The Antecedents and Impacts of Rossby Wave Breaking and PV Streamer Formation in the Tropical Atlantic (Steering Impact on TC Joaquin)

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Motivation

• Potential Vorticity (PV) Streamers
  – Elongated filament of high PV air
  – Formation a result of anticyclonic Rossby wavebreaking (AWB)
    • Ridge amplification often aided by diabatic processes
    • Breakdown of PV streamer into cutoff cyclone
  – Can impact mature TC motion
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    - Breakdown of PV streamer into cutoff cyclone
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    • Breakdown of PV streamer into cutoff cyclone
  – Can impact mature TC motion

Objectives

1) Investigate initial PV streamer formation
   • Antecedent conditions important to its formation
     – Dataset: 0.5° Climate Forecast System Reanalysis (CFSR) v2

2) Investigate PV streamer’s role on track of TC Joaquin
   • Analyze role compared to other synoptic features
     – Dataset: 0.5° Climate Forecast System Reanalysis (CFSR) v2

National Hurricane Center forecast discussion: 0600 UTC 3 October

Joaquin should continue to accelerate northeastward today in the deep-layer southwesterly flow between a deep trough over the southeastern U.S. and the Atlantic subtropical ridge. The cross-track spread in the guidance increases on days 2 and 3 due to differences in how much Joaquin is tugged to the left by an upper-low passing to its north and northwest before the cyclone accelerates into the westerlies over the north Atlantic.

• Compare CFSR to operational forecast evolution of synoptic features
  – Datasets: 0.5° GFS Forecast / 0.5° ECMWF Forecast
Synoptic Overview
Synoptic Overview

350-K PV (shaded, PVU), 350-K winds (barbs, kt)

Precipitable water (shaded, mm), 350-K PV (gray contours, PVU), 350-K irrotational wind (yellow vectors, m s⁻¹), 600–400-hPa layer mean upward vertical motion (red contours, < -5 x 10⁻³ hPa s⁻¹)
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Synoptic Overview

1200 UTC 2 Oct 2015

350-K PV (shaded, PVU), 350-K winds (barbs, kt)
Precipitable water (shaded, mm), 350-K PV (gray contours, PVU),
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Track Influences of Joaquin
Track of Joaquin

- Sharp right hairpin turn between 1 – 3 October
- Cutoff cyclone partially responsible for motion?
- Investigate the individual pieces perceived to be responsible for movement away from US coastline
Track of Joaquin

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Track of Joaquin

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**Piecewise Vorticity Inversion**

Used to quantify what impact different synoptic features have on TC Joaquin track

- 850 – 200-hPa flow inverted (captures steering level for TC Joaquin)

Adapted from Galarneau and Davis (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases} \\
\nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases} 
\]

- Nondivergent Winds
- Irrotational Winds

\[
\vec{V}_\chi = \nabla \chi \\
\vec{V}_\psi = \hat{k} \times \nabla \psi \\
\vec{V} = \vec{V}_\psi + \vec{V}_\chi
\]

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Calculate heading imparted by CFSRv2 layer mean flow
- Compare to actual heading from NHC track

Adapted from Galarneau and Davis (2013)
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\[\vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi\]

Nondivergent Winds \quad Irrotational Winds

\[\vec{V} = \vec{V}_\psi + \vec{V}_\chi\]

Total Wind

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$$\vec{V}_\chi = \nabla \chi$$

$$\vec{V}_\psi = \hat{k} \times \nabla \psi$$

Nondivergent Winds

Irrotational Winds

$$\vec{V} = \vec{V}_\psi + \vec{V}_\chi$$

Total Wind

- Remove TC Joaquin vortex
- \( r_{Joaquin} \geq 3.0^\circ \)
- Calculate heading imparted by CFSRv2 layer mean flow
- Compare to actual heading from NHC track

63° at 5.7 m s⁻¹

59° at 4.9 m s⁻¹

When does CFSR capture steering of Joaquin best?
CFSR Normalized Error

\[
\frac{\text{CFSR heading}_{850-200 \ hPa} - \text{Actual heading}}{\text{Actual heading magnitude}} = \text{CFSR normalized heading error}
\]

- Pick period with lowest normalized error to investigate synoptic influences on heading
CFSR Normalized Error

\[
\text{CFSR normalized heading error} = \frac{\text{CFSR heading}_{850-200 \text{ hPa}} - \text{Actual heading}}{\text{Actual heading magnitude}}
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- Pick period with lowest normalized error to investigate synoptic influences on heading
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\[ \vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi \]

**Nondivergent Winds**

**Irrotational Winds**

**Total Wind**

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin
Piecewise Vorticity Inversion

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Nondivergent Winds \quad Irrotational Winds

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Nondivergent Winds \quad Irrotational Winds

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Total Wind

- Remove TC Joaquin vortex

- \( r_{\text{Joaquin}} \geq 3.0^\circ \)

- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 1  •  Isolate steering from upstream upper-level trough
**Piecewise Vorticity Inversion**

Used to quantify what impact different synoptic features have on TC Joaquin track

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\vec{V}_\chi = \hat{k} \times \nabla \psi \\
\vec{V} = \vec{V}_\psi + \vec{V}_\chi \\
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- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

**Test 2**

- Isolate steering from poleward upper-level ridge
Piecwise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

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Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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Nondivergent Winds \hspace{1cm} Irrotational Winds

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\vec{V} = \vec{V}_\psi + \vec{V}_\chi
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Total Wind

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 3  
- Isolate steering from cutoff cyclone (from PV streamer)
**Piecewise Vorticity Inversion**

Used to quantify what impact different synoptic features have on TC Joaquin track

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Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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- Remove TC Joaquin vortex
- \(r_{\text{Joaquin}} \geq 3.0^\circ\)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

**Test 4**

- Test 1 + Test 2 + Test 3 (Cumulative steering)
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

- 850 – 200-hPa flow inverted (captures steering level for TC Joaquin)

- Adapted from Galarneau and Davis (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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Nondivergent Winds \quad Irrotational Winds

\[
\vec{V} = \vec{V}_\psi + \vec{V}_\chi
\]

Total Wind

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 5

- Total Steering - Test 1 + Test 2 + Test 3 (residual)
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Steering

Observations

- CFSRv2 heading 63$^\circ$ at 5.7 m s$^{-1}$
- Actual TC motion: 59$^\circ$ at 4.9 m s$^{-1}$
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 1

Observations
- CFSRv2 heading: 31$^\circ$ at 9.3 m s$^{-1}$
- Actual TC motion: 59$^\circ$ at 4.9 m s$^{-1}$
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 2

Observations
- CFSRv2 heading 285$^\circ$ at 10.1 m s$^{-1}$
- Actual TC motion: 59$^\circ$ at 4.9 m s$^{-1}$

0600 UTC 3 Oct 2015
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 3

Observations
- CFSRv2 heading $147^\circ$ at 4.9 m s$^{-1}$
- Actual TC motion: $59^\circ$ at 4.9 m s$^{-1}$
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 4

Observations
- CFSRv2 heading 340$^\circ$ at 6.8 m s$^{-1}$
- Actual TC motion: 59$^\circ$ at 4.9 m s$^{-1}$

0600 UTC 3 Oct 2015
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 5

Observations
- CFSRv2 heading 118$^\circ$ at 8.2 m s$^{-1}$
- Actual TC motion: 59$^\circ$ at 4.9 m s$^{-1}$
Steering Flow

Role of building equatorward ridge?

- 200-hPa geopotential height anomalies (shaded, dam)

Increasing 200-hPa Heights
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s\(^{-1}\)) and wind vectors (arrows, m s\(^{-1}\))

Equatorward Ridge

Observations
- CFSRv2 heading 62\(^\circ\) at 5.3 m s\(^{-1}\)
- Actual TC motion: 59\(^\circ\) at 4.9 m s\(^{-1}\)

15\(^\circ\) circle centered on 65\(^\circ\)W, 10\(^\circ\)N

0600 UTC 3 Oct 2015
Conclusions

- Development of PV streamer from repeated AWB
  - Result of ridge amplification and advection of flow downstream of the ridge
  - PV streamer breakdown into cutoff cyclone
    - Possible result of additional AWB and downstream convection filamenting high PV air

- Piecewise inversion of flow suggests that cutoff upper-level cyclone from PV streamer only piece of larger steering puzzle
  - Adding steering from upstream upper-level trough, poleward upper-level ridge, and cutoff cyclone still induces westerly heading on Joaquin closer to US coastline.
  - Role of residual planetary westerlies needs to be investigated further
  - Future work will compare this analysis to operational forecast models (i.e., GFS and ECMWF)
QUESTIONS?
Extra Slides
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Equatorward Ridge

Observations
- **CFSRv2 Heading**
  6$^\circ$ at 8.5 m s$^{-1}$
- **Actual TC Motion:**
  59$^\circ$ at 4.9 m s$^{-1}$

15$^\circ$ circle
Centered on 65$^\circ$W, 10$^\circ$N
Synoptic Overview

350 K PV (shaded, PVU), pressure (black contours, every 10 hPa), winds (barbs, kt)

Precipitable water (shaded, mm), 200-300 hPa wind magnitude (shaded, m s\(^{-1}\)) 200-300 hPa layer mean PV (gray contours, PVU), 200-300 hPa irrotational wind (vectors, m s\(^{-1}\)), 600-400 hPa upward vertical motion (red contours, > 5 \(\times\) 10\(^{-3}\) hPa s\(^{-1}\))
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

- Adapted from Davis et al. (2008)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases}
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\nabla^2 \chi = \begin{cases} 
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\vec{V}_\chi = \nabla \chi \\
\vec{V}_\psi = \hat{k} \times \nabla \psi
\]

Nondivergent Winds \hspace{1cm} Irrotational Winds

\[
\vec{V} = \vec{V}_\psi + \vec{V}_\chi
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Total Wind

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use the 350-K 2-PVU contour to isolate key upper-level features
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**Test 1**

- Isolate steering from upstream upper-level trough
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Nondivergent Winds Irrotational Winds

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Total Wind

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- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use the 350-K 2-PVU contour to isolate key upper-level features

Test 2
- Isolate steering from poleward upper-level ridge
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Total Wind

- Remove TC Joaquin vortex
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Test 3
- Isolate steering from cutoff cyclone (from PV streamer)
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Nondivergent Winds \quad Irrotational Winds

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\vec{V} = \vec{V}_\psi + \vec{V}_\chi
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- **Remove TC Joaquin vortex**
- **r_{Joaquin} \geq 3.0^\circ**
- **Use the 350-K 2-PVU contour to isolate key upper-level features**

**Test 4**
- **Test 1 + Test 2 + Test 3 (Cumulative steering)**
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- \(r_{Joaquin} \geq 3.0^\circ\)
- Use the 350-K 2-PVU contour to isolate key upper-level features

Test 5 • Total Steering - Test 1 + Test 2 + Test 3 (residual)
Trough Steering Flow

- Removal of TC Joaquin vortex
  - $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$))

Test 1

Observations
- CFSRv2 Steering
  - $28^\circ$ at 8.1 m s$^{-1}$
- Actual TC Motion:
  - $50^\circ$ at 6.2 m s$^{-1}$
Ridge Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$))

Test 2

Observations
- CFSRv2 Steering 285$^\circ$ at 11.1 m s$^{-1}$
- Actual TC Motion: 50$^\circ$ at 6.2 m s$^{-1}$
Cutoff Steering Flow

- Removal of TC Joaquin vortex
  - $r_{Joaquin} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 3

Observations
- CFSRv2 Steering
  - $130^\circ$ at 5.0 m s$^{-1}$
- Actual TC Motion:
  - $50^\circ$ at 6.2 m s$^{-1}$
Cumulative Steering Flow

- Removal of TC Joaquin vortex
  \( r_{\text{Joaquin}} \geq 3.0^\circ \)

850 – 200-hPa layer mean wind magnitude (shaded, m s\(^{-1}\)) and wind vectors (arrows, m s\(^{-1}\))

Test 4

Observations
- CFSRv2 Steering: 335\(^\circ\) at 7.5 m s\(^{-1}\)
- Actual TC Motion: 50\(^\circ\) at 6.2 m s\(^{-1}\)
Residual Steering Flow

- Removal of TC Joaquin vortex
  \[ r_{\text{Joaquin}} \geq 3.0^\circ \]

850 – 200-hPa layer mean wind magnitude (shaded, m s\(^{-1}\)) and wind vectors (arrows, m s\(^{-1}\))

**Test 5**

**Observations**

- **CFSRv2 Steering**
  108° at 10.9 m s\(^{-1}\)

- **Actual TC Motion**
  50° at 6.2 m s\(^{-1}\)
Residual Steering Flow
1200 UTC 29 Sep 2015
Residual Steering Flow

1200 UTC 1 Oct 2015
Residual Steering Flow

1200 UTC 2 Oct 2015
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

- Adapted from Galarneau et al. (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases} \\
\nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases} 
\]

\[ \vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi \]

Nondivergent Winds \quad Irrotational Winds

\[ \vec{V} = \vec{V}_\psi + \vec{V}_\chi \]

Total Wind

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^o \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 1
- Isolate steering from upstream upper-level trough
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

• Adapted from Galarneau et al. (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases} \\
\nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0 
\end{cases}
\]

\[
\vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi
\]

Nondivergent Winds \quad Irrotational Winds

\[
\vec{V} = \vec{V}_\psi + \vec{V}_\chi
\]

Total Wind

• Remove TC Joaquin vortex
• \( r_{Joaquin} \geq 3.0^\circ \)
• Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 2
• Isolate steering from poleward upper-level ridge
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

- Adapted from Galarneau et al. (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases} \quad \nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases}
\]

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

Test 3  • Isolate steering from cutoff cyclone (from PV streamer)
Piecewise Vorticity Inversion

Used to quantify what impact different synoptic features have on TC Joaquin track

- Adapted from Galarneau et al. (2013)
- Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases} \quad \nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases}
\]

\[
\vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi 
\]

- Nondivergent Winds
- Irrotational Winds

\[
\vec{V} = \vec{V}_\psi + \vec{V}_\chi 
\]

- Remove TC Joaquin vortex
- \( r_{\text{Joaquin}} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnose upper-tropospheric features related to steering of Joaquin

Test 4  •  Test 1 + Test 2 + Test 3 (Cumulative steering)
**Piecewise Vorticity Inversion**

Used to quantify what impact different synoptic features have on TC Joaquin track

- Adapted from Galarneau et al. (2013)

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

\[
\nabla^2 \psi = \begin{cases} 
\zeta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases} \quad \nabla^2 \chi = \begin{cases} 
\delta & \text{for } r \leq r_0 \\
0 & \text{for } r > r_0
\end{cases}
\]

\[
\vec{V}_\chi = \nabla \chi \quad \vec{V}_\psi = \hat{k} \times \nabla \psi
\]

**Nondivergent Winds**

\[\vec{V} = \vec{V}_\psi + \vec{V}_\chi\]

**Irrotational Winds**

- Remove TC Joaquin vortex
- \( r_{Joaquin} \geq 3.0^\circ \)
- Use PV anomalies (+/- 0.5 PVU) to diagnosis upper-tropospheric features related to steering of Joaquin

**Test 5**

- Total Steering - Test 1 + Test 2 + Test 3 (residual)
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Steering Observations

- CFSRv2 Steering
  65$^\circ$ at 8.0 m s$^{-1}$
- Actual TC Motion:
  50$^\circ$ at 6.2 m s$^{-1}$
Steering Flow

• Removal of TC Joaquin vortex
• $r_{\text{Joaquin}} \geq 3.0^\circ$

Observations

• CFSRv2 Steering
  26° at 8.6 m s$^{-1}$
• Actual TC Motion:
  50° at 6.2 m s$^{-1}$
Steering Flow

- **Removal of TC Joaquin vortex**
- \( r_{Joaquin} \geq 3.0 \)^°

850 – 200-hPa layer mean wind magnitude (shaded, m s\(^{-1}\)) and wind vectors (arrows, m s\(^{-1}\))

**Test 2**

**Observations**

- **CFSRv2 Steering**
  
  286° at 9.3 m s\(^{-1}\)

- **Actual TC Motion:**
  
  50° at 6.2 m s\(^{-1}\)
Steering Flow

- Removal of TC Joaquin vortex
- $r_{\text{Joaquin}} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 3

Observations
- CFSRv2 Steering $129^\circ$ at 5.0 m s$^{-1}$
- Actual TC Motion: $50^\circ$ at 6.2 m s$^{-1}$
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^{\circ}$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 4

Observations
- CFSRv2 Steering: $350^{\circ}$ at 7.2 m s$^{-1}$
- Actual TC Motion: $50^{\circ}$ at 6.2 m s$^{-1}$
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^\circ$

850 – 200-hPa layer mean wind magnitude (shaded, m s$^{-1}$) and wind vectors (arrows, m s$^{-1}$)

Test 5

Observations
- **CFSRv2 Steering**
  113$^\circ$ at 9.3 m s$^{-1}$
- **Actual TC Motion:**
  50$^\circ$ at 6.2 m s$^{-1}$
Synoptic Overview

350 K PV (shaded, PVU), pressure (black contours, every 10 hPa), winds (barbs, kt)

Precipitable water (shaded, mm), 200-300 hPa wind magnitude (shaded, m s⁻¹) 200-300 hPa layer mean PV (gray contours, PVU), 200-300 hPa irrotational wind (vectors, m s⁻¹), 600-400 hPa upward vertical motion (red contours, > 5 x 10⁻³ hPa s⁻¹)
Synoptic Overview

350 K PV (shaded, PVU), pressure (black contours, every 10 hPa), winds (barbs, kt)

Precipitable water (shaded, mm), 200-300 hPa wind magnitude (shaded, m s$^{-1}$) 200-300 hPa layer mean PV (gray contours, PVU), 200-300 hPa irrotational wind (vectors, m s$^{-1}$), 600-400 hPa upward vertical motion (red contours, > 5 x 10$^{-3}$ hPa s$^{-1}$)
Synoptic Overview

350 K PV (shaded, PVU), pressure (black contours, every 10 hPa), winds (barbs, kt)

Precipitable water (shaded, mm), 200-300 hPa wind magnitude (shaded, m s\(^{-1}\)) 200-300 hPa layer mean PV (gray contours, PVU), 200-300 hPa irrotational wind (vectors, m s\(^{-1}\)), 600-400 hPa upward vertical motion (red contours, > 5 \times 10^{-3} \text{ hPa} \text{ s}^{-1})