells
    - Lower boundary conditions (BC)
  - TC boundary layer (TCBL) roll orientation (ubiquitous)
- Retrieve Sea-Level Pressure (SLP) pattern (Foster, 2017)
  - Calculate P_r
  - Derive gradient wind V_g at top of TCBL
    - Upper BCs
- Assume a range of realistic eddy-viscosity profiles $(K(z))$
  - Calculate TCBL $(U_{rad}(z), V_{tan}(z))$ (Foster, 2009)
    - Calculate TCBL roll orientation (Foster, 2005)
    - Best agreement $\leftrightarrow$ best estimate of $(U_{rad}(z), V_{tan}(z))$
  - Calculate nonlinear roll circulation (Foster, 2005)
- Compare $(U_{rad}(z), V_{tan}(z))$ & TCBL roll circulation to IWRAP
  - SAR-derived mean flow a little shallow & a little weak
  - SAR-derived roll magnitude, structure & orientation agree well
  - SAR-derived roll wavelength a little too long
- Currently upgrading Foster (2009) in light of these results

Larry 7 Sep, 2021

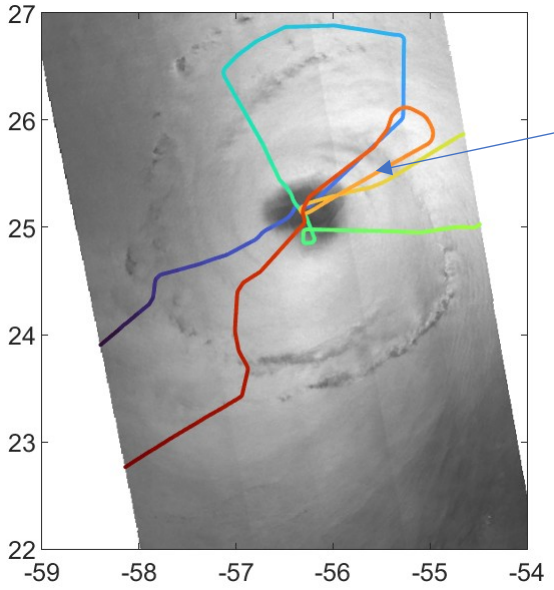
- S-1B Ascending (~18:00 local) overpass at 21:46 UTC
- NOAA N43 P-3 flight, Δt= -3 to +1.5 hours of S-1B
  - IWRAP (downward, conical scan, Ku-band)
  - SFMR
  - TDR
  - 4 drop sondes (near storm center)
- NOAA G-IV flight
  - Environment soundings, far from center
  - 7 drop sondes in-image within P-3 time window

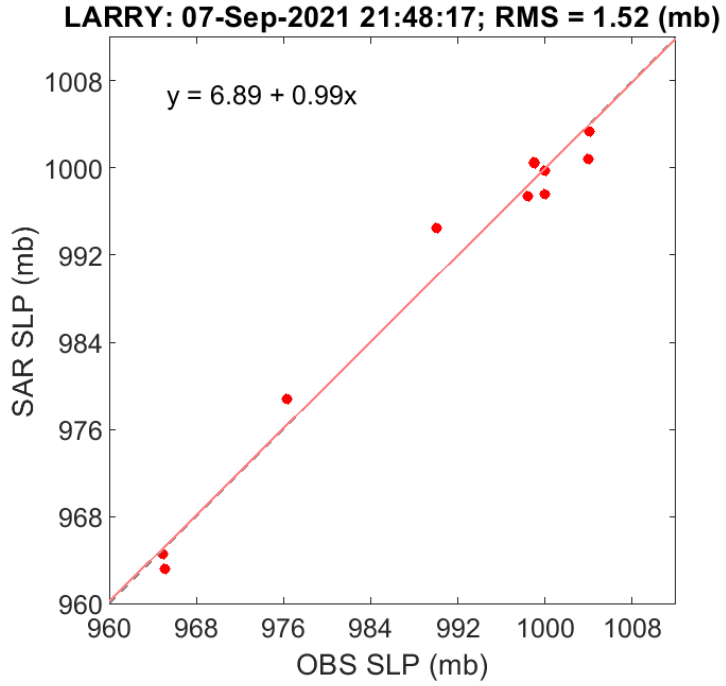


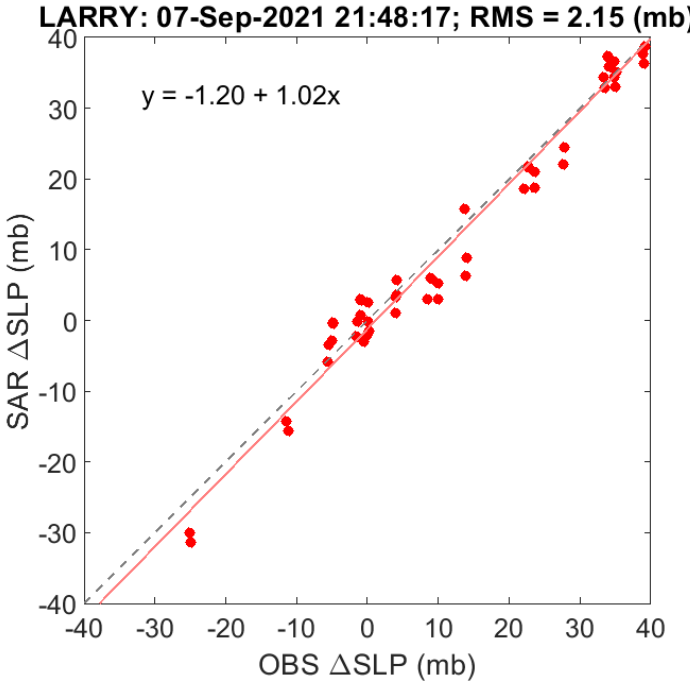


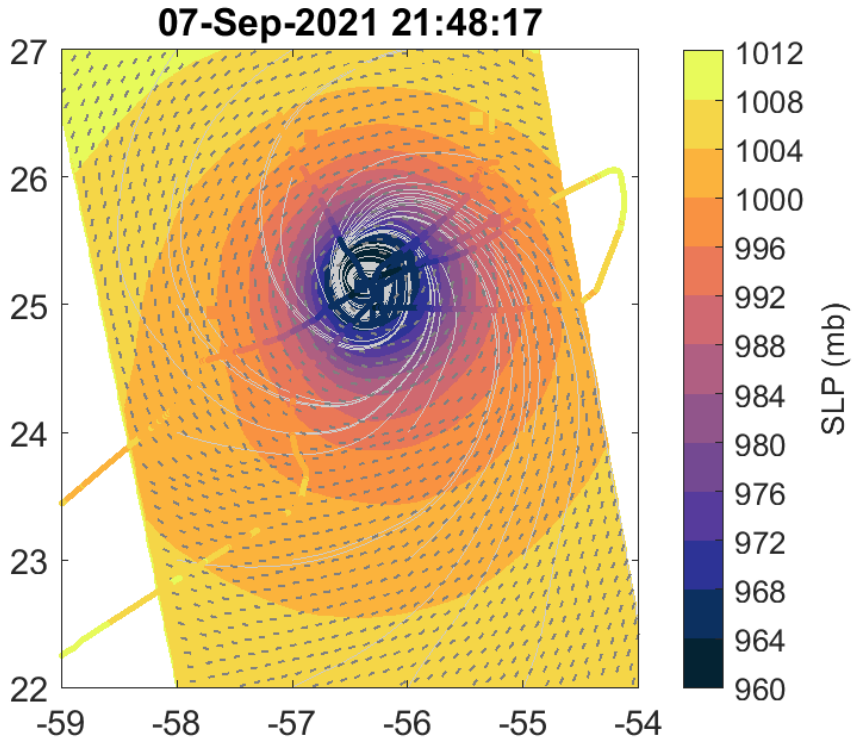
Operational SFMR winds
RMS ~ 4 (m/s) (within 150 km)

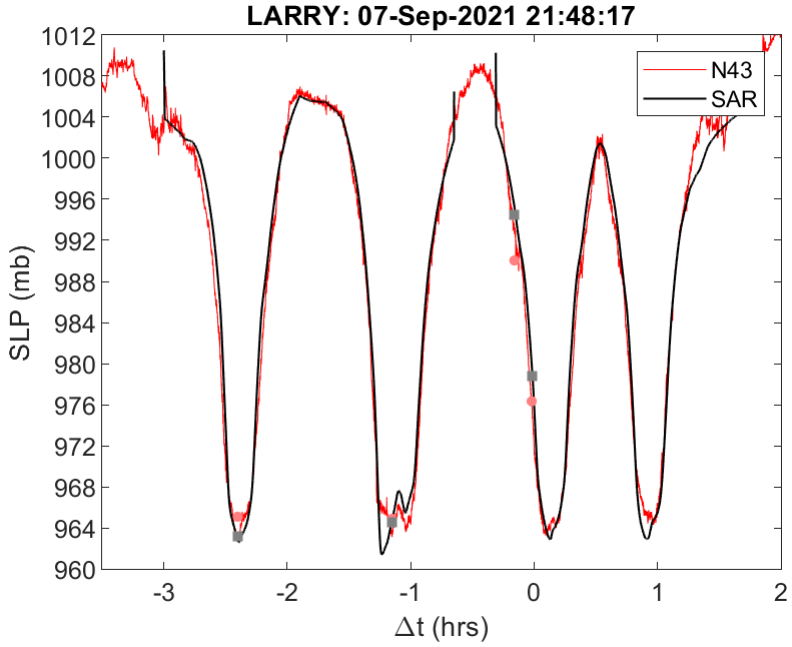
SFMR used to adjust P-3 observations to SAR overpass time
(most difficult aspect of analysis)







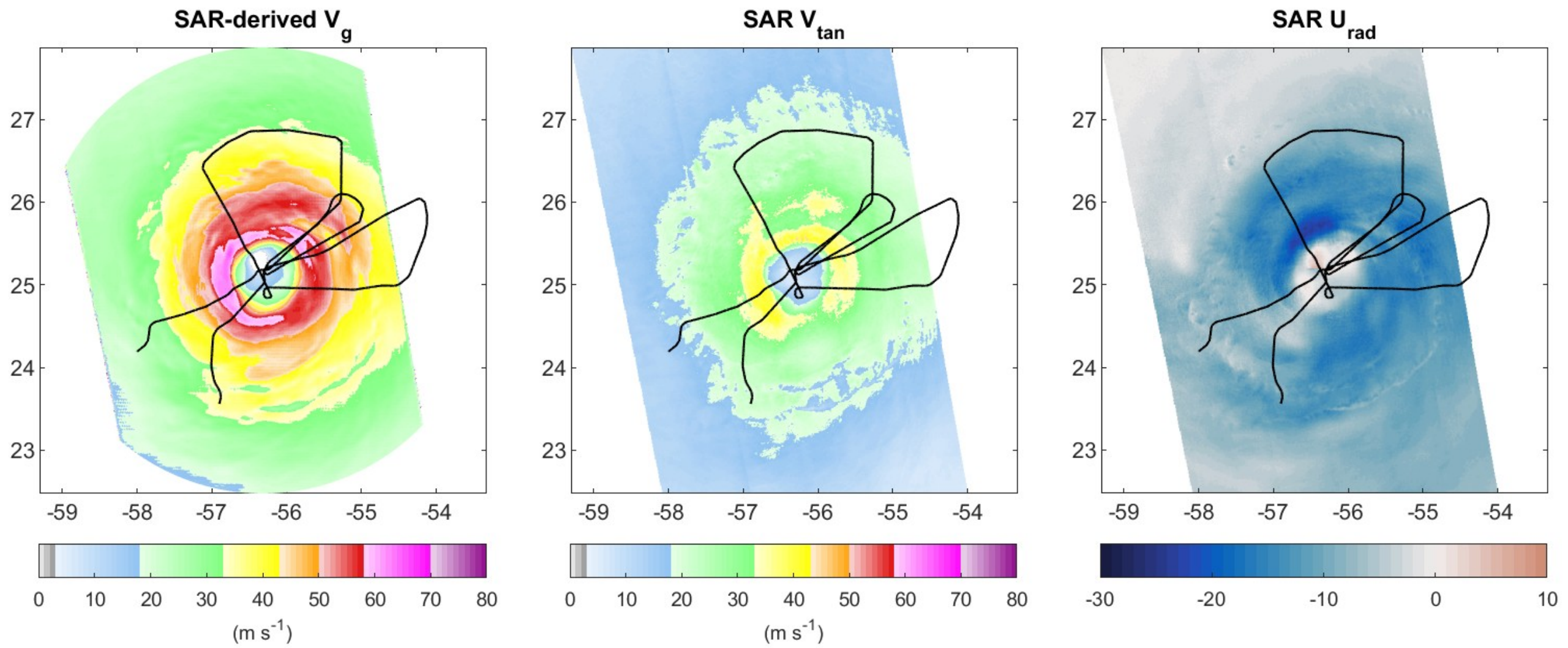




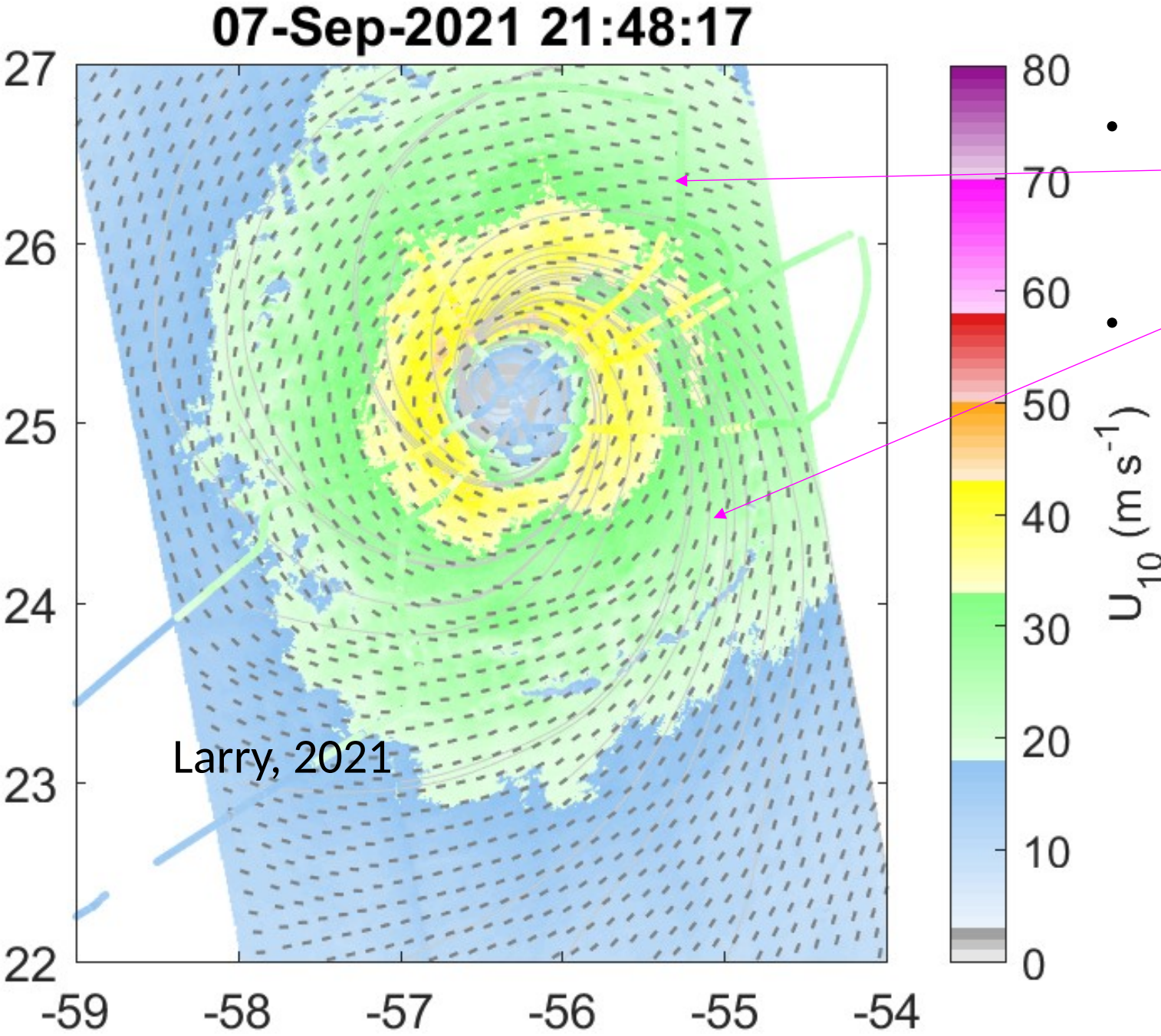
SLP Retrieval

- Scatterplots ~along 1:1 line
  - **Total-least-squares**
  - 4 sondes from P-3
  - 7 sondes from G-IV
- $\frac{N(N-1)}{2}\Delta P$ from Sondes
  - RMS 2.2 mb
- Good agreement with P3 SLP

Foster (2017)

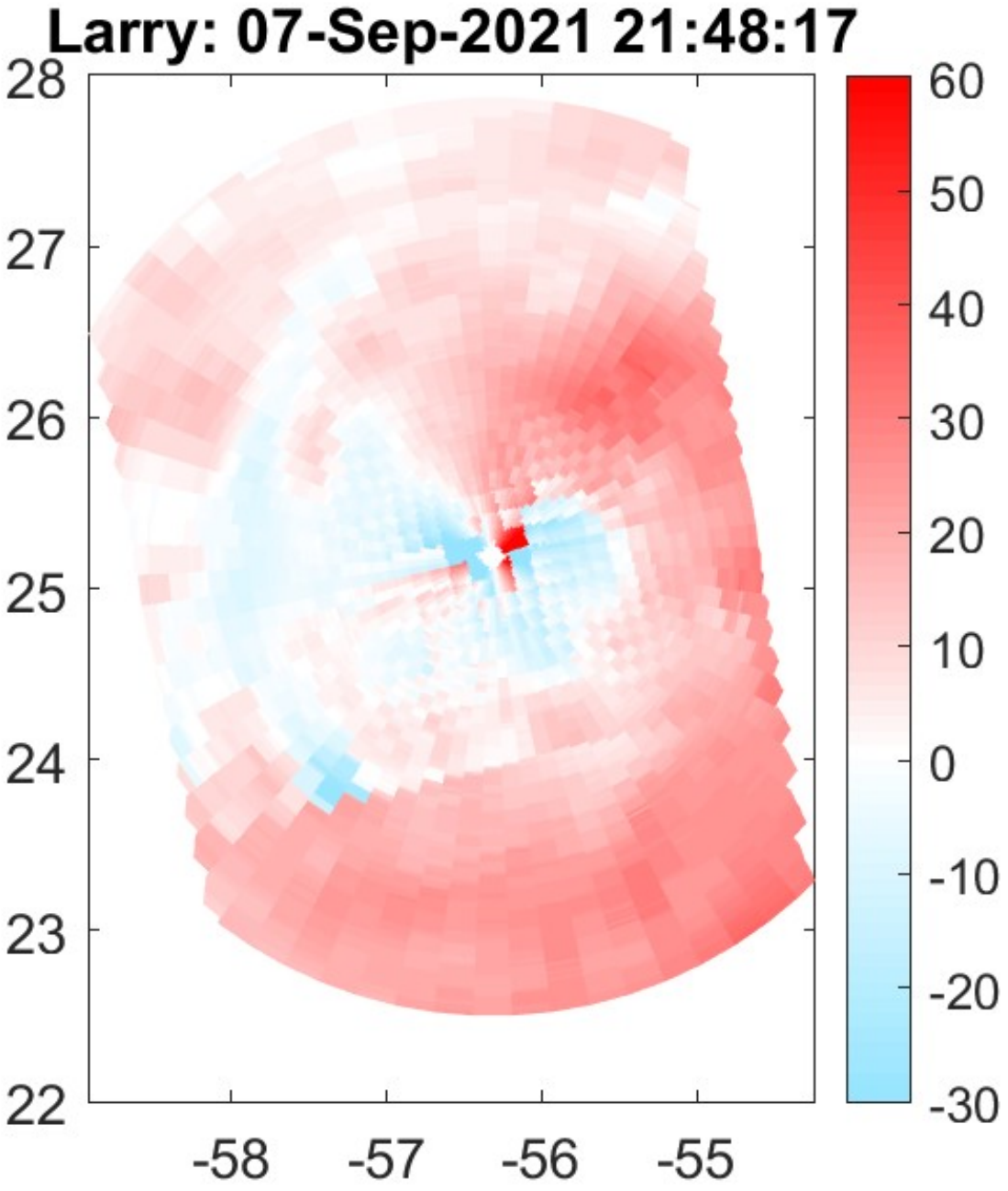


SAR-derived BC for Foster (2009) TCBL similarity model



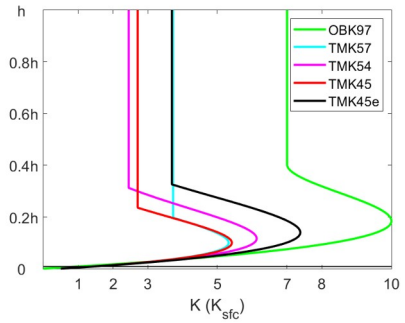
TCBL Roll Orientations

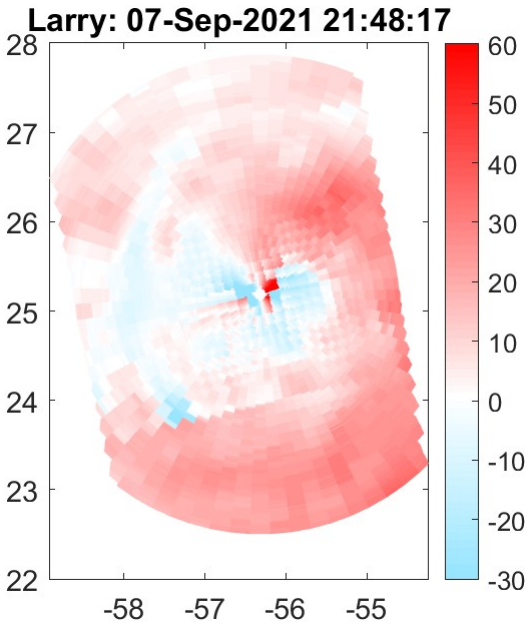
- Extract roll orientation in 20 km blocks
  - Heavy gray dashes
  - Close, but not exactly, wind-aligned
    - Light gray streamlines
- Roll signature ubiquitous
  - Morrison et al., 2005; Foster, 2005

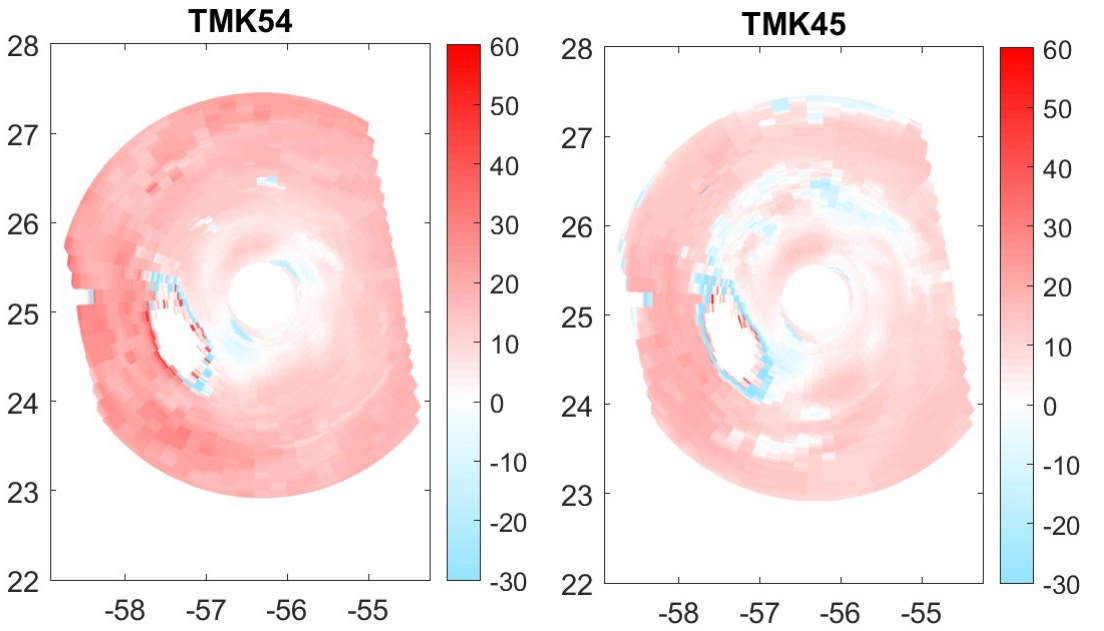


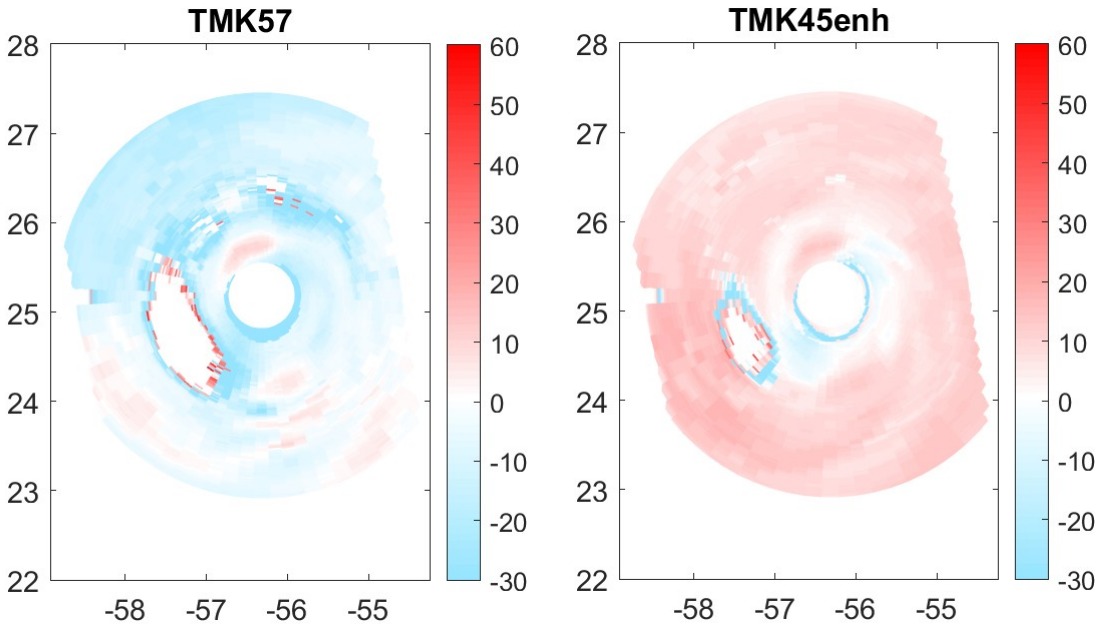
TCBL rolls “Inflow” Angle

Positive Angle: rolls point <u>toward</u> low pressure









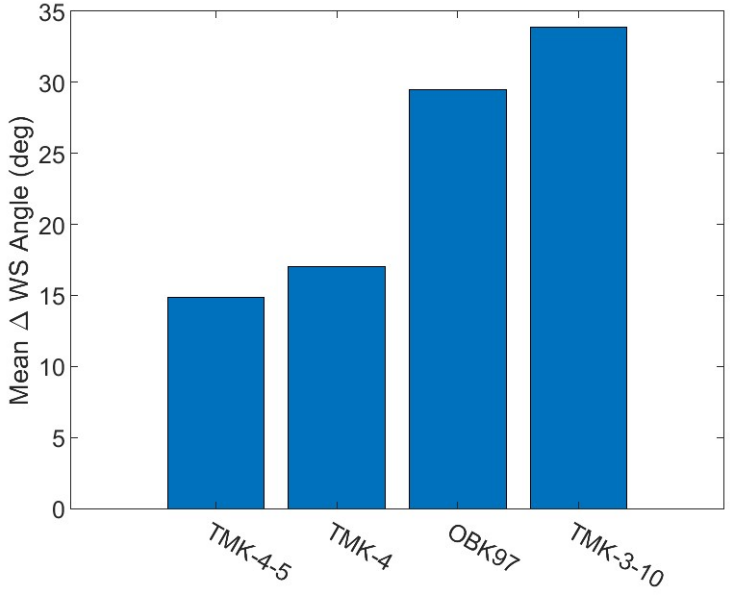
Orientation of TCBL rolls

<u>Assumptions</u>:

- Roll orientation primarily determined by TCBL mean shear profiles
- SAR-estimated mean shear profiles primarily determined by assumed K(z)

<u>Seek best agreement with OBS</u>

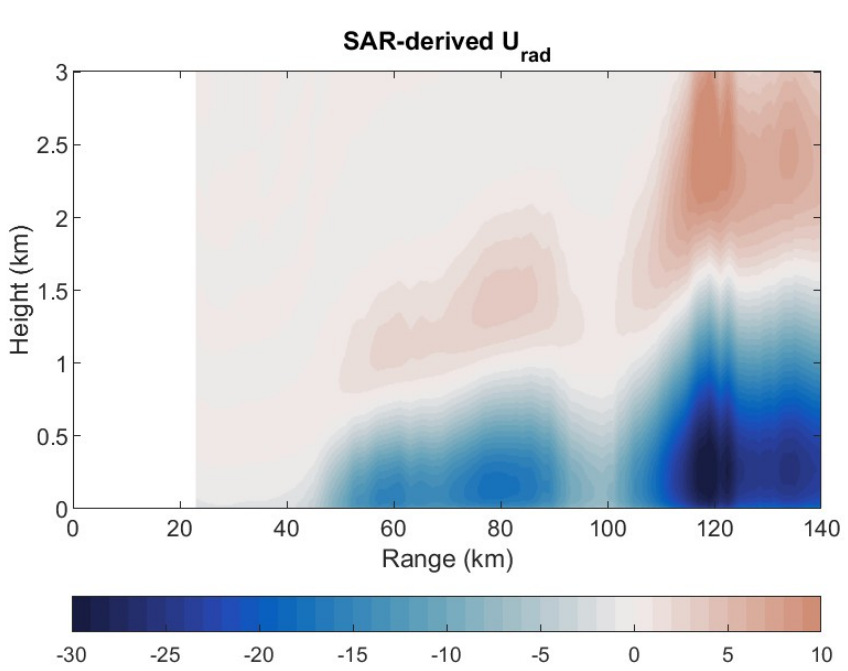
- Insight into TCBL roll dynamics
- Insight into K(z) distributions (small-scale turbulence)

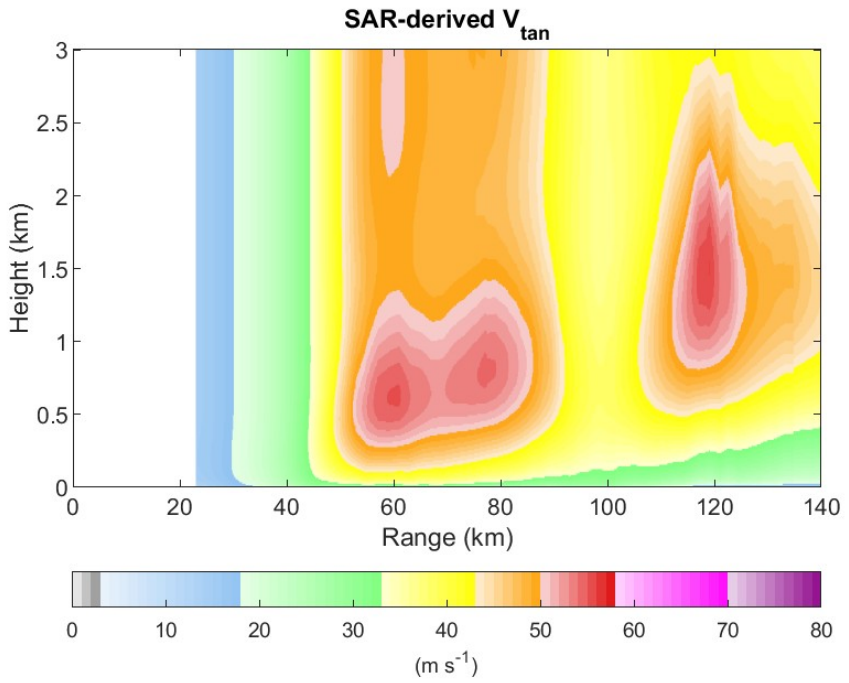


Calculated using Foster (2005; 2009)

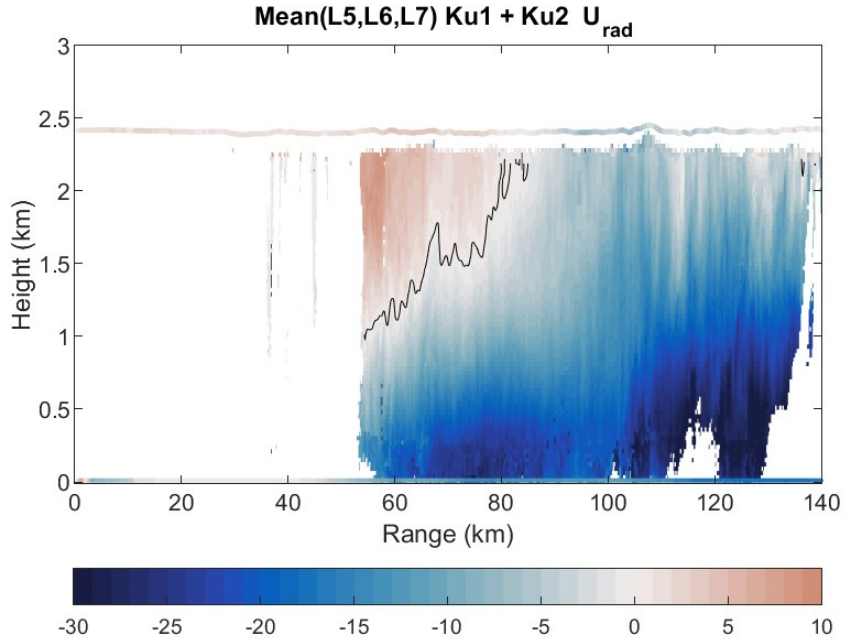
IWRAP Winds

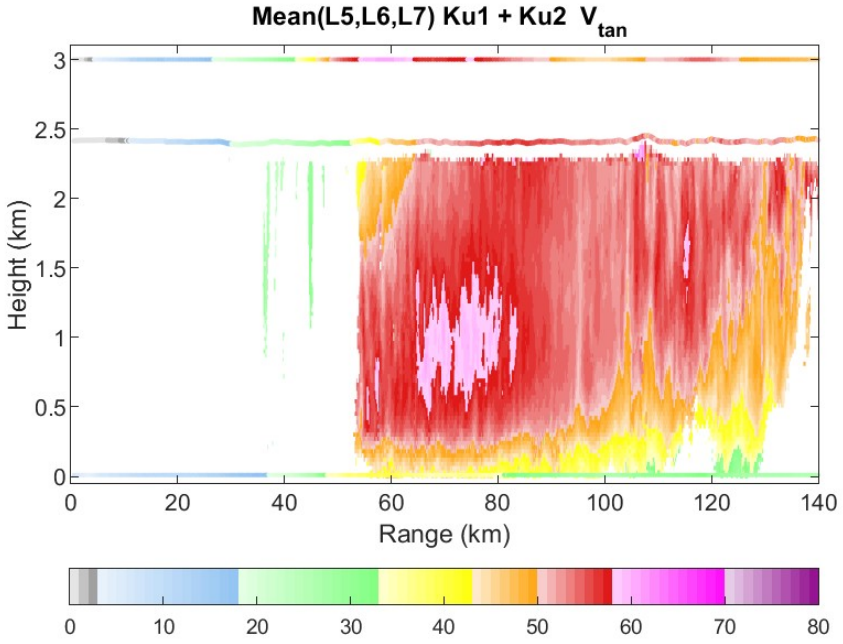
- P-3 penetration at overpass time





- SAR-derived wind profiles
  - <u>No additional data input</u>
  - PBL depth too shallow
  - K(z) a bit diffusive
  - Circulation a bit weak
- Improvements are likely





Note the ubiquitous km-scale modulation in IWRAP winds

Analyze IWRAP km-scale Modulation

- Choose P-3 leg near overpass
  - r = 65 - 95 km (RMW = 65)
  - Use SAR to rotate into roll-coordinates (~5°)
    - Roll overturning circulation is (Upar, w)
      - Upar is approximately radial
    - Along-roll perturbation is (Uperp)
      - Uperp is approximately azimuthal
- Perturbation from 5-km running mean
  - Decompose into wavelets from near-surface to 3 km
  - Extract 95% significant peaks based on red noise (MLE estimate of lag-1 autocorrelation)
    - Distinct 1.5 to 4 km wavelength band across P-3 pass
    - “turbulent” small-scale peaks
  - Reconstruct winds with only locally-significant 1.5 to 4 km contributions
    - Roll circulation in IWRAP

Observed

SAR-predicted

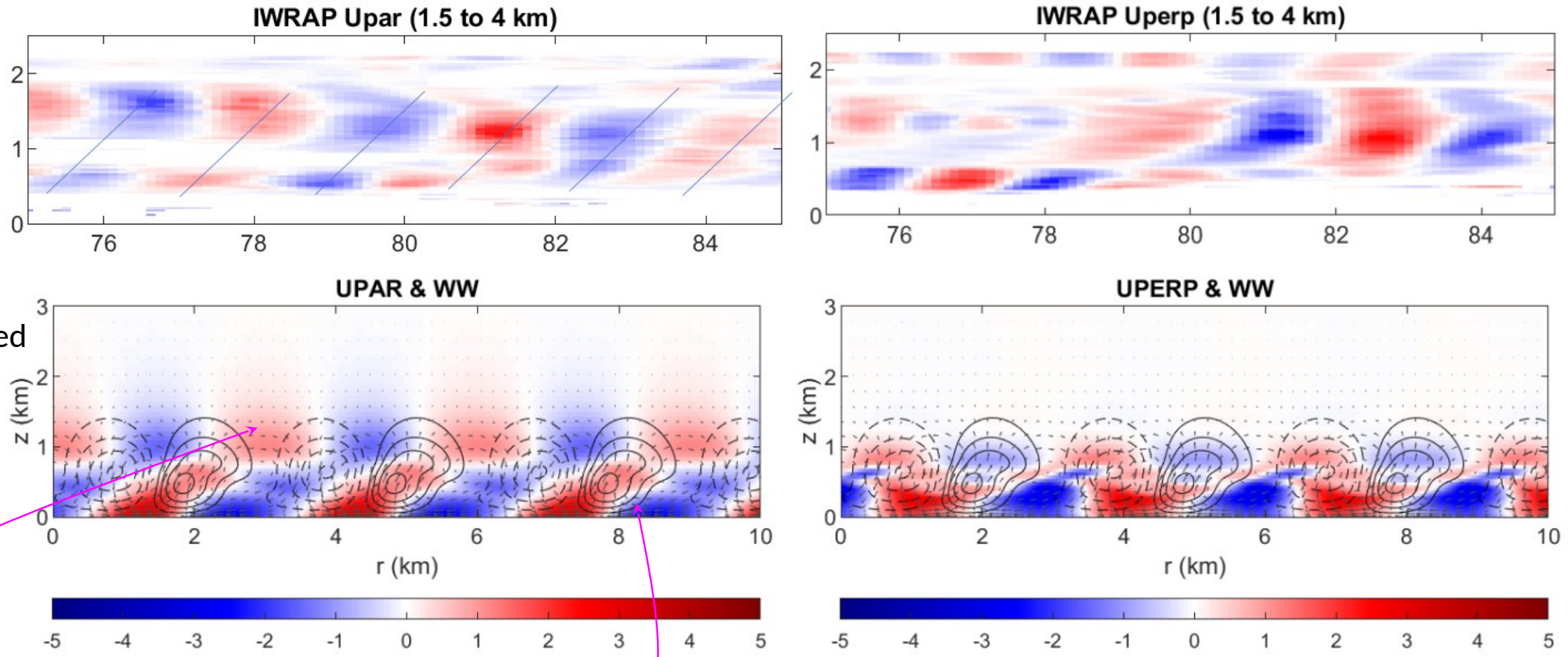


Figure 4: TCBL roll signature extracted from IWRAP winds. (a) Upar; (b) Uperp. Calculated TCBL rolls using mean wind and eddy viscosity profiles derived from IWRAP and SAR. (c) Upar; (d) Uperp. Calculated vertical velocity included on c & d with 0.5 m s-1 contours. Vectors show calculated overturning roll circulation (Upar, W).

Contours are SAR-predicted vertical velocity (0.5 m s^{-1} contours)
Vectors are SAR-predicted overturning circulation

Upar: horizontal component of overturning flow (nearly radial)
Uperp: horizontal along-roll flow (in/out of page; nearly azimuthal)

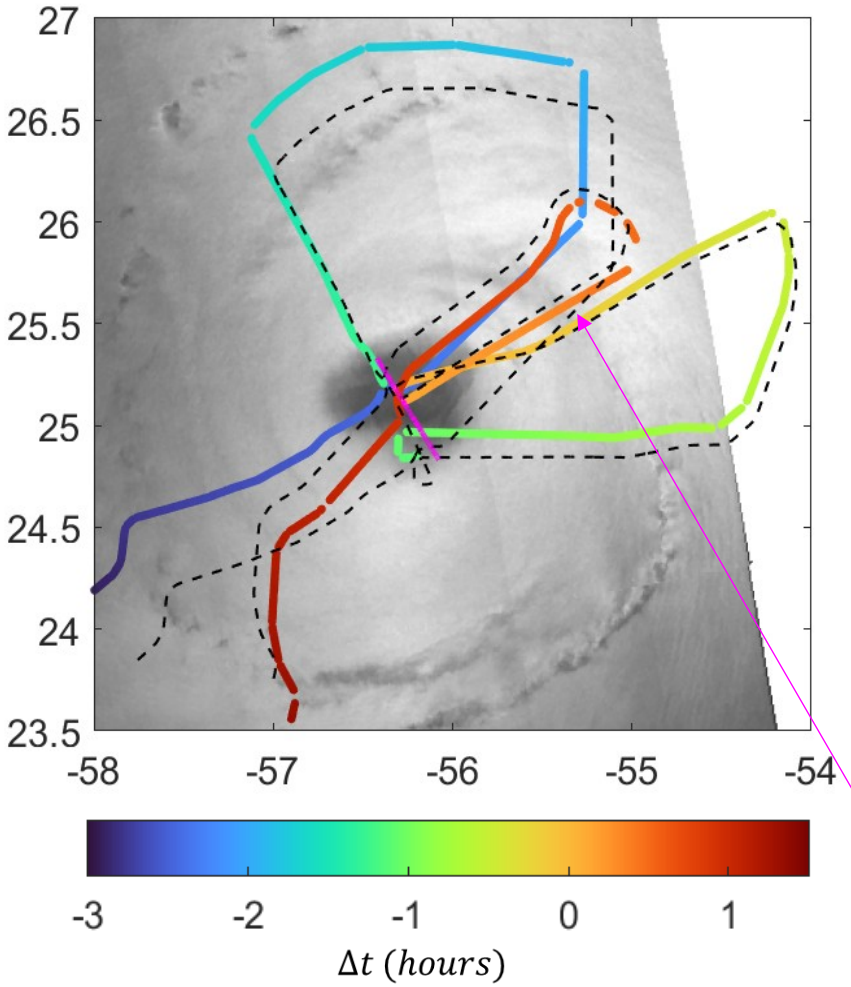
Note that the primary instability (Upar, w) leans into the mean shear

These are NOT convective rolls!

Extra

Predict IWRAP Roll Circulation from SAR

- Use only data extracted from the SAR image
  - SAR-Derived Mean Wind Profiles
    - Derived from $V_g(r,\theta)$ & $U_{rad}{}_{10}^{N}, V_{tan}{}_{10}^{N}$
  - Previously predicted wavelengths and orientations
    - Determines $K(z)$
- Modified non-linear TCBL rolls theory (Foster, 2005)
  - Arbitrary $\big(U(z), V(z)\big)$ & $K(z)$
  - Predict TCBL roll Structure & Magnitude
  - Compare to IWRAP extracted roll signature
    - Significant 1.5 to 4 km wavelength band only



Dashed: Actual P-3 flight track
Colored: P-3 adjusted to SAR overpass time
Magenta: Storm track

- Approximate center fixes
  - Four NHC 6-hourly locations
  - First-guess SAR surface wind circulation center
- Minimize RMS between SAR - SFMR U_{10}
  - Do not require track to match any of the center fixes
  - Smooth path, keep within 10 km of NHC and 4 km of SAR
  - Optimization cost function restricted to ~150 km of storm center
  - RMS:
    - Initial ~6.5 m/s
    - Final ~4 m/s

Radial pass at S-1 overpass

Adjusting aircraft to SAR is the most difficult aspect and contributes significantly to RMS!

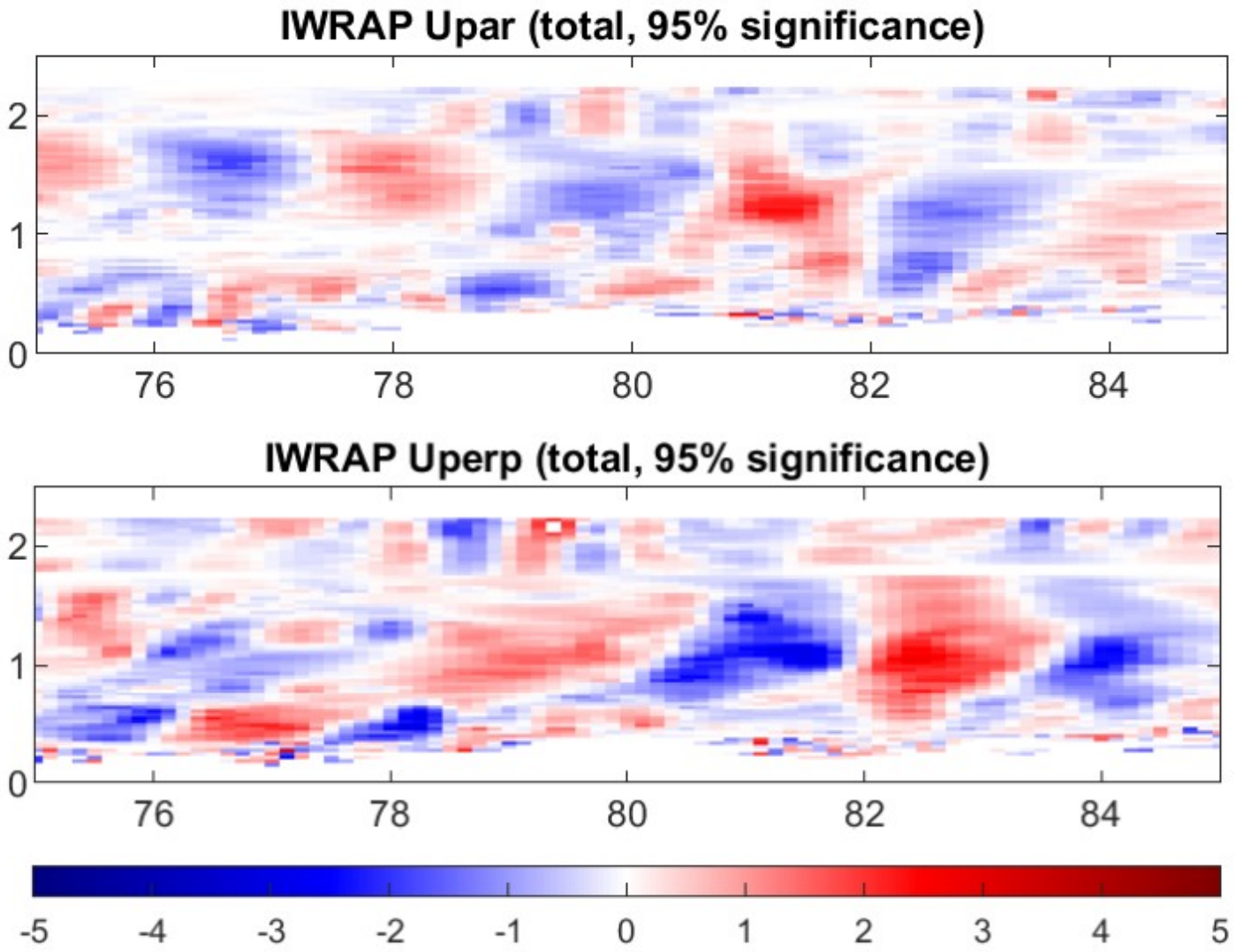


Figure 15: Hurricane Larry (2021) (a) Upar perturbation wind reconstructed using only significant spectral peaks (b) As in (a), but for Uperp

Upper: Upar: horizontal component of overturning flow (nearly radial)
Lower: Uperp: horizontal along-roll flow (in/out of page; nearly azimuthal)