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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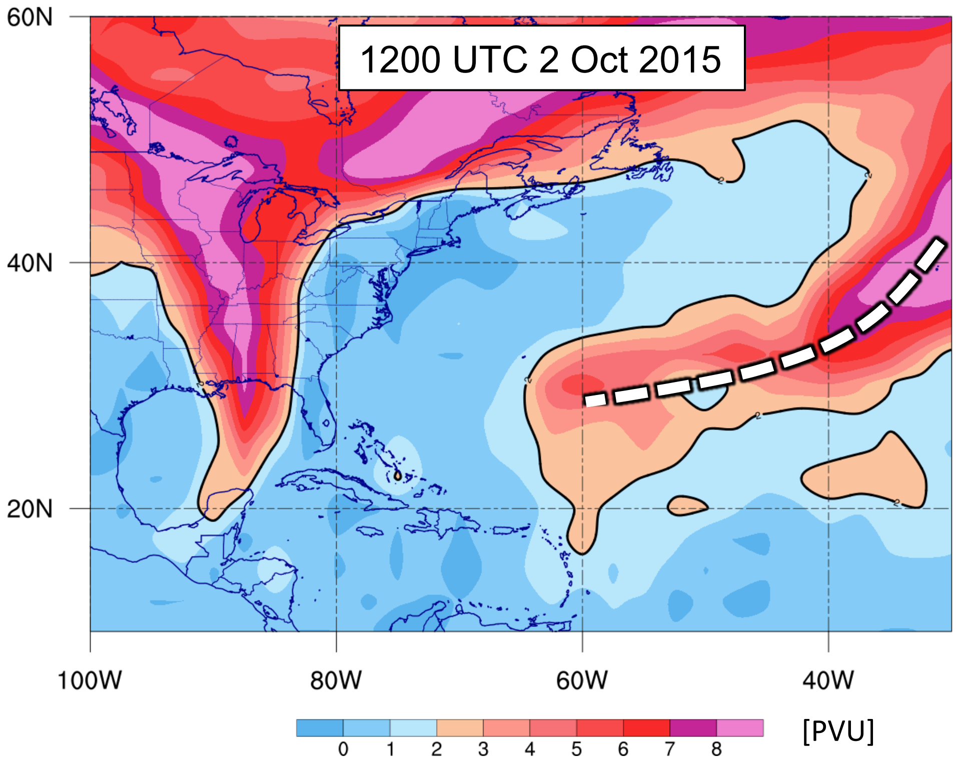
17th Cyclone Workshop - 27 October 2015

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

350-K PV (shaded, PVU), 2-PVU contour highlighted (black contour)



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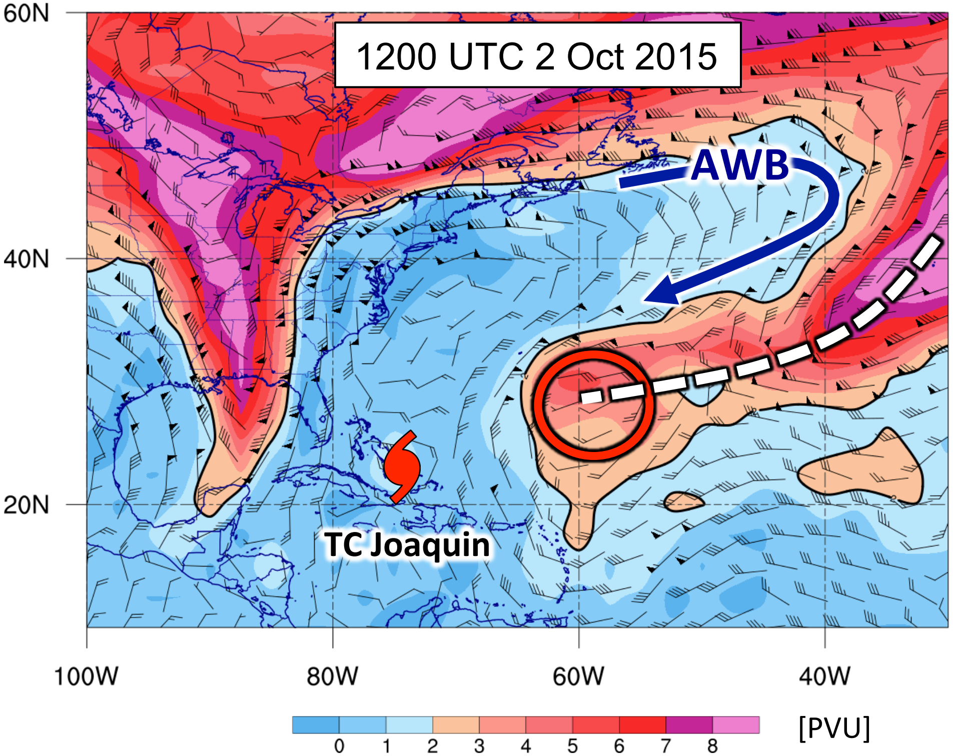

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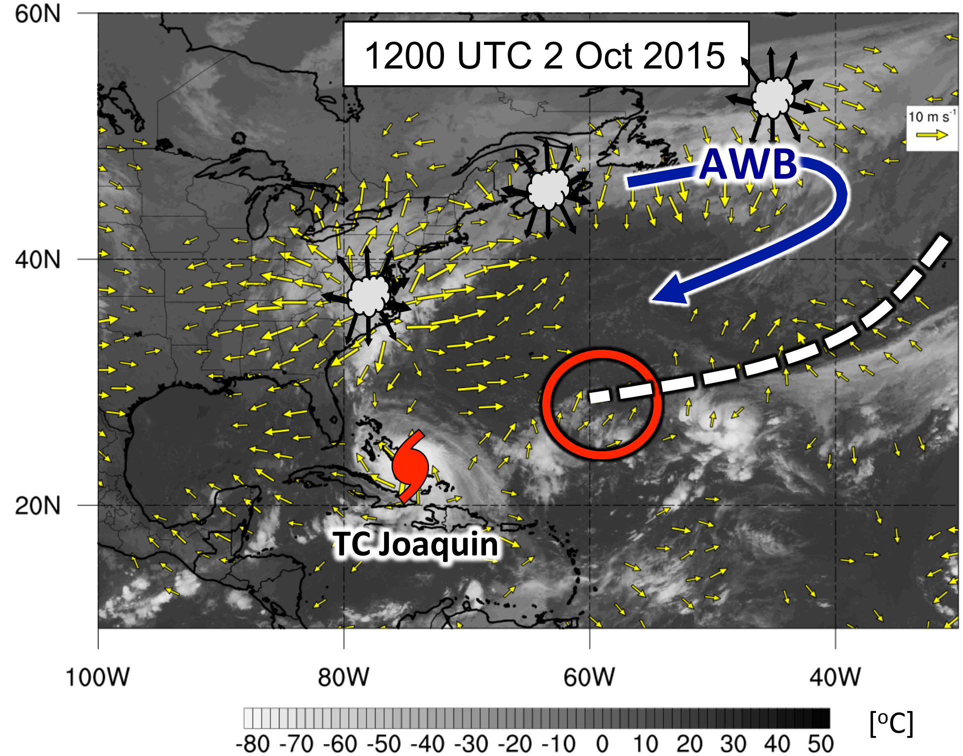
Infrared brightness temperature (shading, °C), 350-K irrotational winds (vectors, > 5 m s^{-1})



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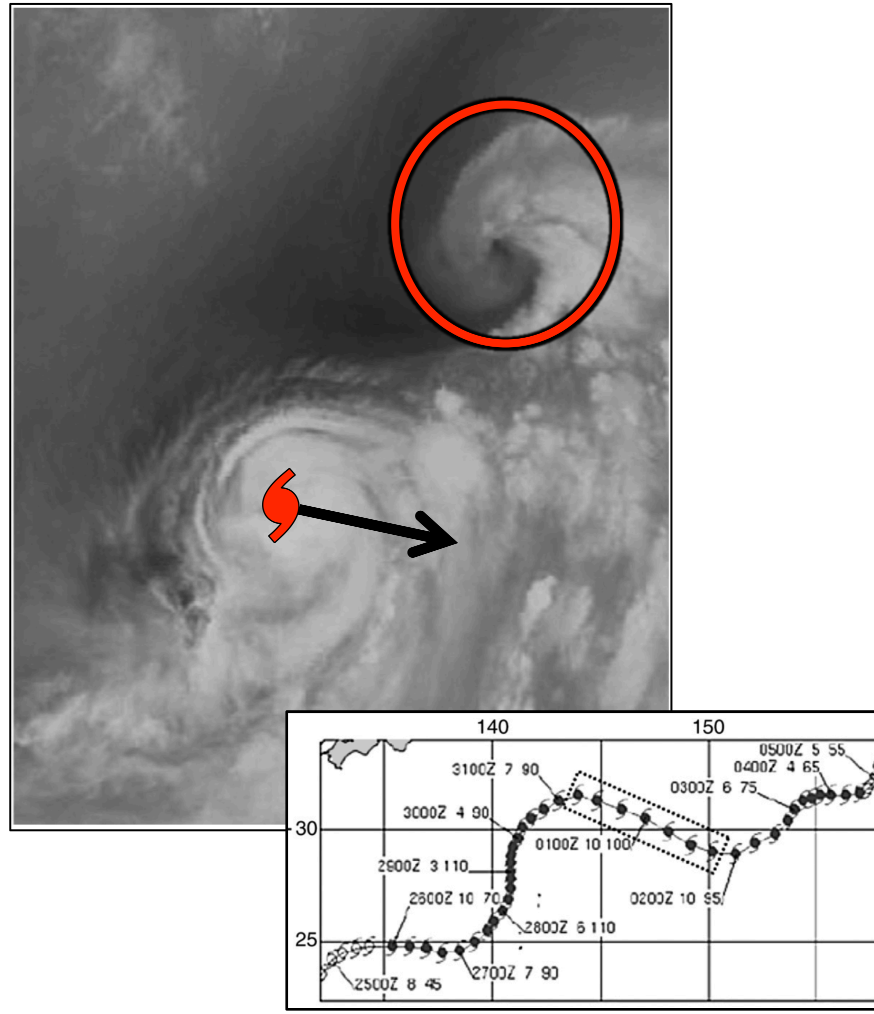

Patla et al. (2009) on PV streamer / cutoff cyclone influence on TC Rex (1998) in WPAC

Objectives

1) Investigate initial PV streamer formation

- **Antecedent conditions important to its formation**
  - **Dataset: 0.5º 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: 0.5º 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: 0.5º GFS Forecast / 0.5º ECMWF Forecast

Synoptic Overview

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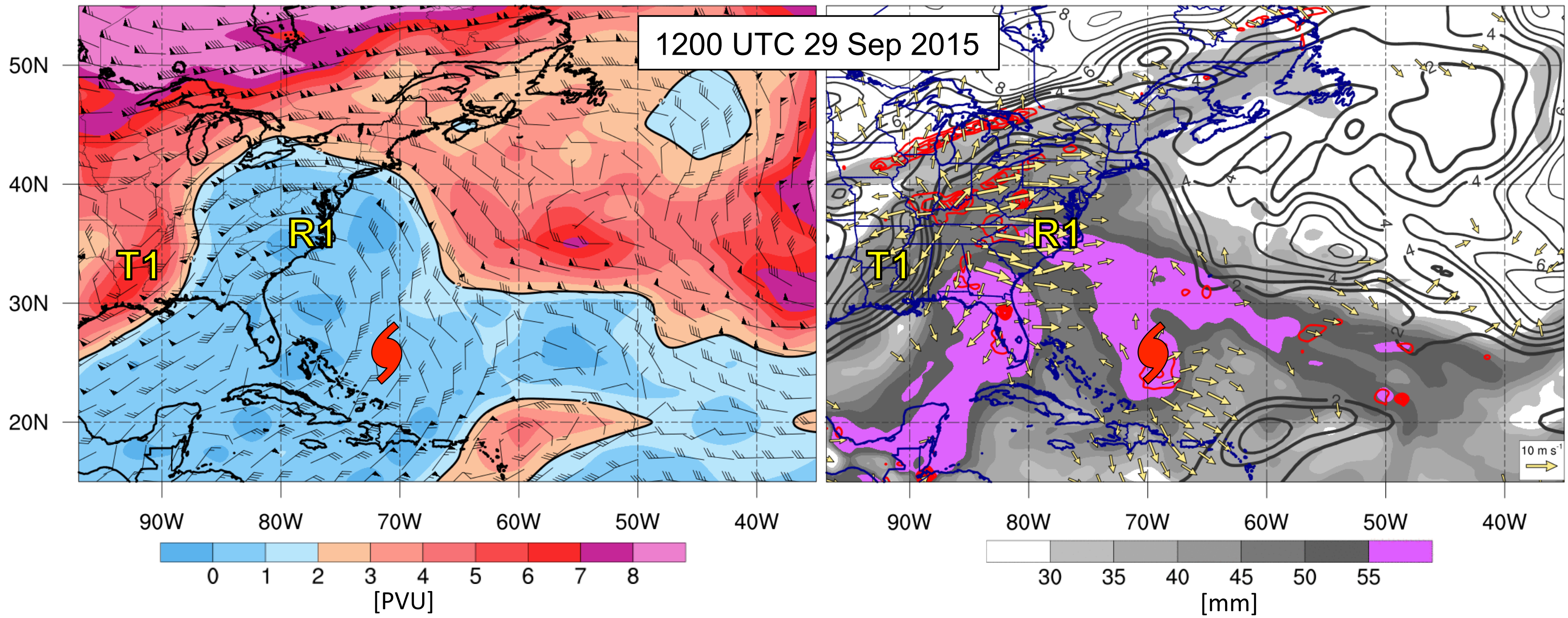

350-K PV (shaded, PVU), 350-K winds (barbs, kt)

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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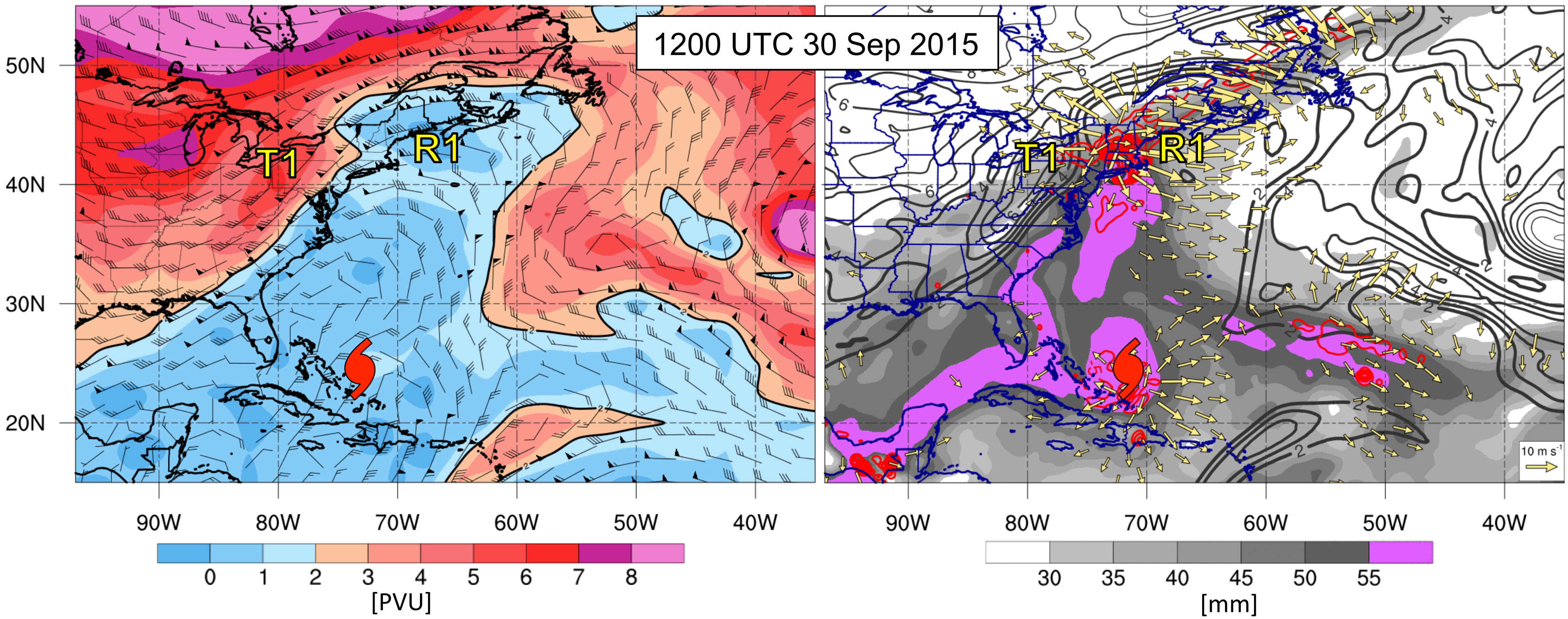

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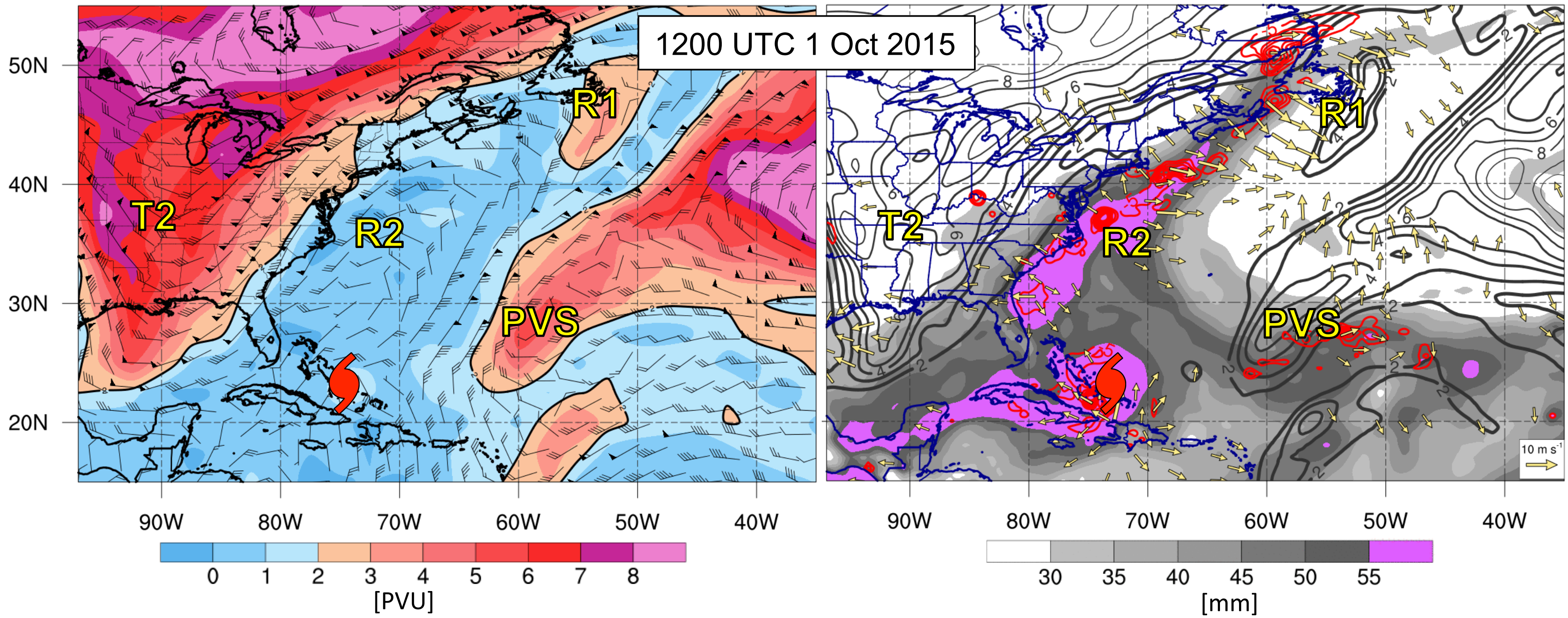

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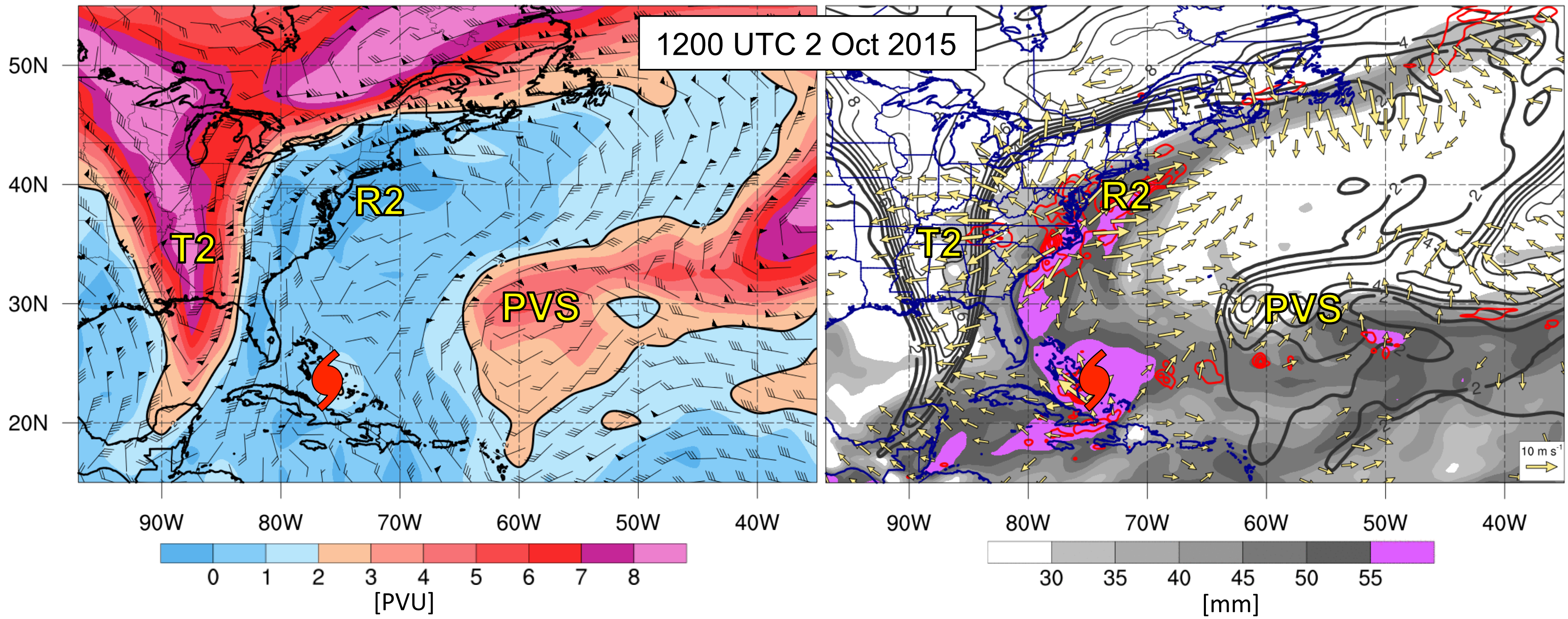

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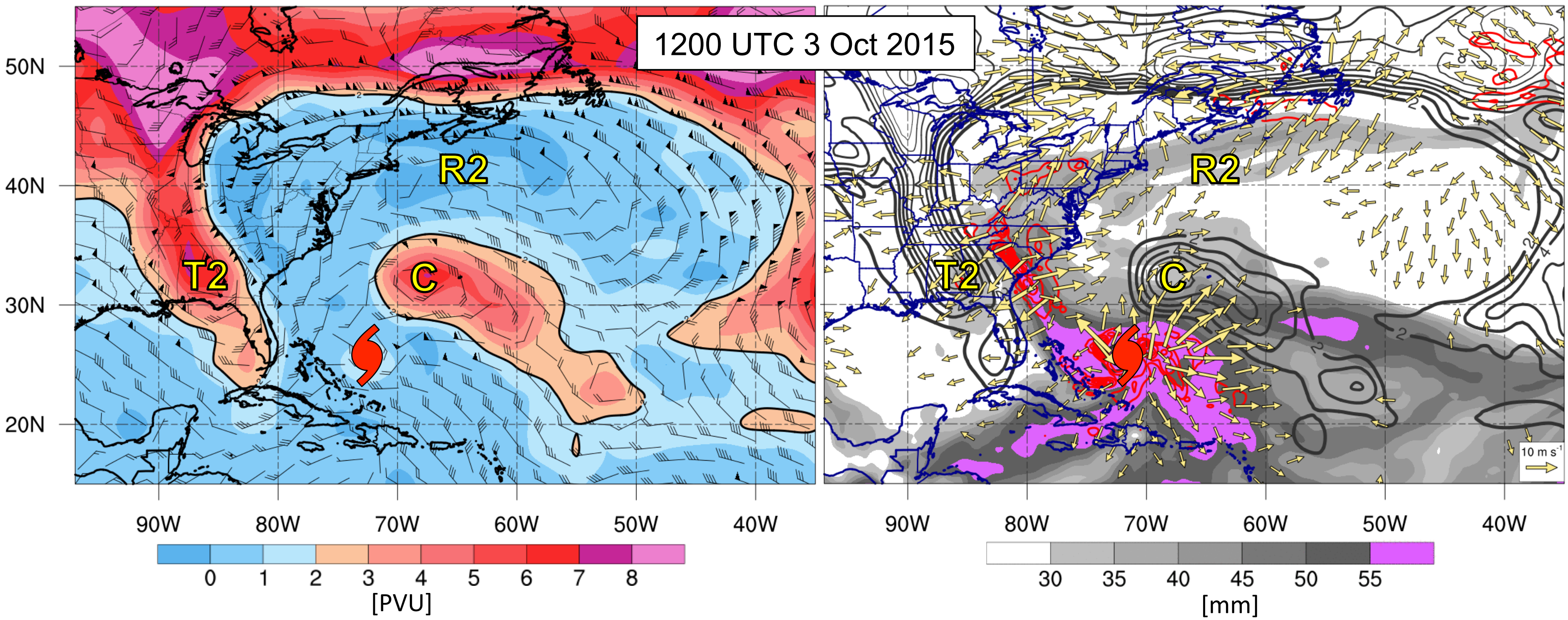

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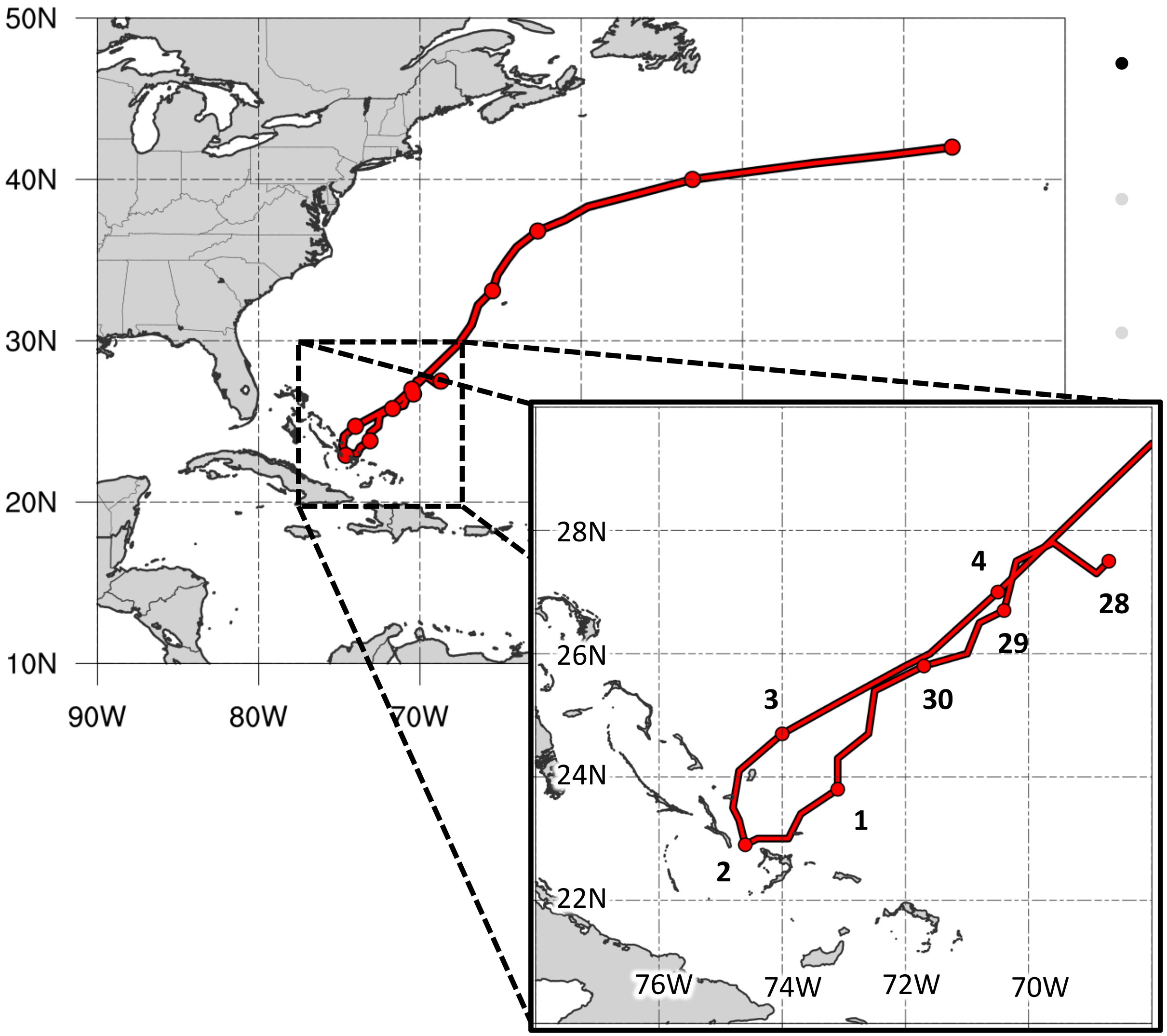
Track Influences of Joaquin

Track of Joaquin



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- Cutoff cyclone partially responsible for motion?
- Investigate the individual pieces perceived to be responsible for movement away from US coastline

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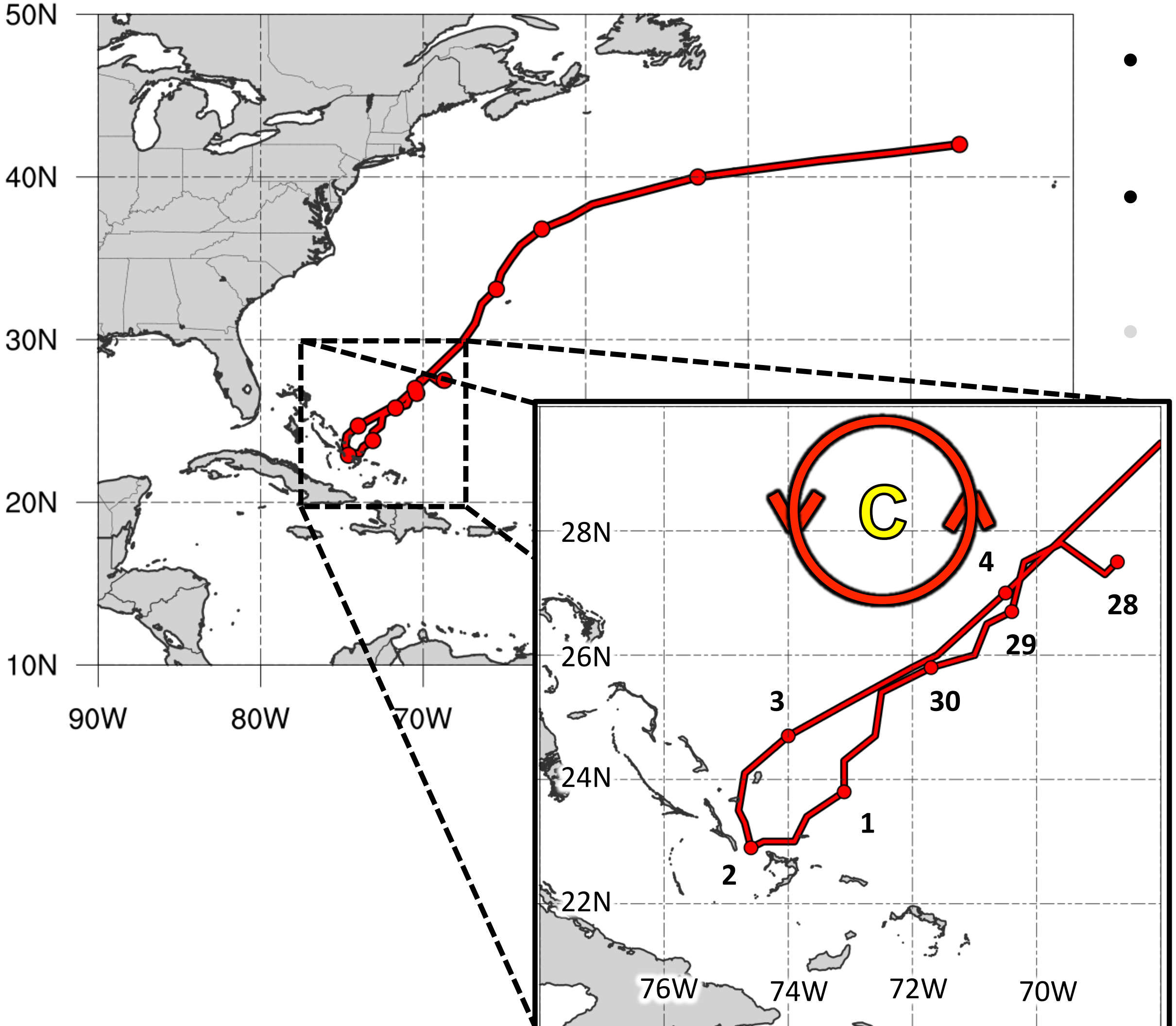

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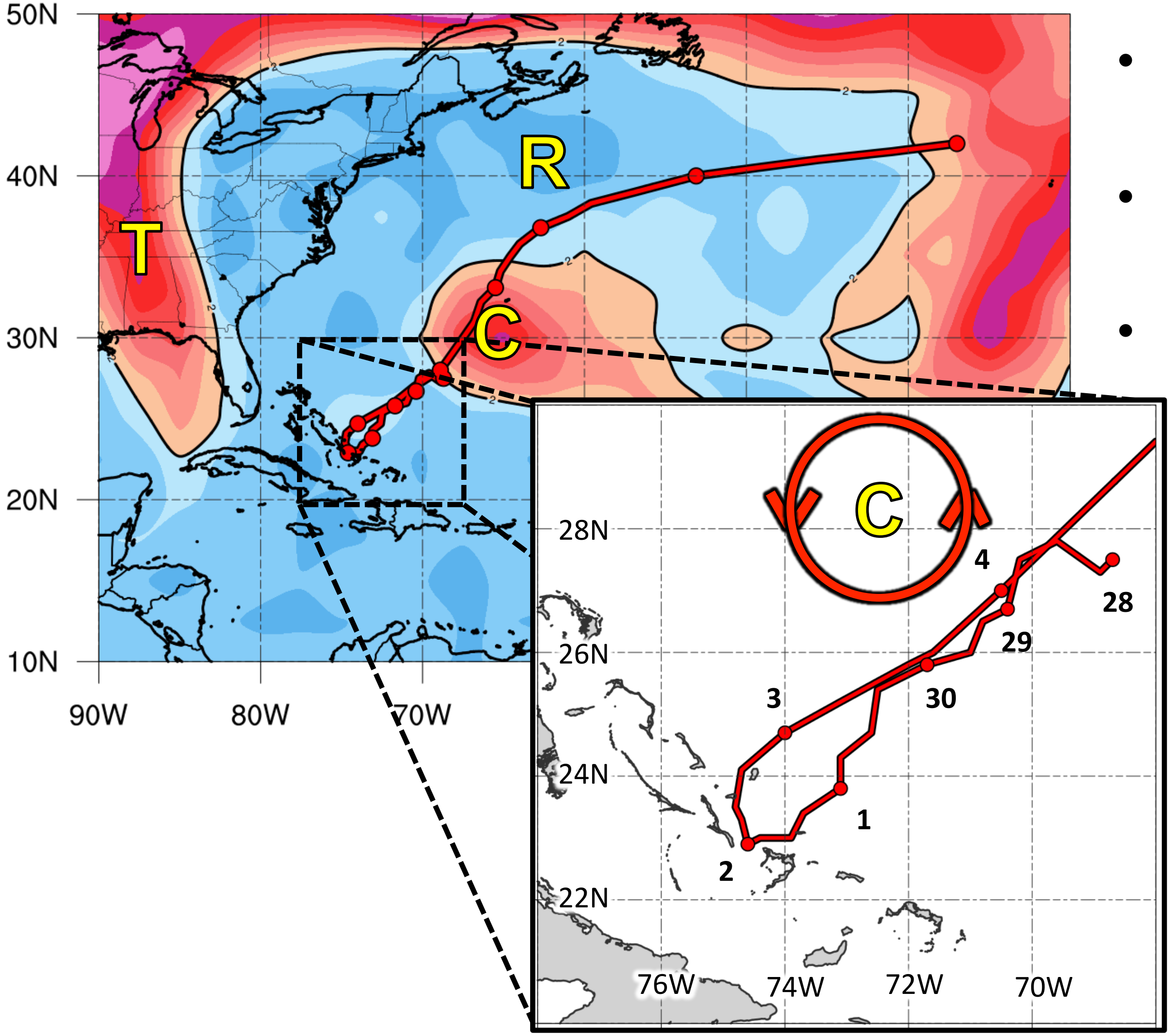

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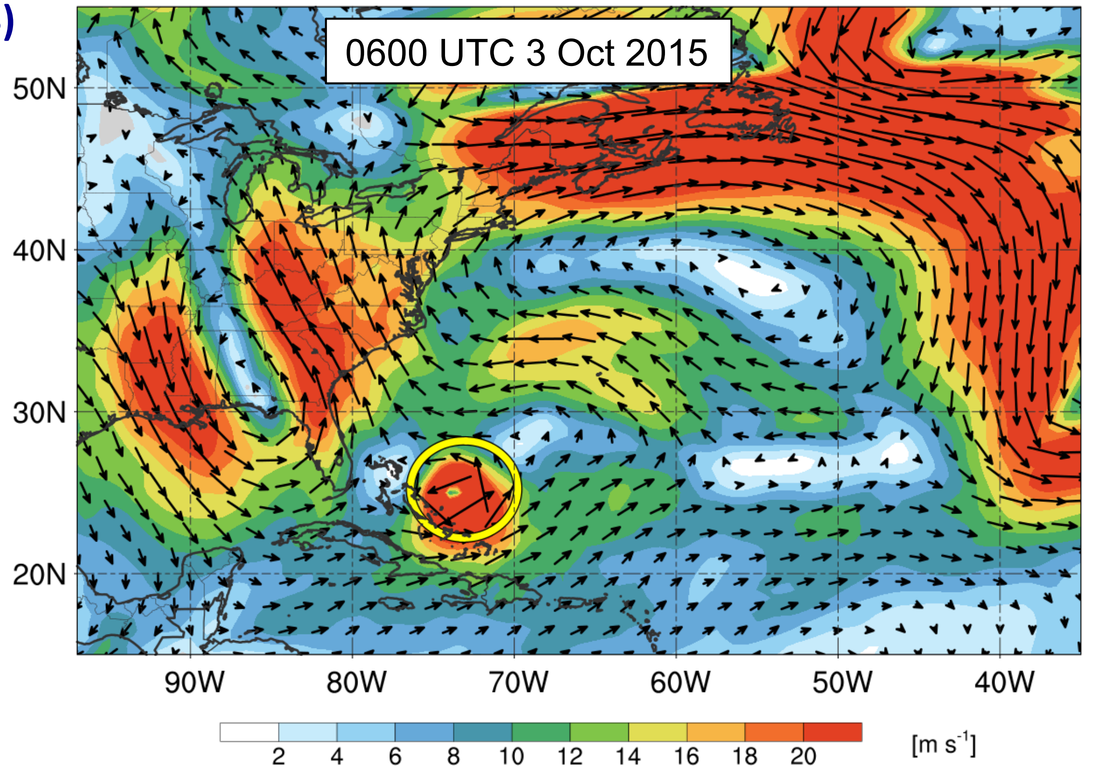
Piecewise Vorticity Inversion

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

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Nondivergent Winds **Irrotational Winds**

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

Total Wind

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

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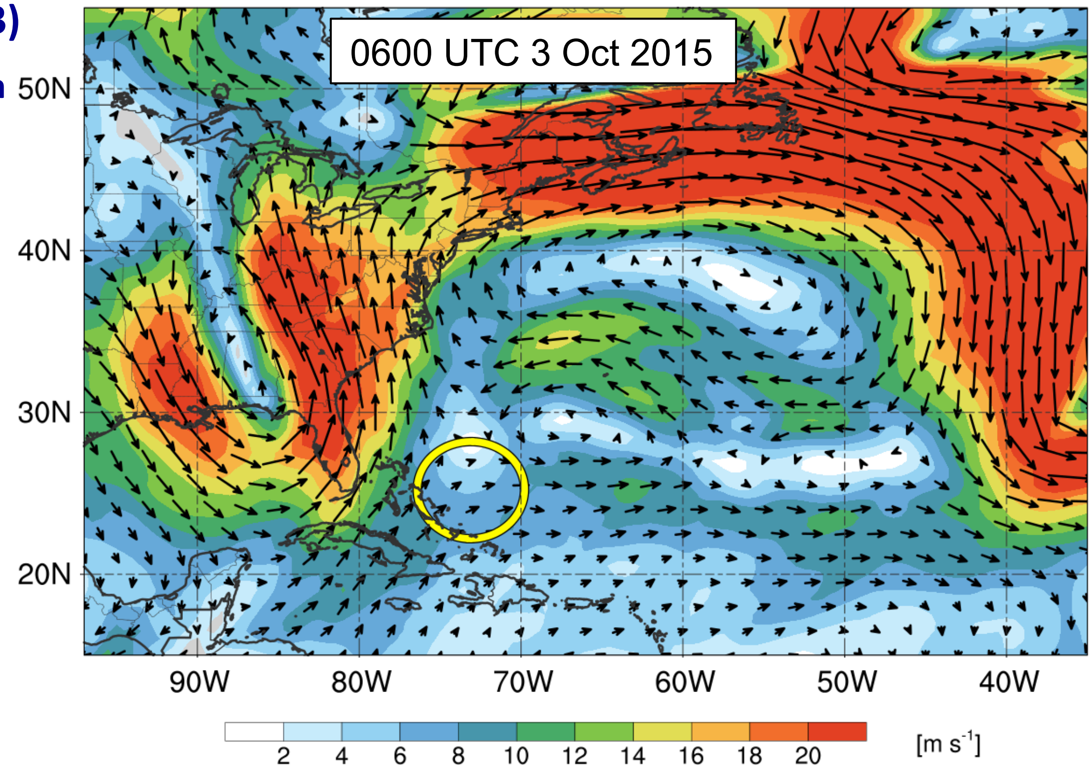

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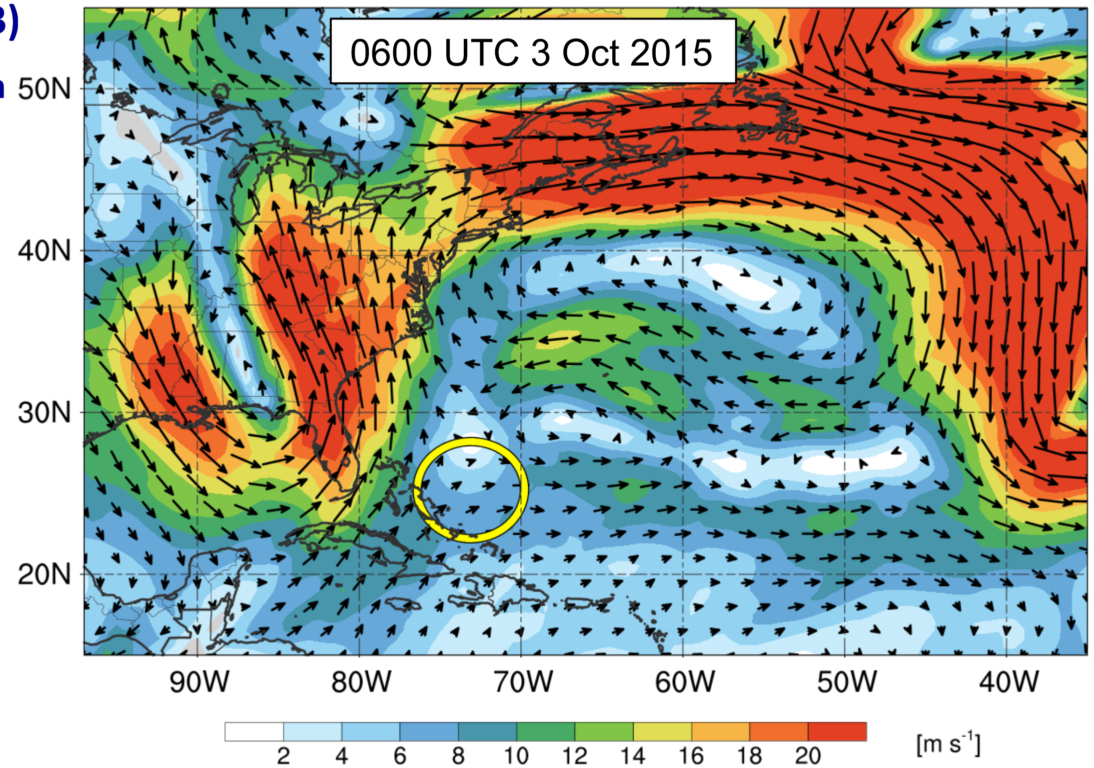

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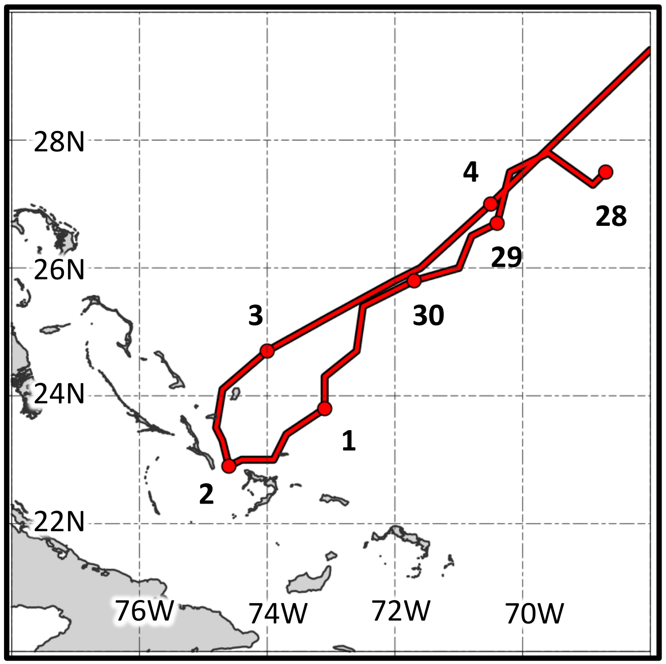
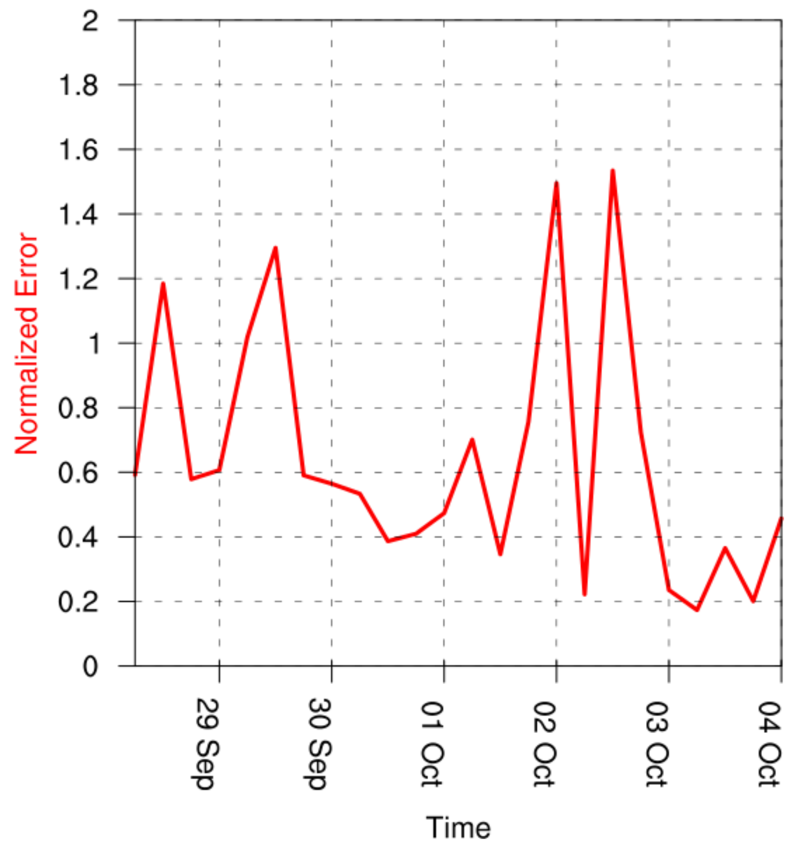
- Calculate heading imparted by CFSRv2 layer mean flow — 63^o at 5.7 m s^{-1}
- Compare to actual heading from NHC track — 59^o at 4.9 m s^{-1}

When does CFSR capture steering of Joaquin best?

CFSR Normalized Error

$$\frac{CFSR\ heading_{850-200\ hPa} - Actual\ heading}{Actual\ heading\ magnitude}$$ = CFSR normalized heading error





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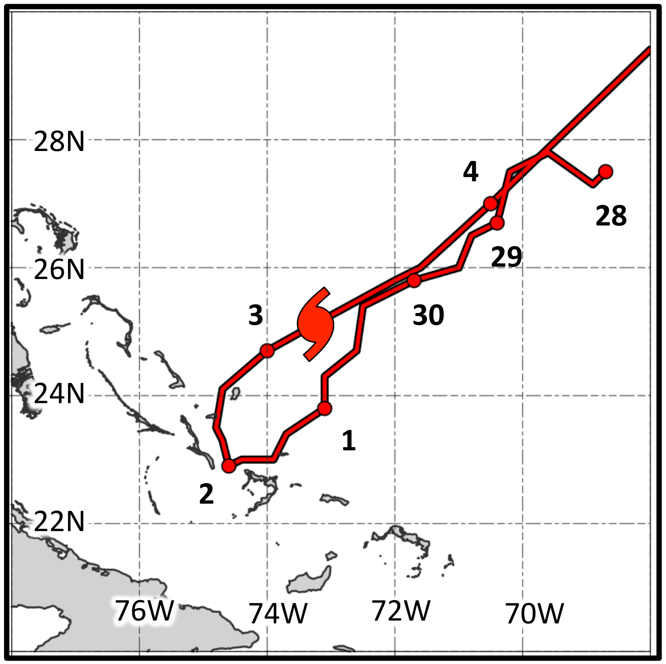

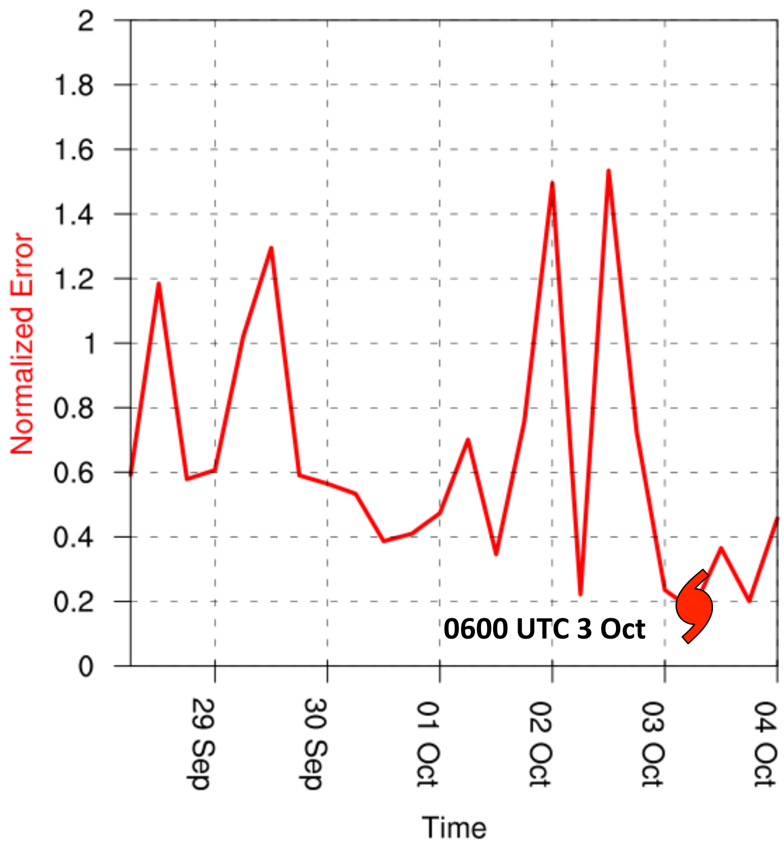

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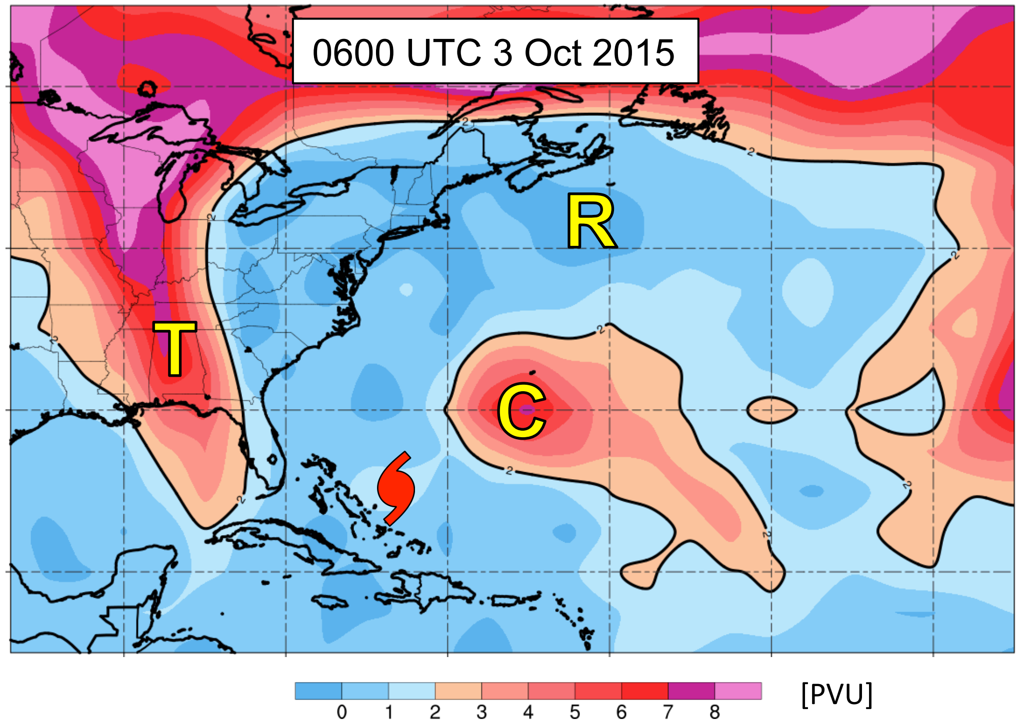

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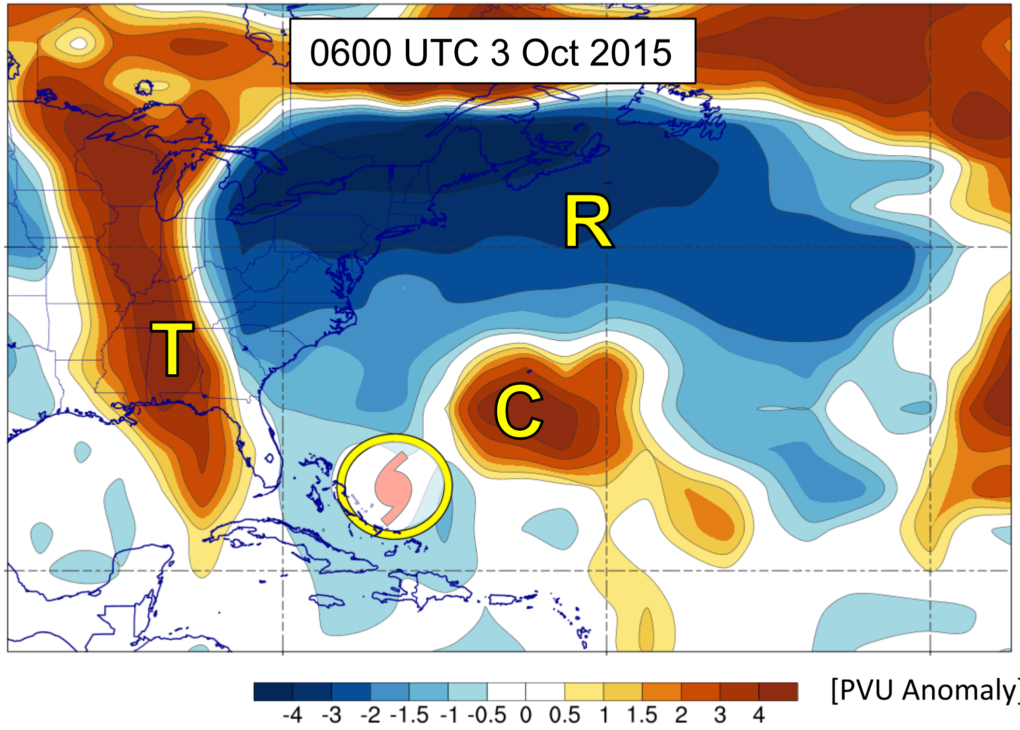

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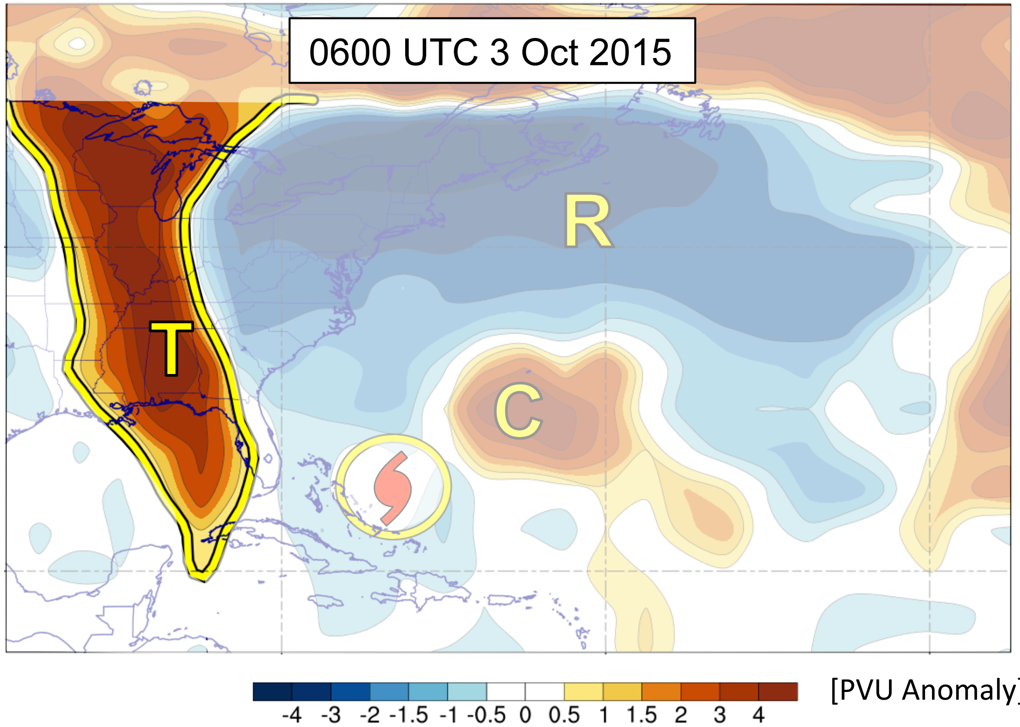

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Test 1
- Isolate steering from upstream upper-level trough

Piecewise Vorticity Inversion

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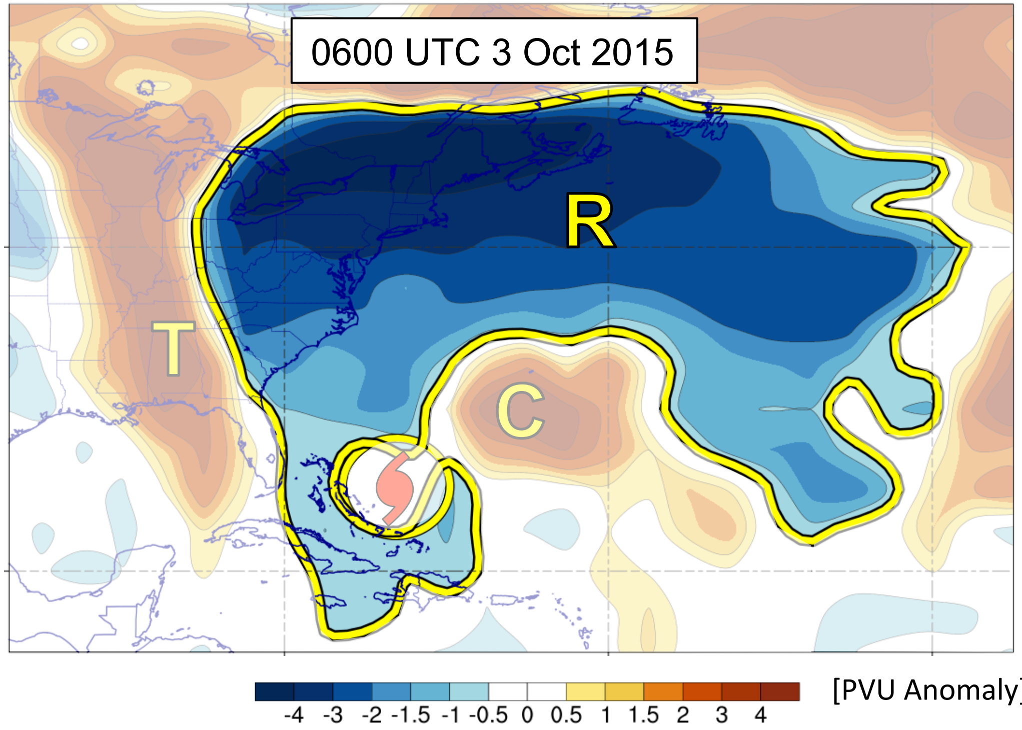

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Nondivergent Winds   **Irrotational Winds**

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Total Wind

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- **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

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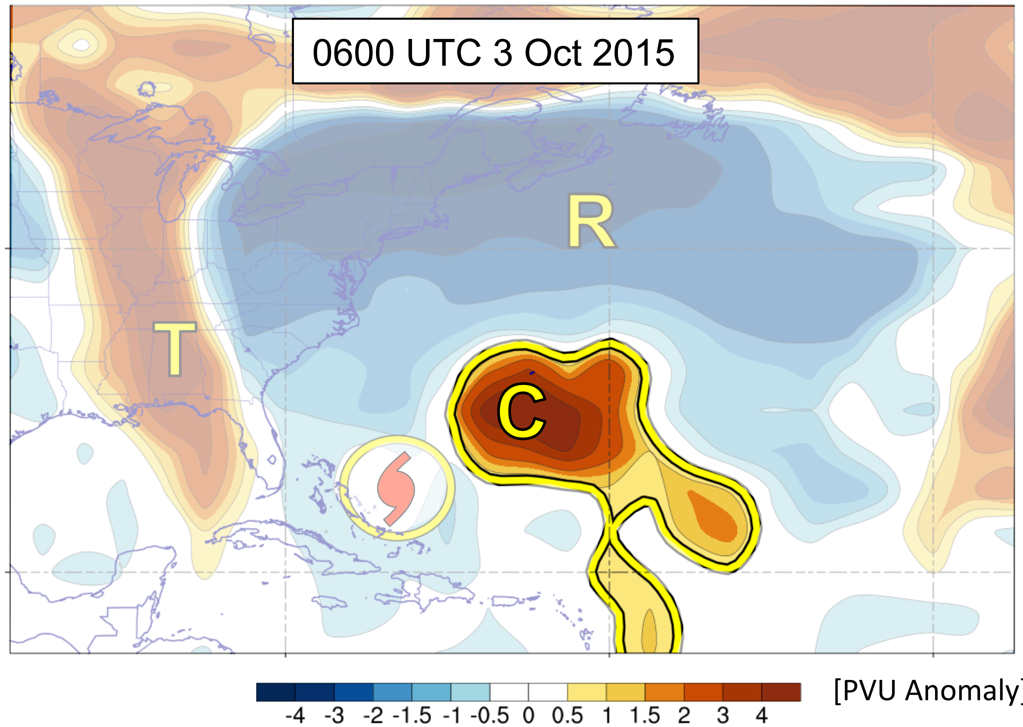

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Test 3

- **Isolate steering from cutoff cyclone (from PV streamer)**

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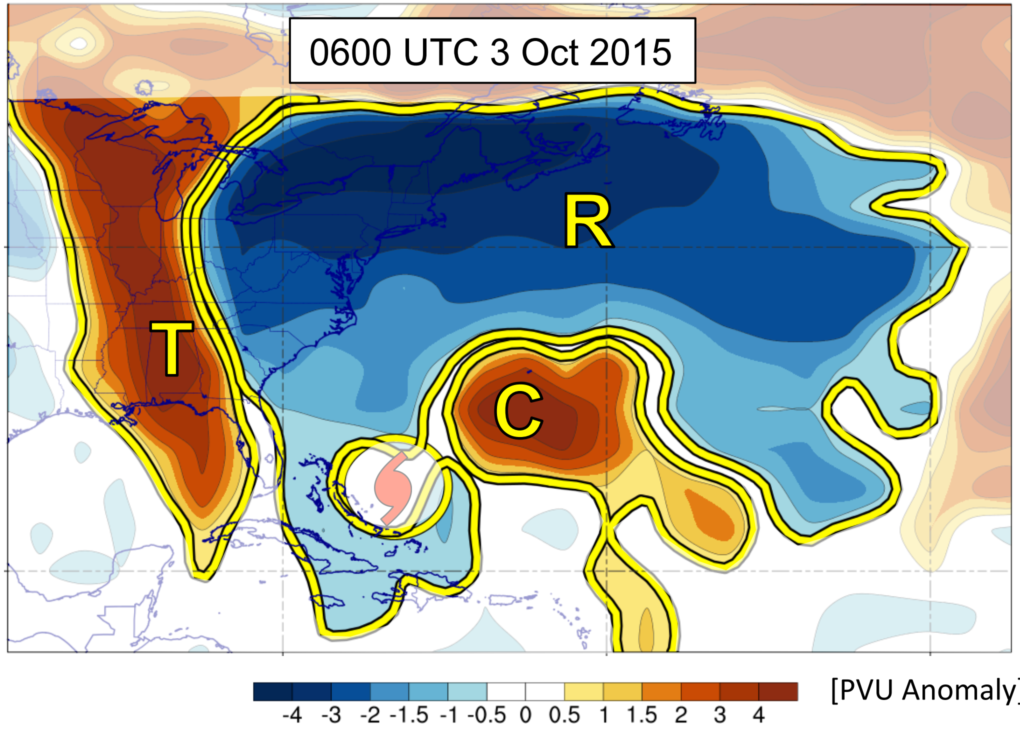

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Total Wind

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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

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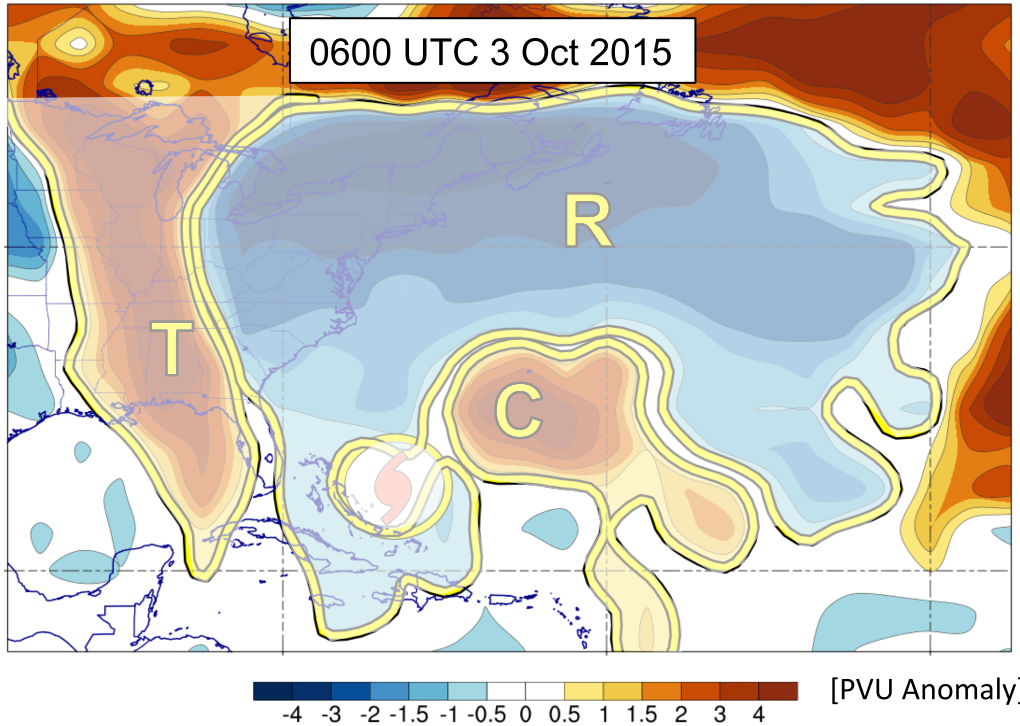

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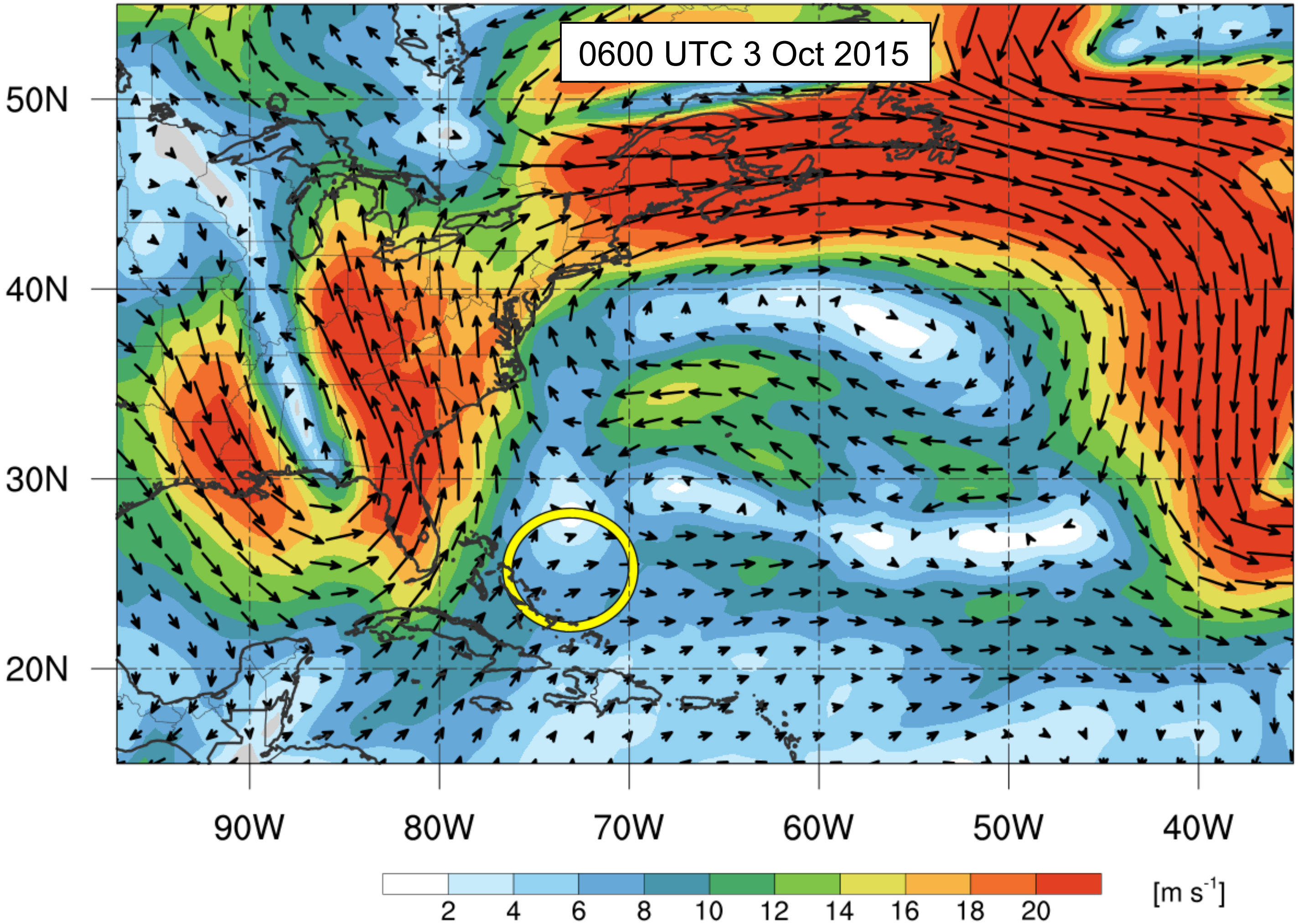
Test 5

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

Steering Flow

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

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



Steering

Observations

- **CFSRv2 heading**
  63° at 5.7 m s^{-1}
- **Actual TC motion:**
  59° at 4.9 m s^{-1}

Steering Flow

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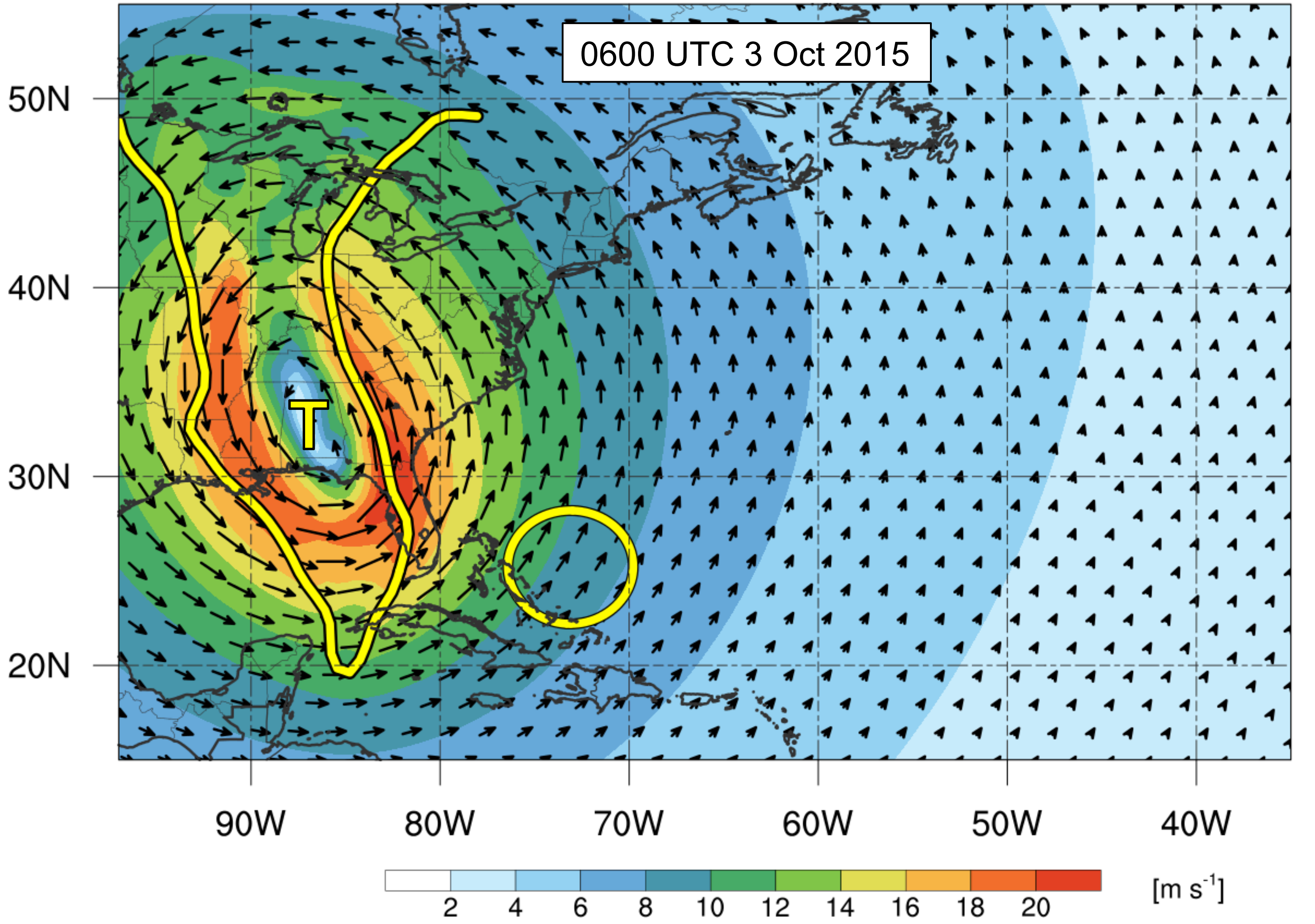
- **$r_{Joaquin} \geq 3.0^{o}$**

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

Test 1

Observations

- **CFSRv2 heading**
  31^{o} at 9.3 m s^{-1}
- **Actual TC motion:**
  59^{o} at 4.9 m s^{-1}



Steering Flow

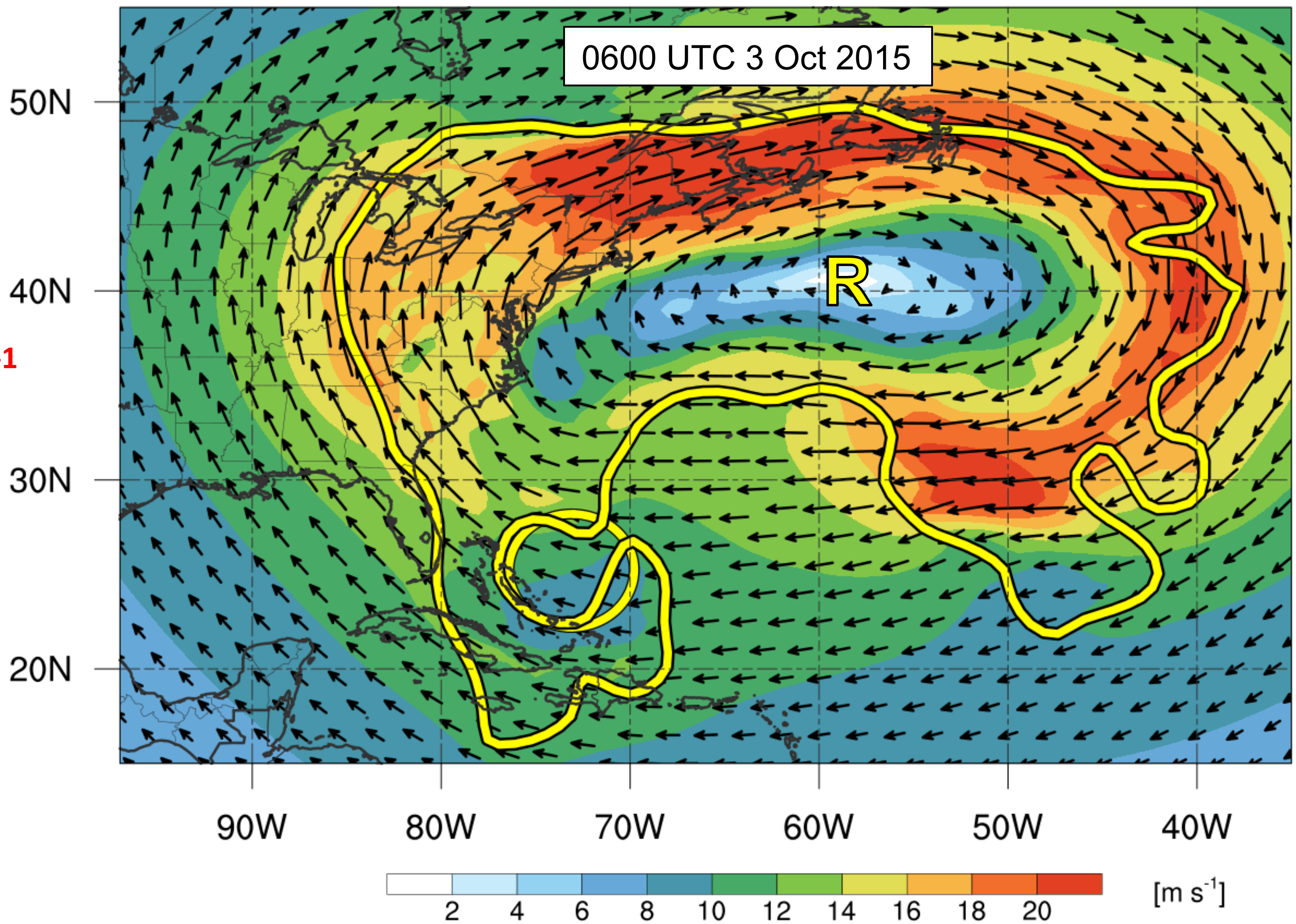
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^{o}$**

Test 2

Observations

- **CFSRv2 heading**
  285^{o} at 10.1 m s^{-1}
- **Actual TC motion:**
  59^{o} at 4.9 m s^{-1}

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

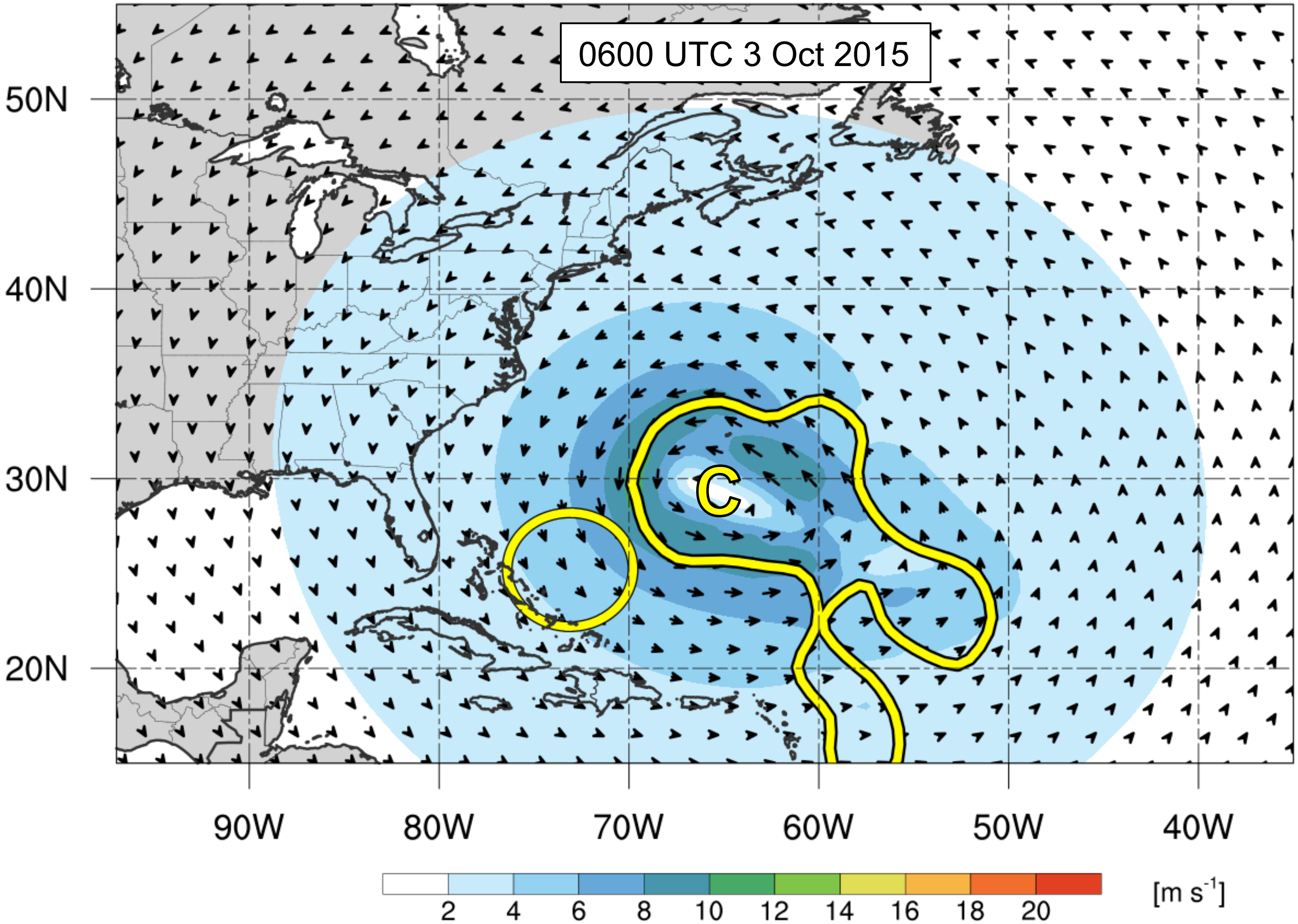


Steering Flow

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

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

Test 3



Observations

- **CFSRv2 heading**
  147° at 4.9 m s^{-1}
- **Actual TC motion:**
  59° at 4.9 m s^{-1}

Steering Flow

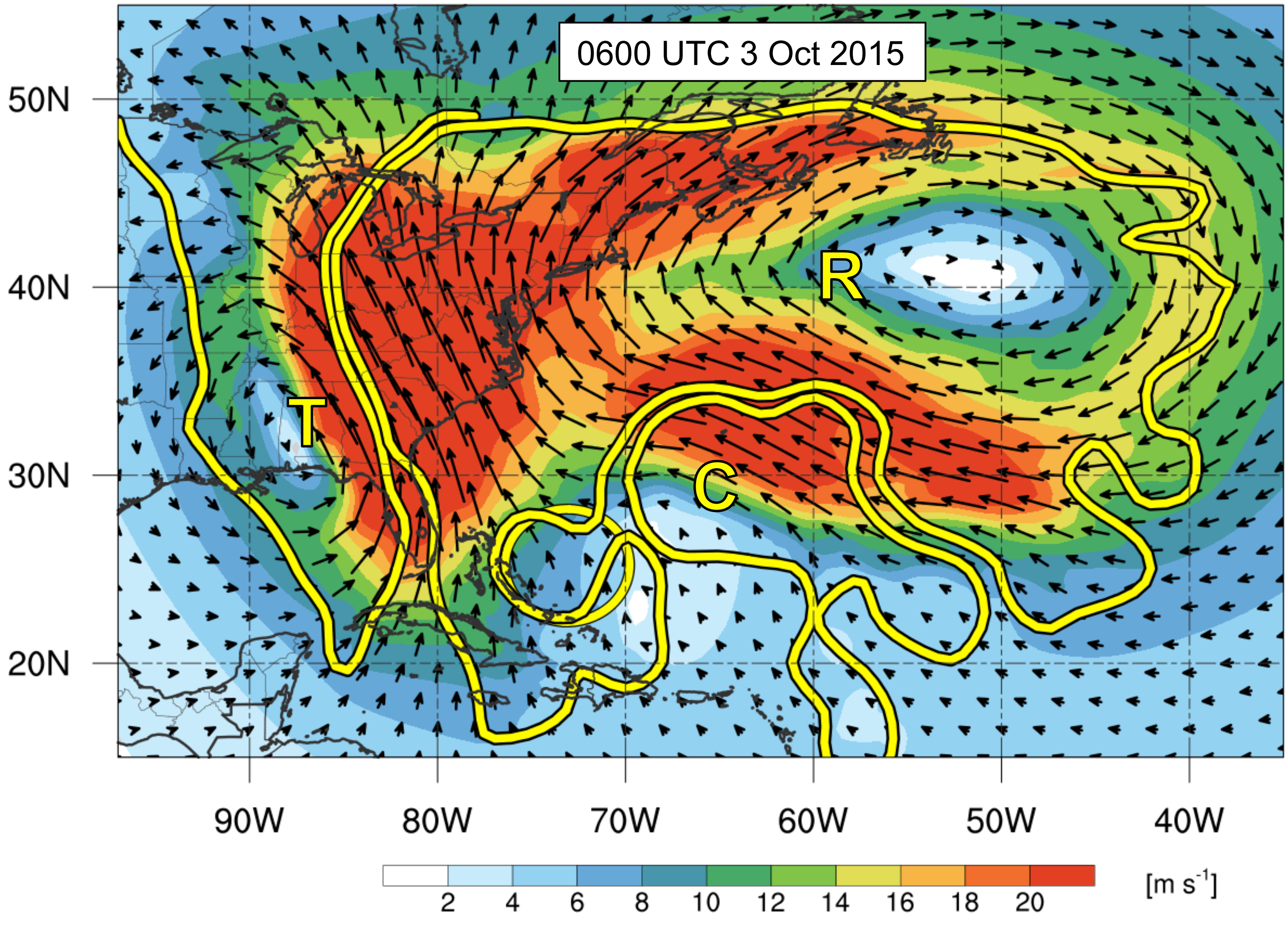
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 4

Observations

- **CFSRv2 heading**
  340º at 6.8 m s^{-1}
- **Actual TC motion:**
  59º at 4.9 m s^{-1}



Steering Flow

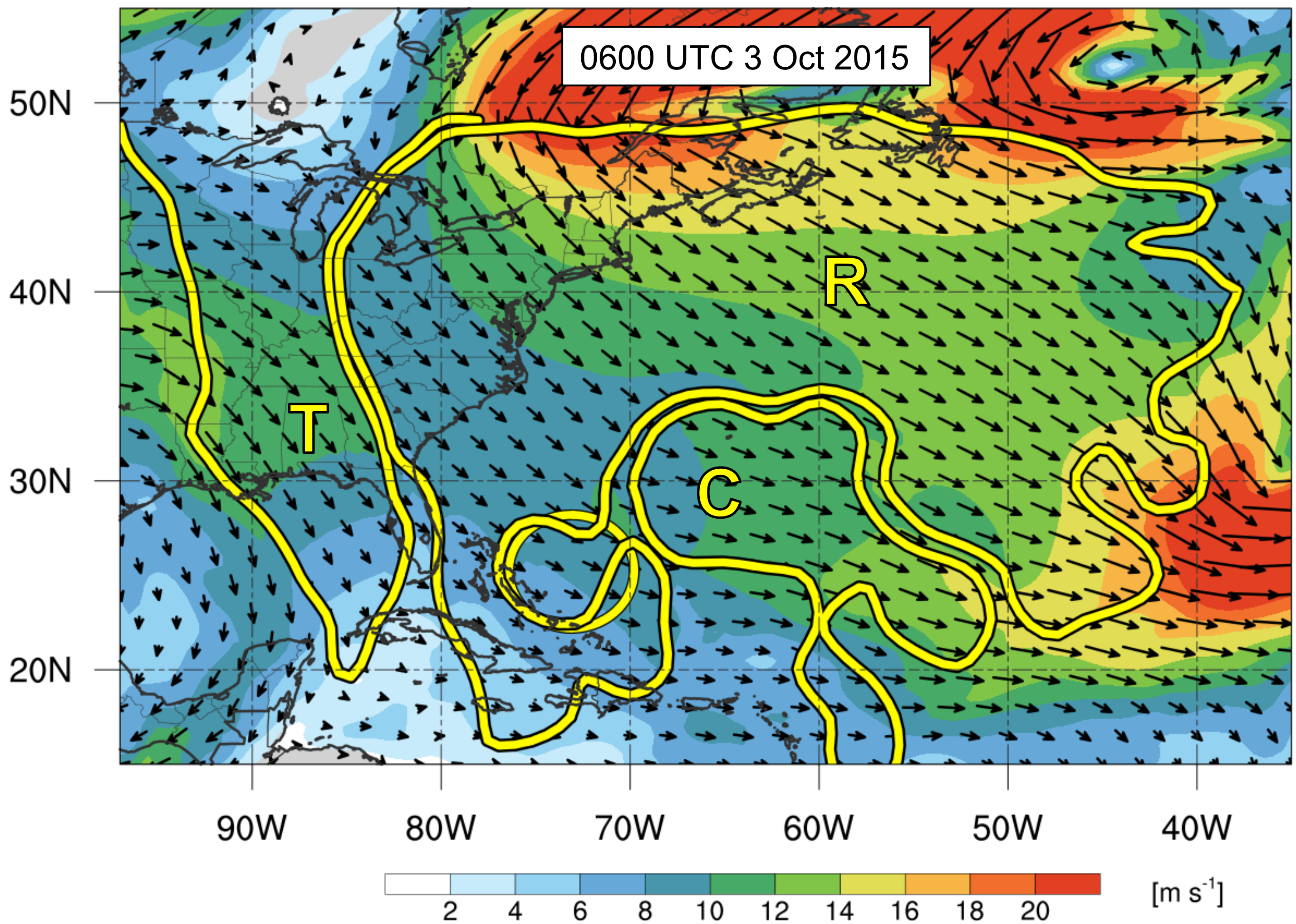
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 5

Observations

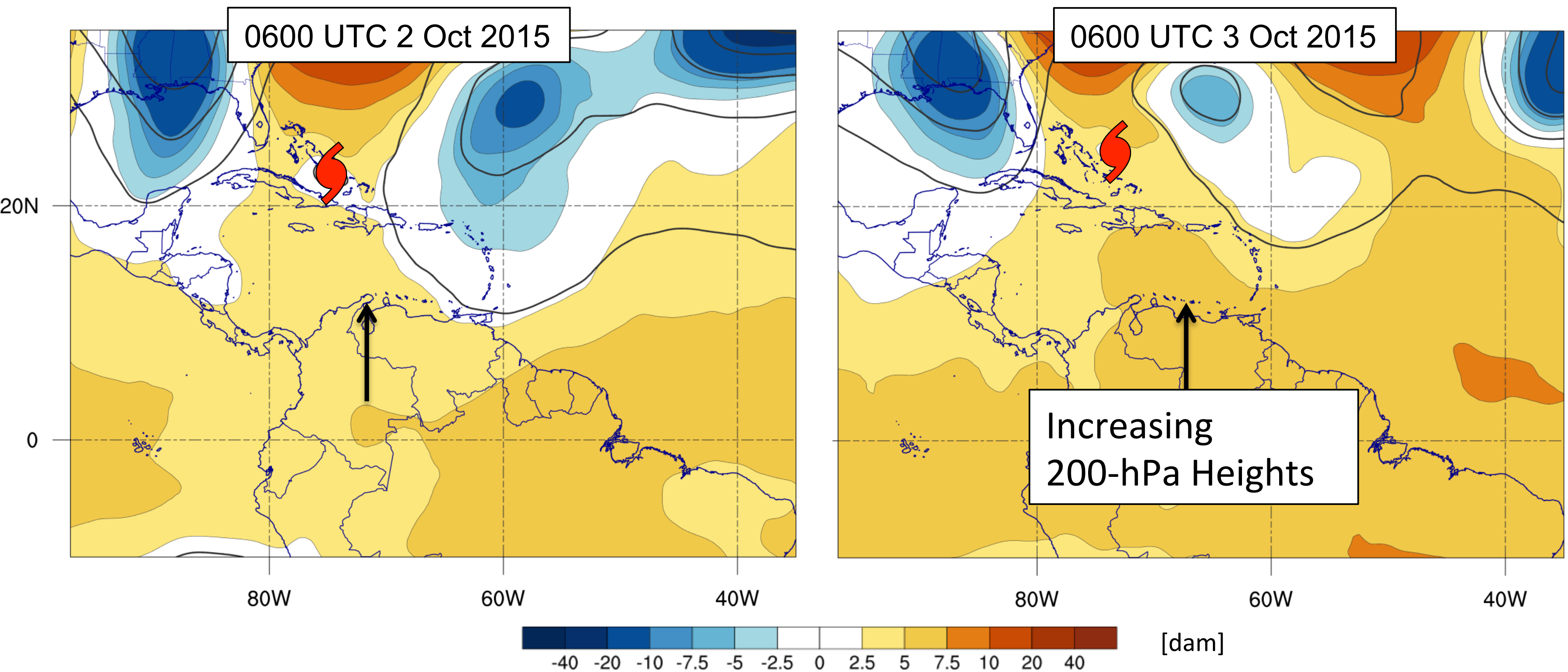
- **CFSRv2 heading** **118º at 8.2 m s^{-1}**
- **Actual TC motion:** **59º at 4.9 m s^{-1}**



Steering Flow

Role of building equatorward ridge?

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



Steering Flow

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

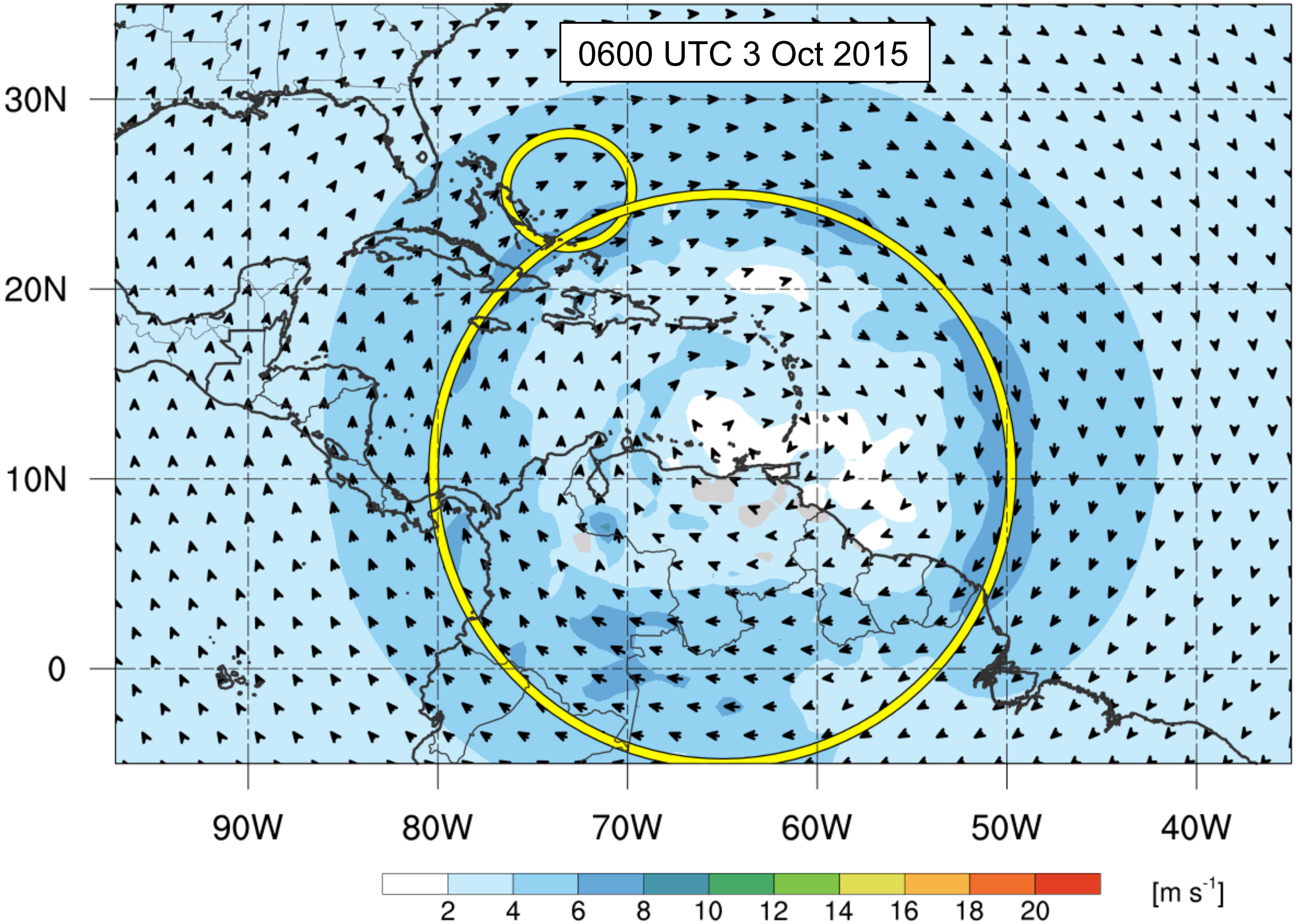
850 – 200-hPa layer mean wind magnitude (shaded, m s^{-1}) and wind vectors (arrows, m s^{-1})

Equatorward Ridge

Observations

- CFSRv2 heading
  62^o at 5.3 m s^{-1}
- Actual TC motion:
  59^o at 4.9 m s^{-1}

15° circle centered on 65°W, 10°N



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**
- **$r_{Joaquin} \geq 3.0^{o}$**

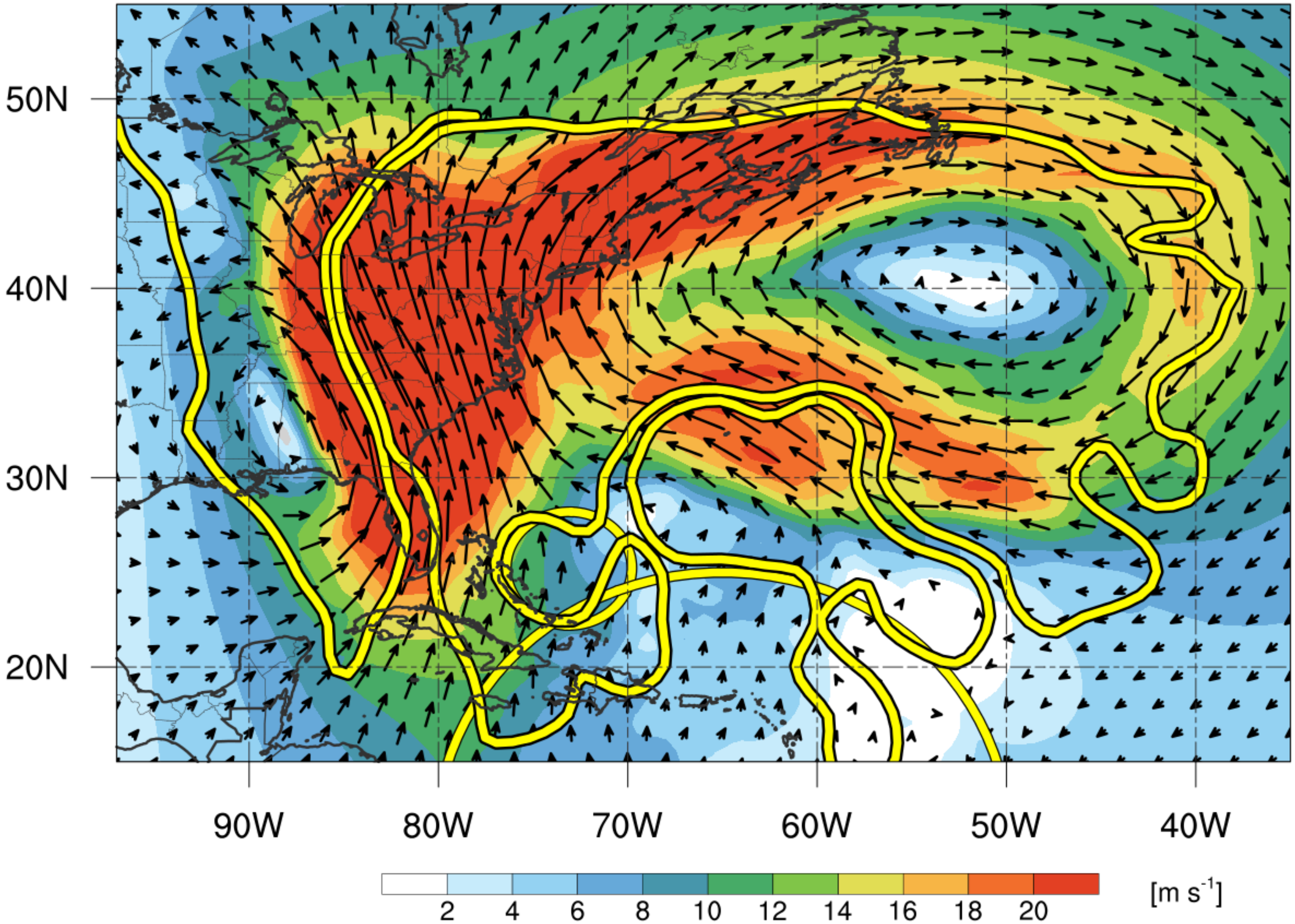
850 – 200-hPa layer mean wind magnitude (shaded, m s^{-1}) and wind vectors (arrows, m s^{-1})

Equatorward Ridge

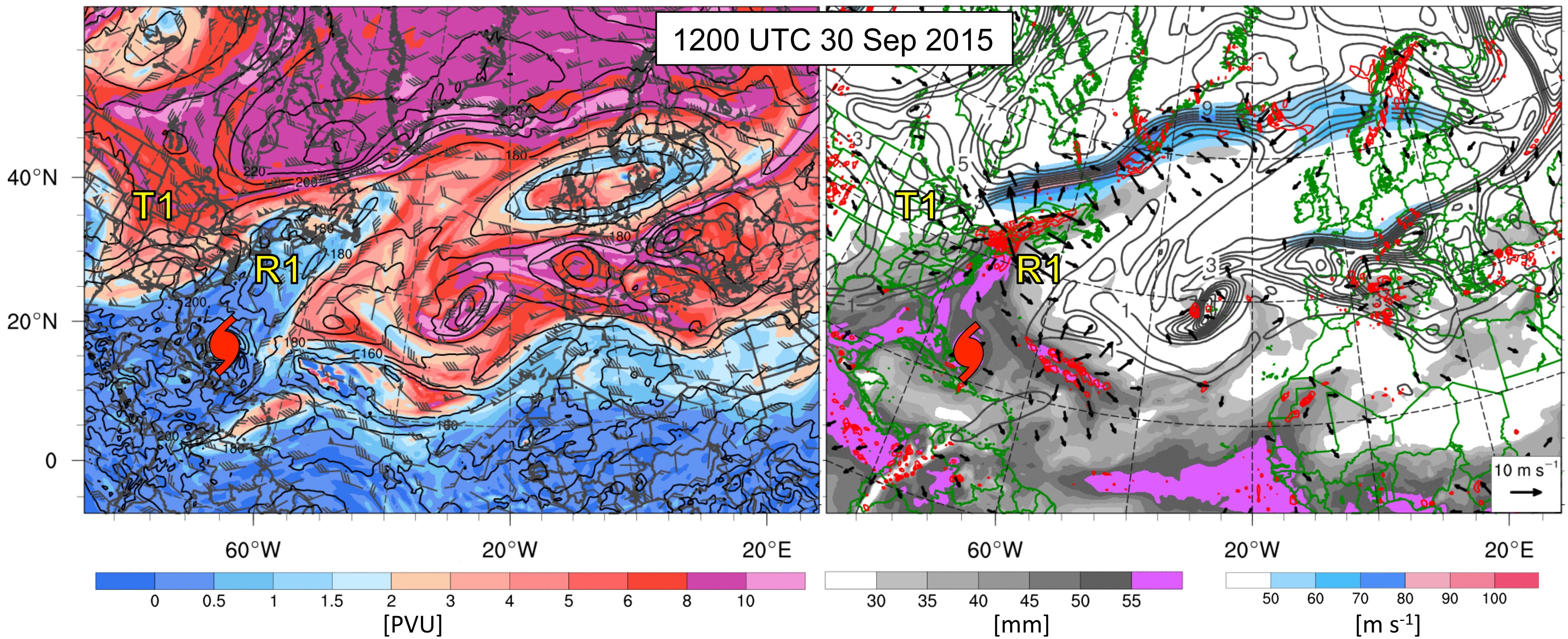
Observations

- **CFSRv2 Heading**
  6^{o} at 8.5 m s^{-1}
- **Actual TC Motion:**
  59^{o} at 4.9 m s^{-1}

15^{o} circle Centered on 65^{o}W, 10^{o}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 x 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

$$\nabla^2\psi = \begin{cases} \zeta & \text{for} \quad r \le r_0 \\ 0 & \text{for} \quad r > r_0 \end{cases} \qquad \nabla^2\chi = \begin{cases} \delta & \text{for} \quad r \le r_0 \\ 0 & \text{for} \quad r > r_0 \end{cases}$$

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

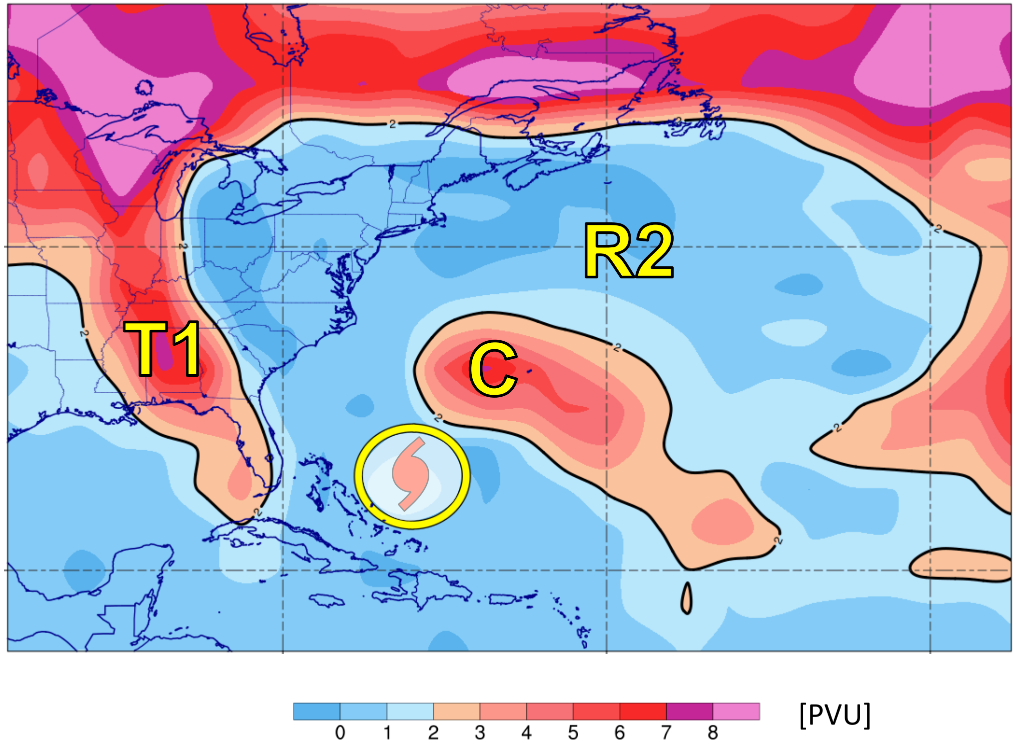
Nondivergent Winds | **Irrotational Winds**

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

Total Wind

- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^{o}$**
- **Use the 350-K 2-PVU contour to isolate key upper-level features**

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



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Nondivergent Winds   Irrotational Winds

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

Total Wind

- Remove TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^o$
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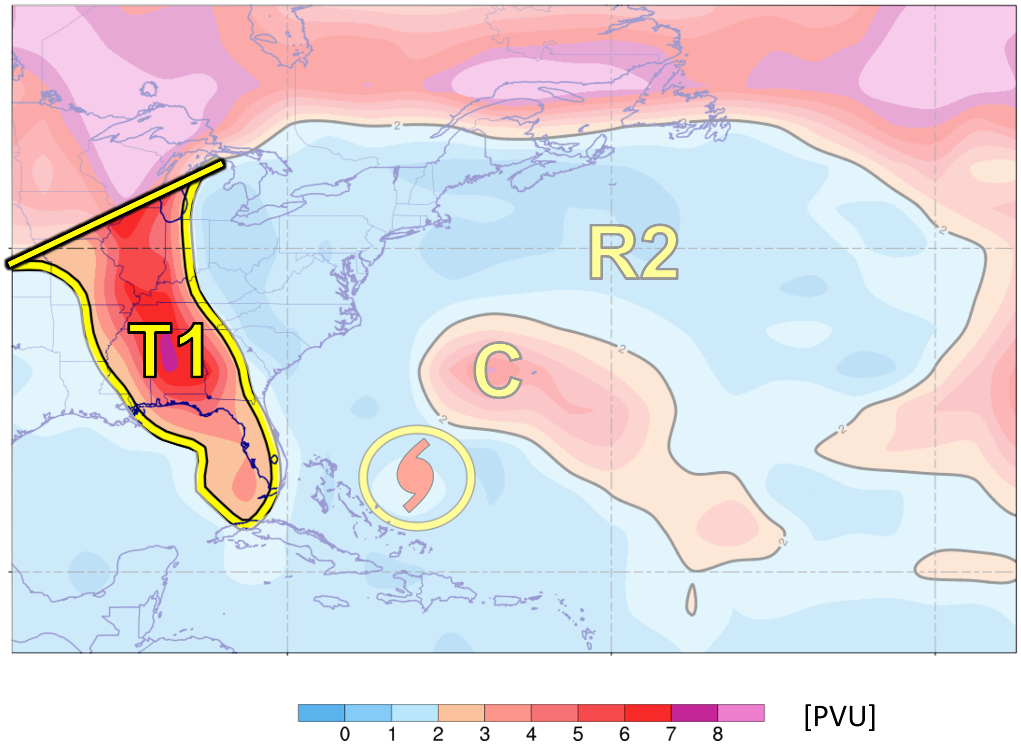
- 850 – 200-hPa flow inverted (captures steering level for TC Joaquin)



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

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

- **Adapted from Davis et al. (2008)**

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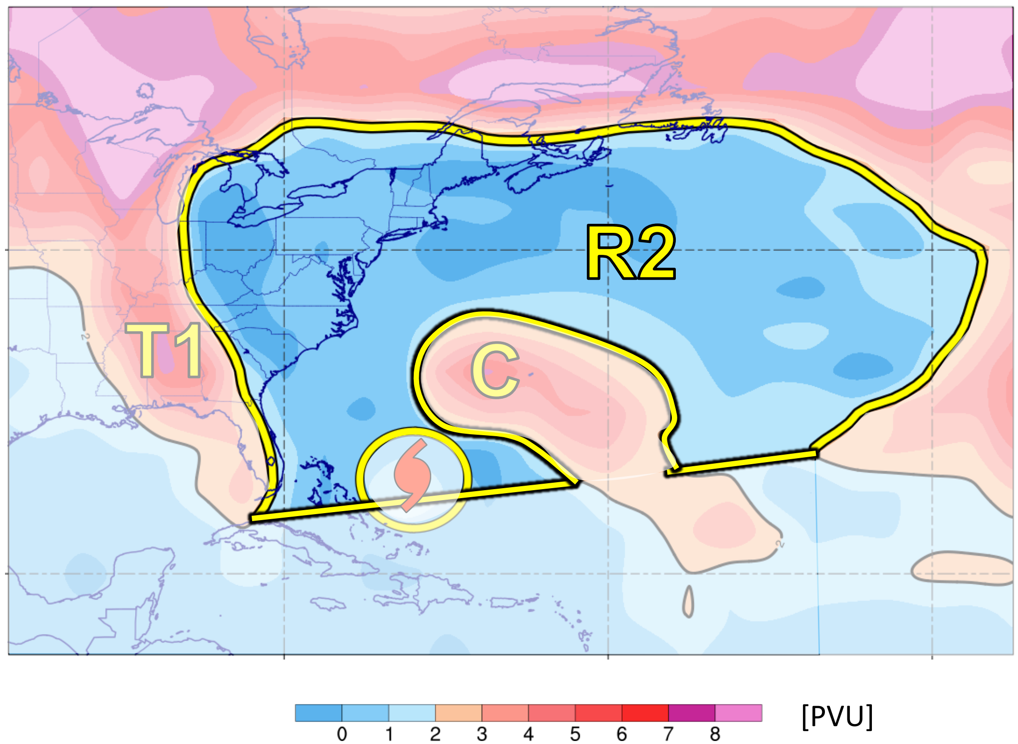
$$\vec{V}_\chi = \nabla\chi \qquad \vec{V}_\psi = \hat{k} \times \nabla\psi$$

Nondivergent Winds **Irrotational Winds**

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

Total Wind



- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^{o}$**
- **Use the 350-K 2-PVU contour to isolate key upper-level features**

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

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

- **Adapted from Davis et al. (2008)**

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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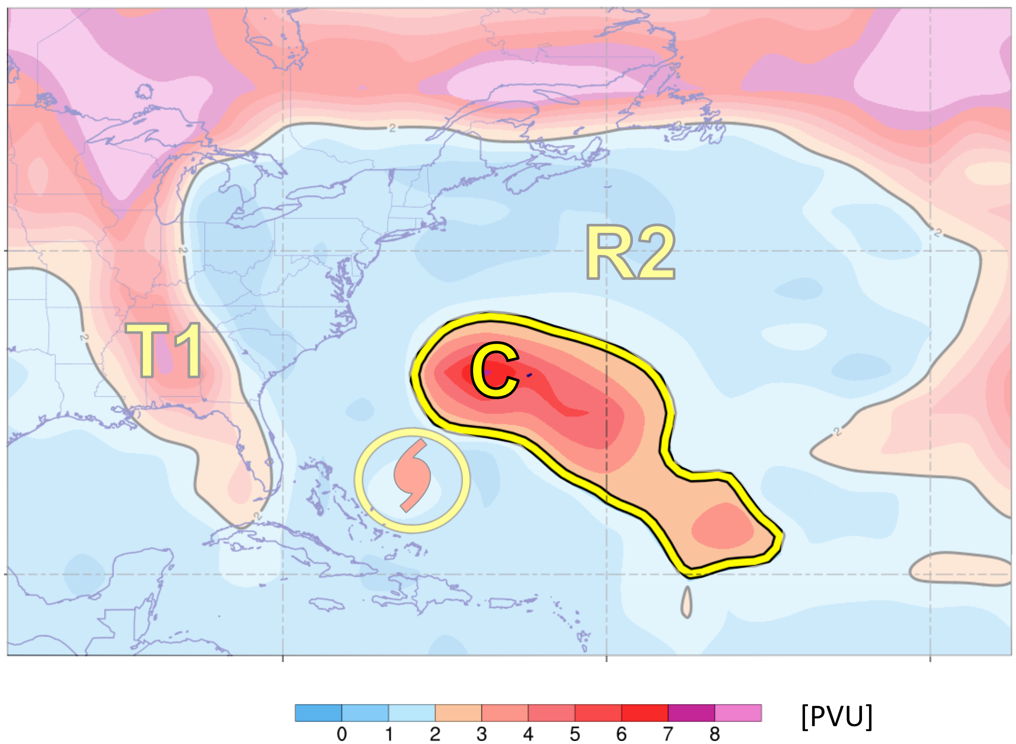
Nondivergent Winds   **Irrotational Winds**

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

Total Wind



- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**
- **Use the 350-K 2-PVU contour to isolate key upper-level features**

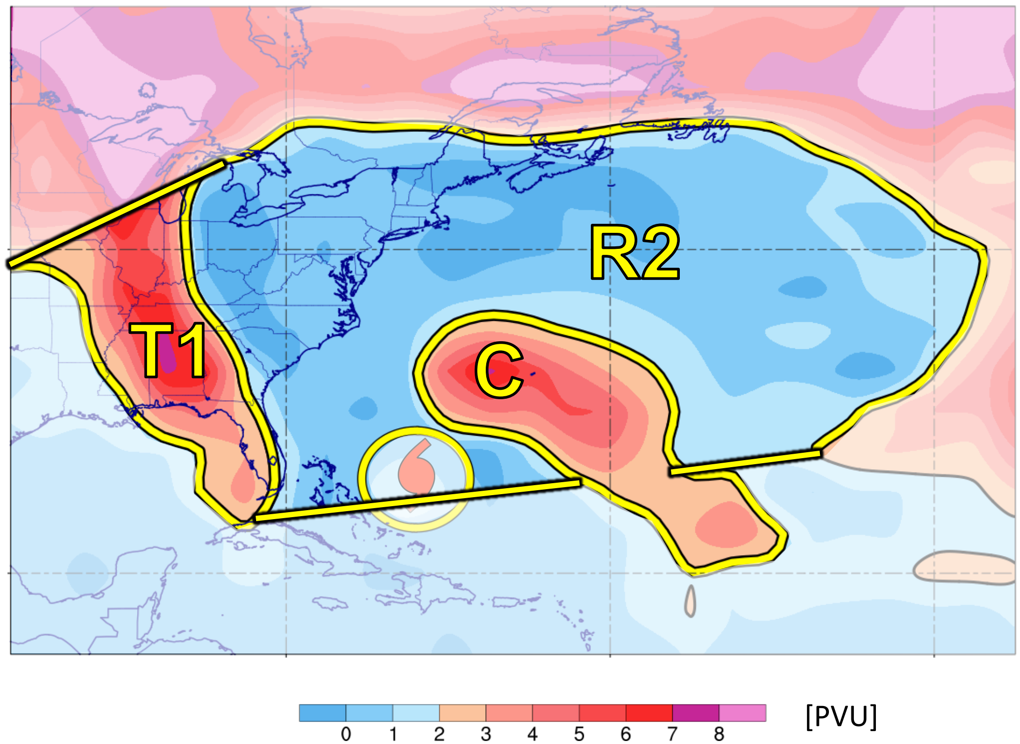
Test 3

- **Isolate steering from cutoff cyclone (from PV streamer)**

Piecewise Vorticity Inversion

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

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



- **Adapted from Davis et al. (2008)**

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

Nondivergent Winds — **Irrotational Winds**

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

Total Wind

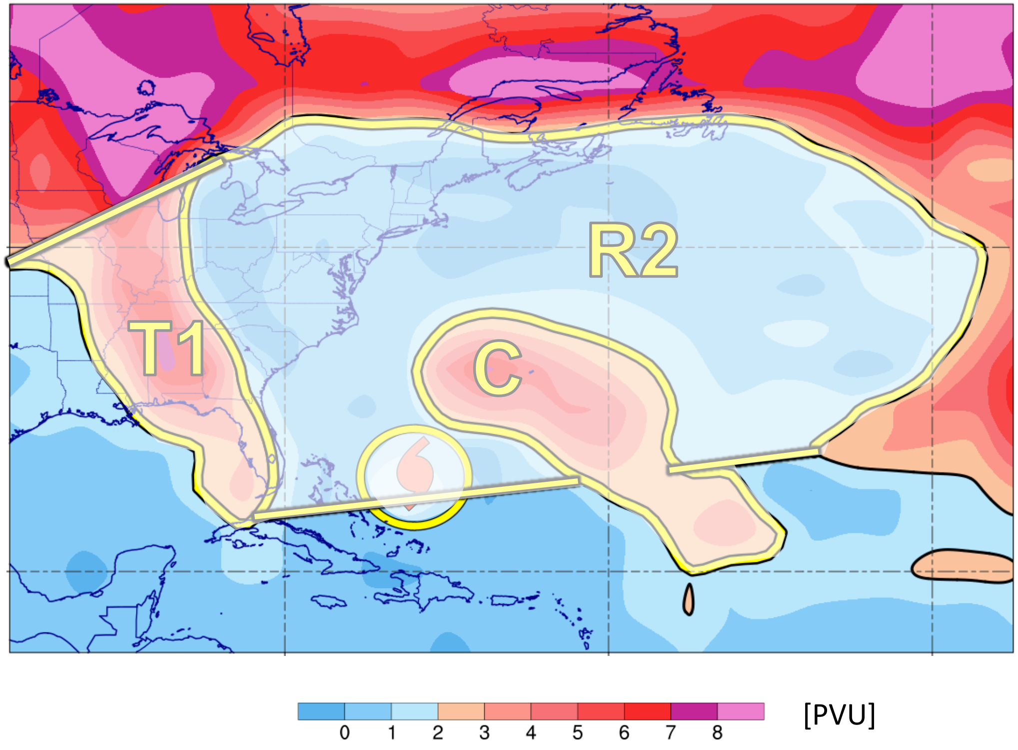
- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^{o}$**
- **Use the 350-K 2-PVU contour to isolate key upper-level features**

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)



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

Nondivergent Winds **Irrotational Winds**

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

Total Wind

- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \ge 3.0^o$**
- **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

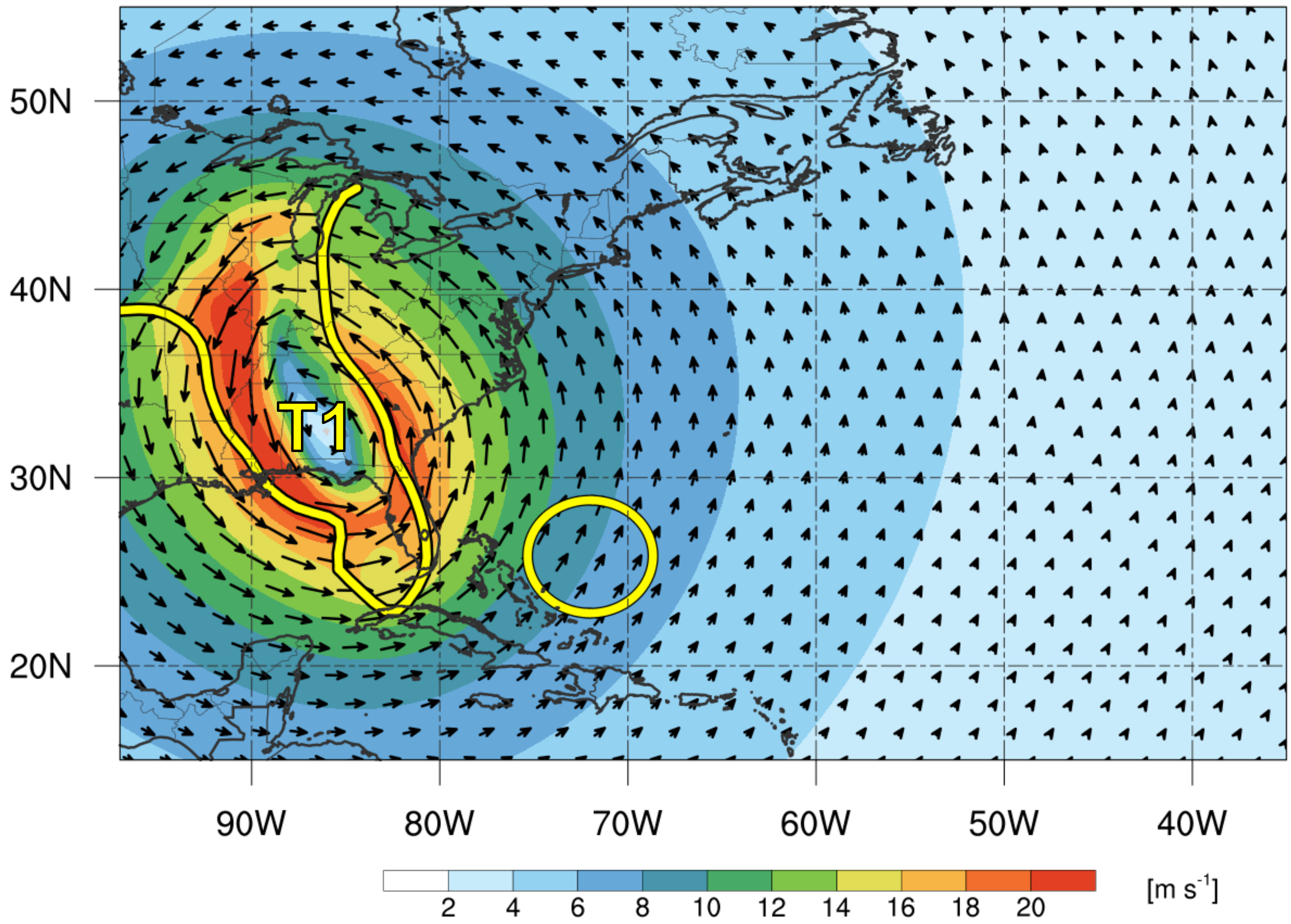
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 1

Observations

- **CFSRv2 Steering**
  28º at 8.1 m s^{-1}
- **Actual TC Motion:**
  50º at 6.2 m s^{-1}



Ridge Steering Flow

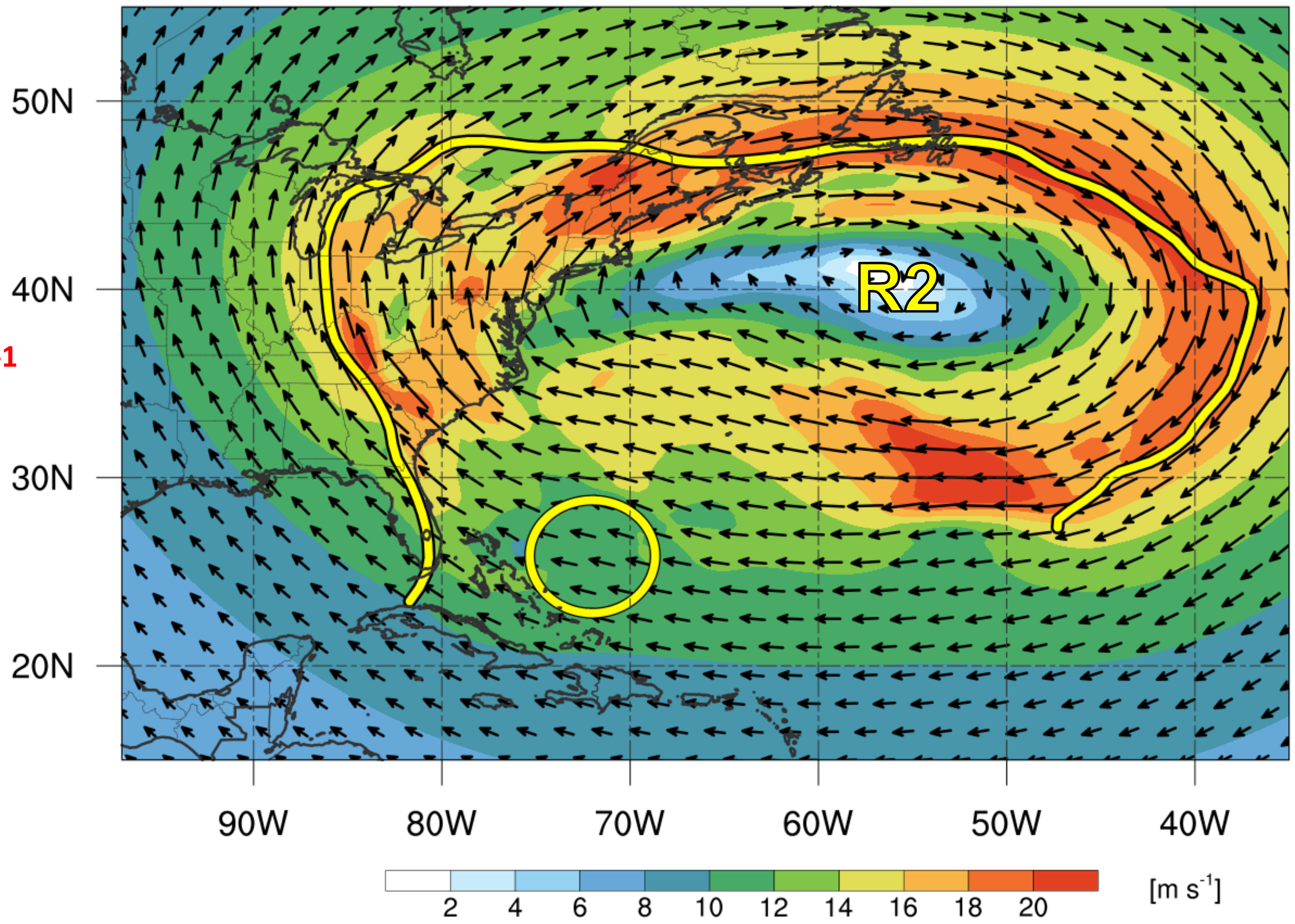
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^{o}$**

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

Test 2

Observations

- **CFSRv2 Steering**
  285° at 11.1 m s^{-1}
- **Actual TC Motion:**
  50° at 6.2 m s^{-1}

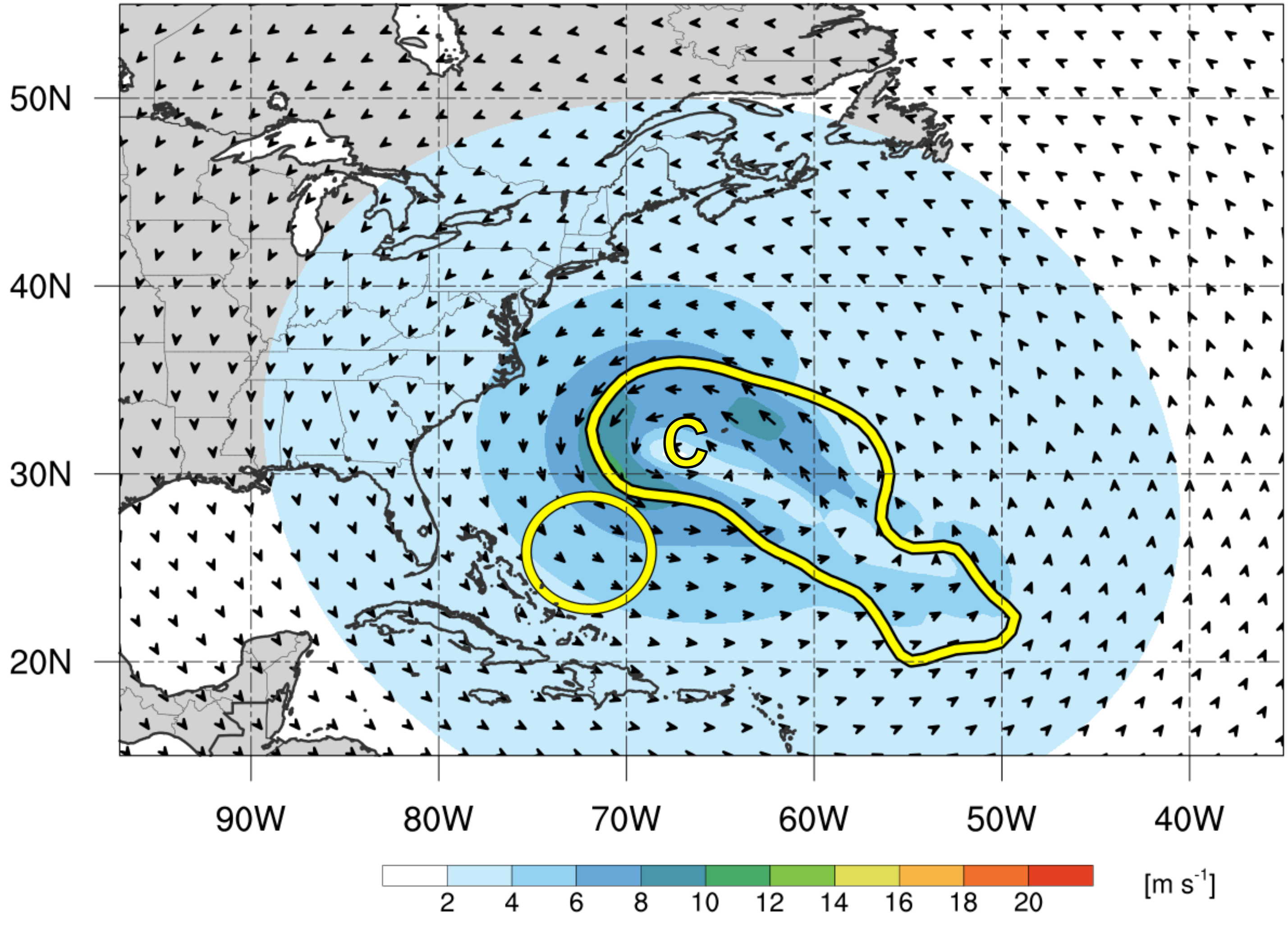


Cutoff Steering Flow

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

Test 3

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



Observations

- **CFSRv2 Steering**
  130^o at 5.0 m s^{-1}
- **Actual TC Motion:**
  50^o at 6.2 m s^{-1}

Cumulative Steering Flow

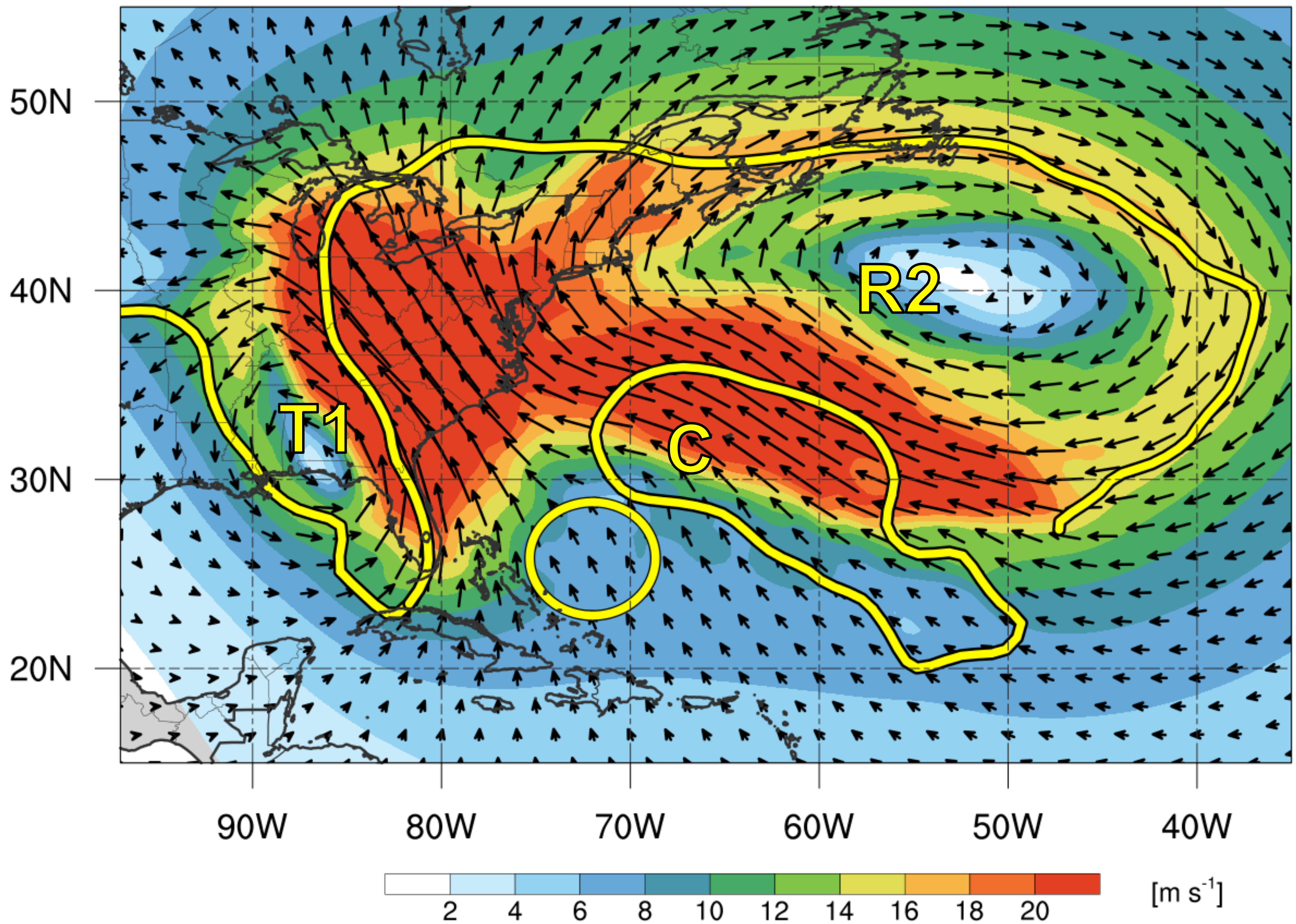
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

Test 4

Observations

- **CFSRv2 Steering**
  335° at 7.5 m s^{-1}
- **Actual TC Motion:**
  50° at 6.2 m s^{-1}

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

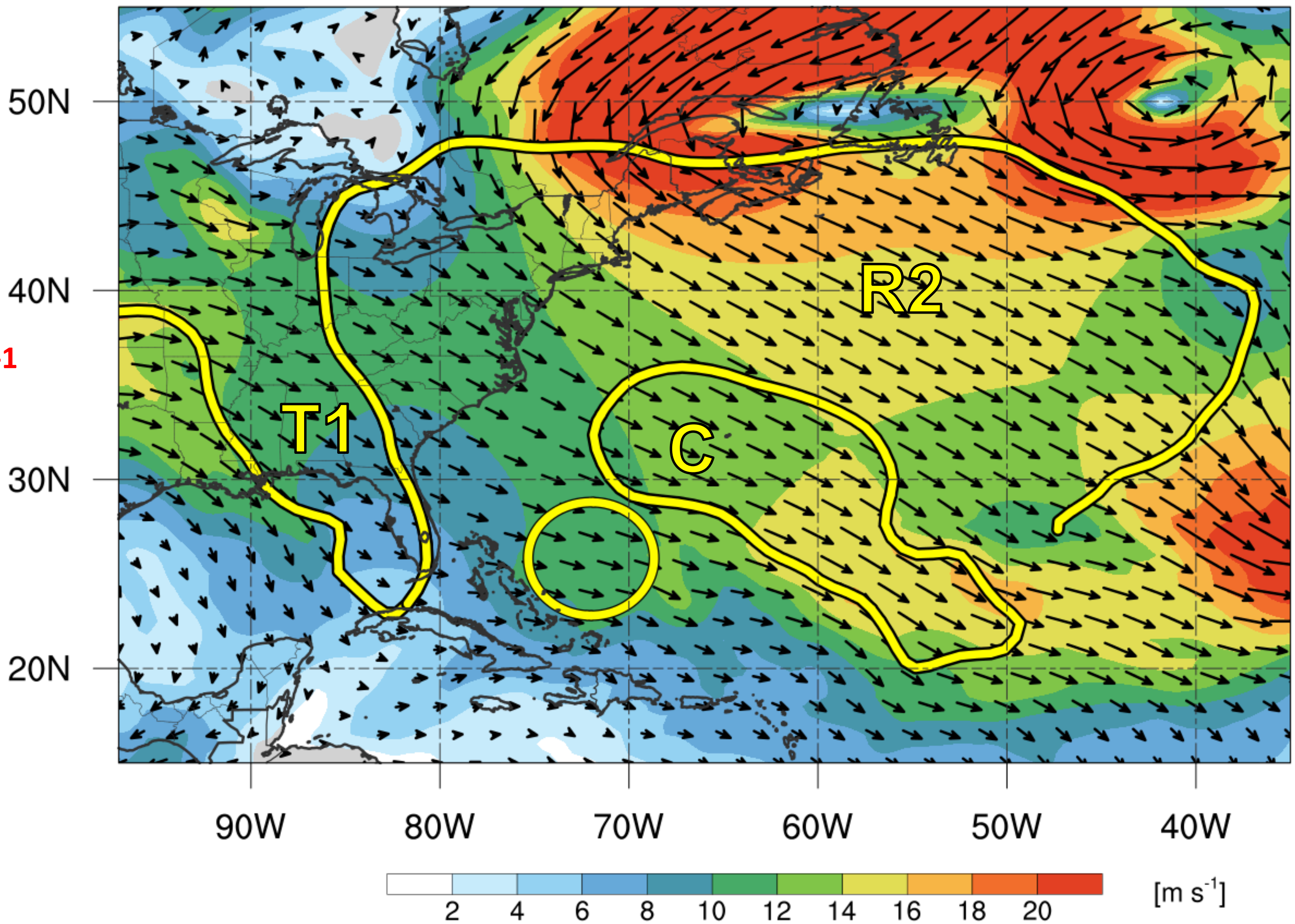


Residual Steering Flow

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

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

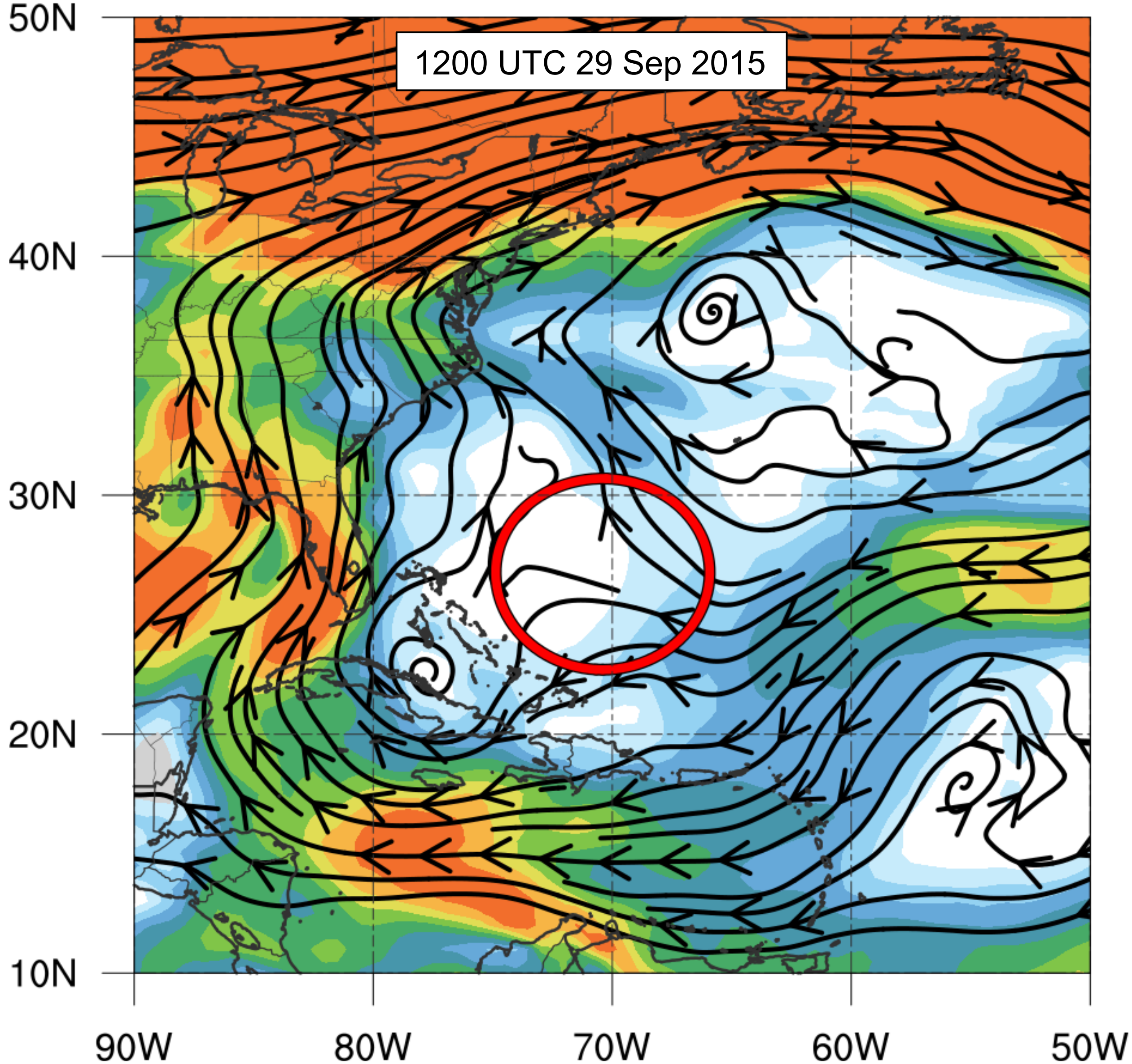
Test 5



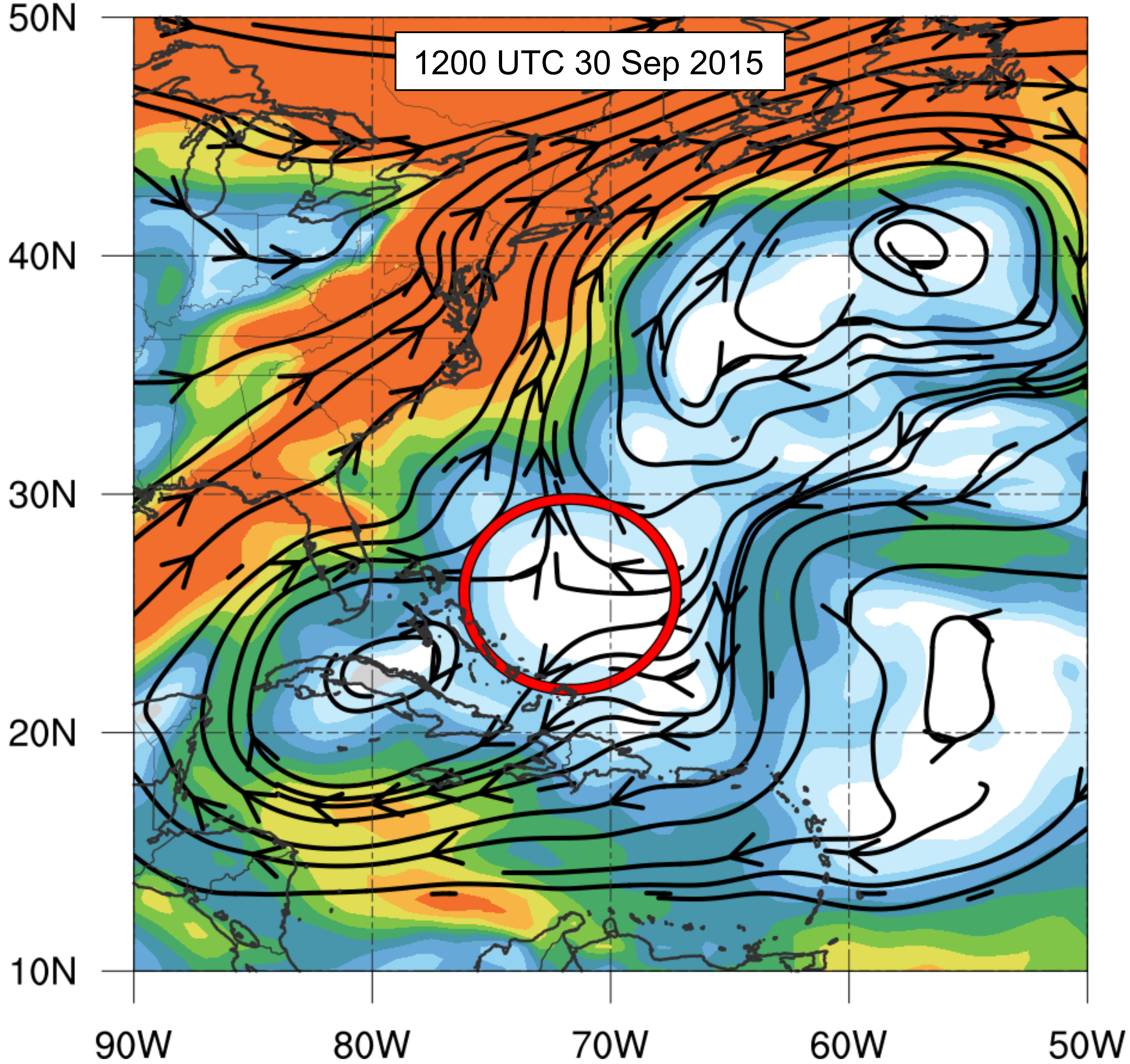
Observations

- **CFSRv2 Steering**
  108° at 10.9 m s^{-1}
- **Actual TC Motion:**
  50° at 6.2 m s^{-1}

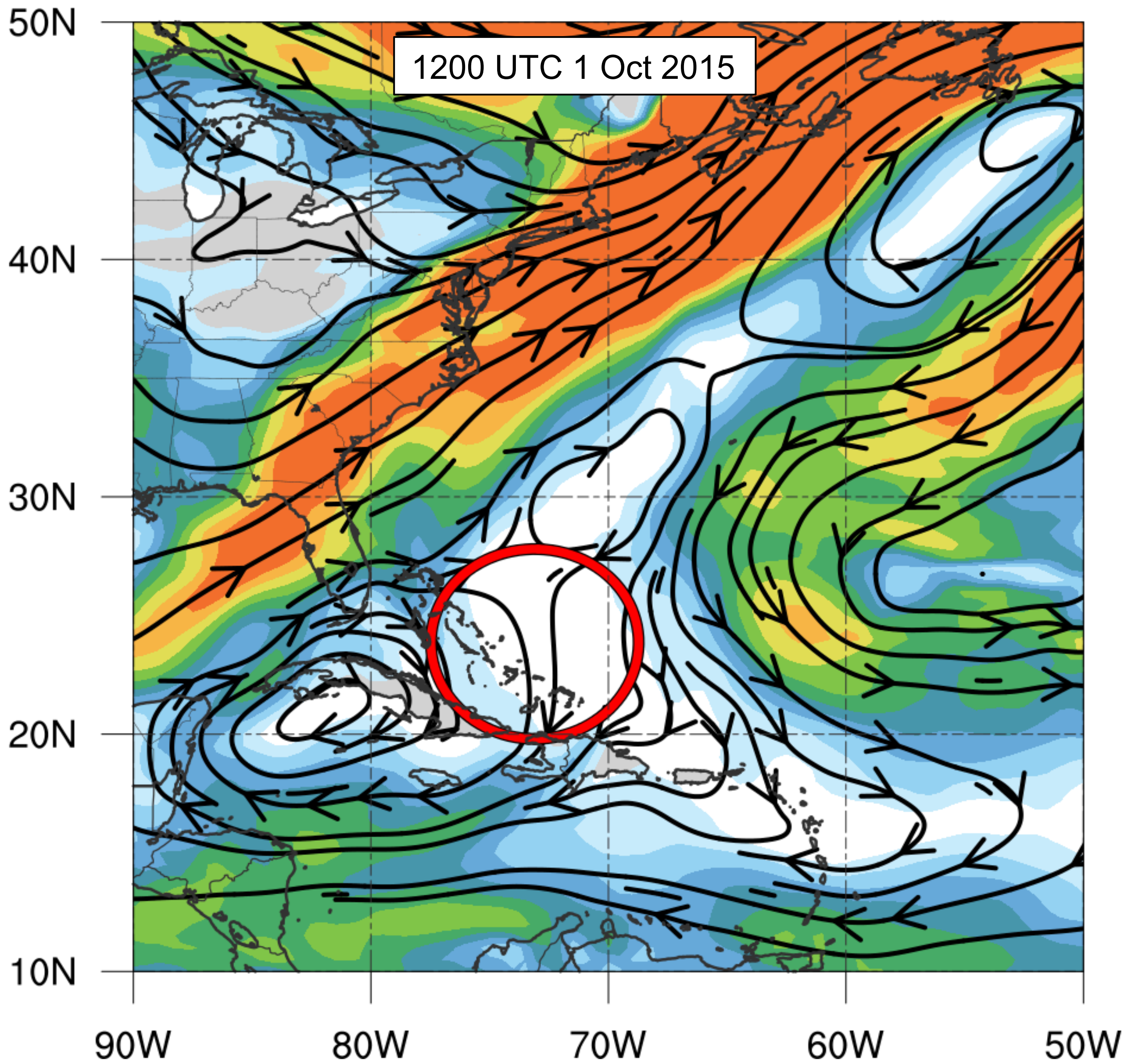
Residual Steering Flow



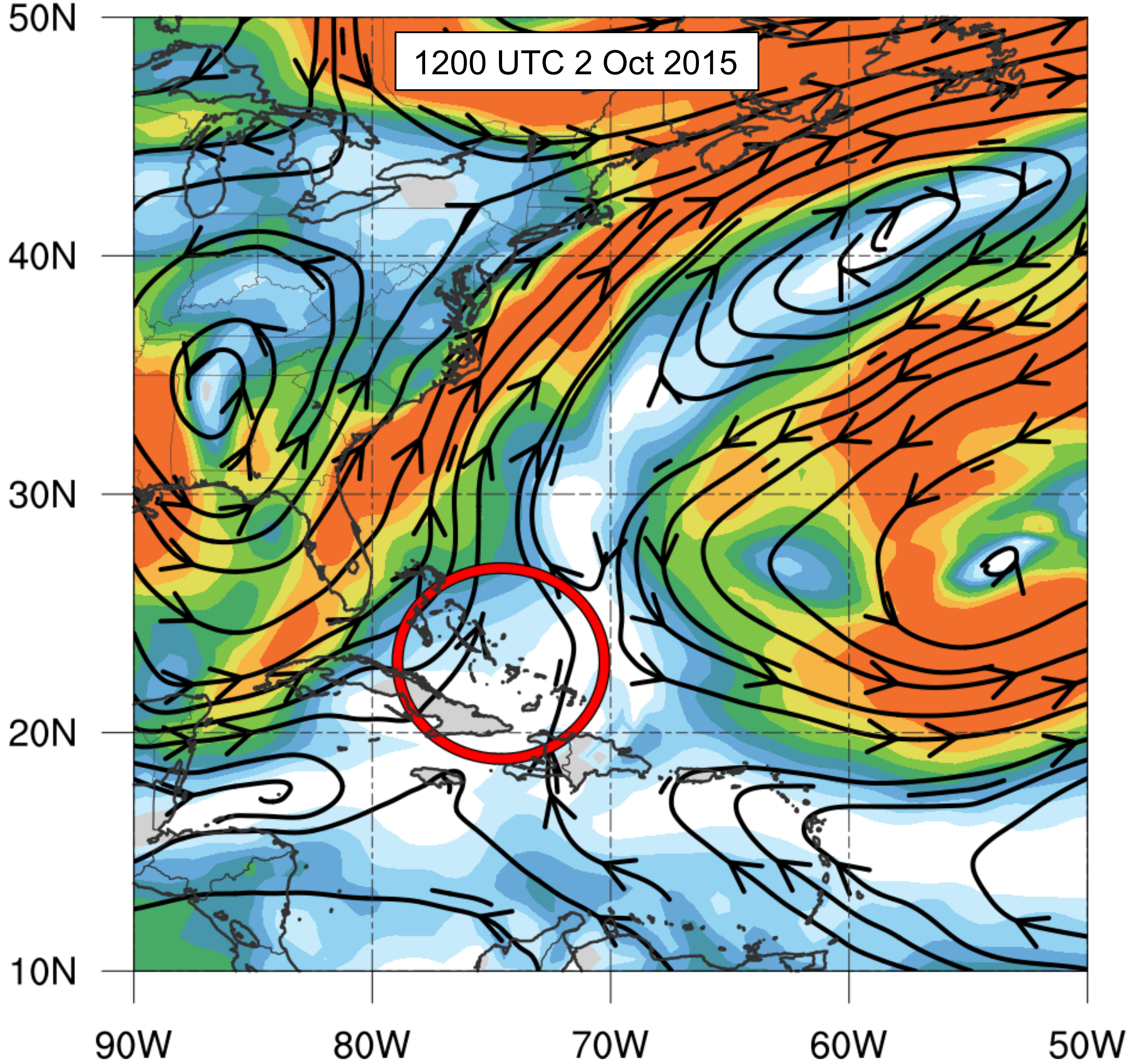
Residual Steering Flow



Residual Steering Flow



Residual Steering Flow



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

$$\nabla^2\psi = \begin{cases} \zeta & \text{for} \quad r \le r_0 \\ 0 & \text{for} \quad r > r_0 \end{cases} \qquad \nabla^2\chi = \begin{cases} \delta & \text{for} \quad r \le r_0 \\ 0 & \text{for} \quad r > r_0 \end{cases}$$

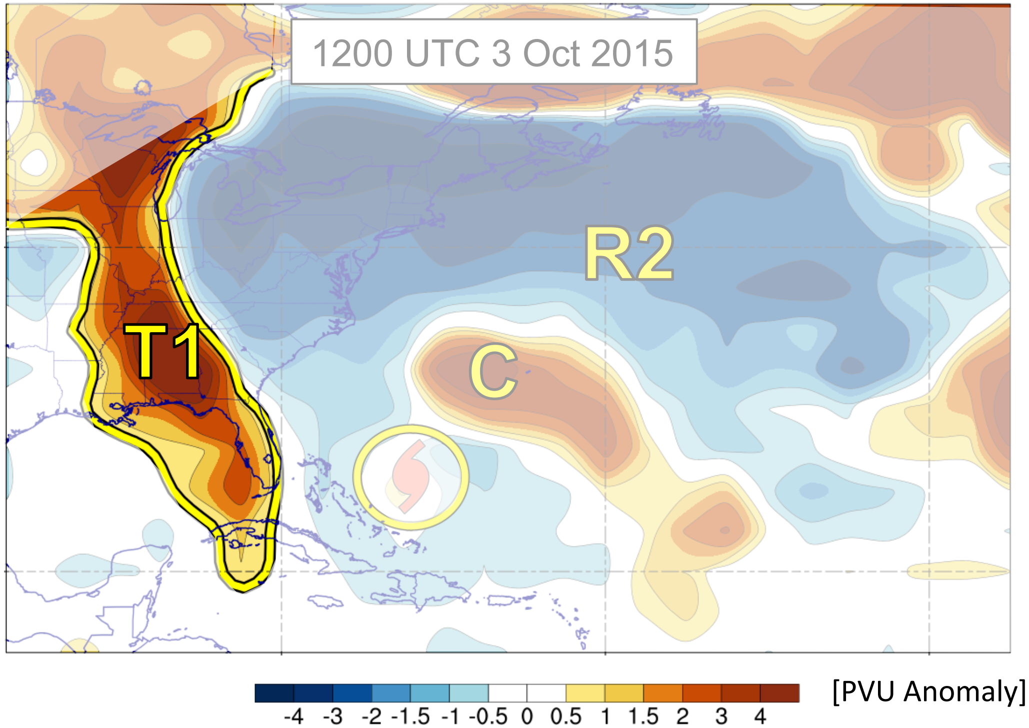
$$\vec{V}_\chi = \nabla\chi \qquad \vec{V}_\psi = \hat{k} \times \nabla\psi$$

Nondivergent Winds **Irrotational Winds**

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

Total Wind

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



- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**
- **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

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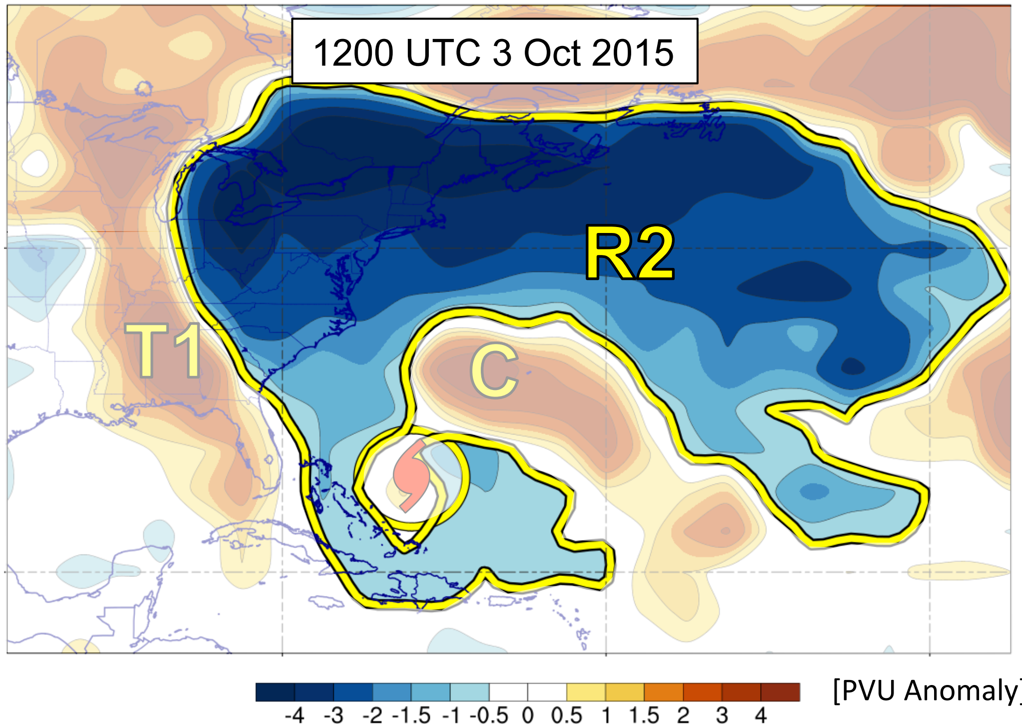
Nondivergent Winds — **Irrotational Winds**

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

Total Wind

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



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

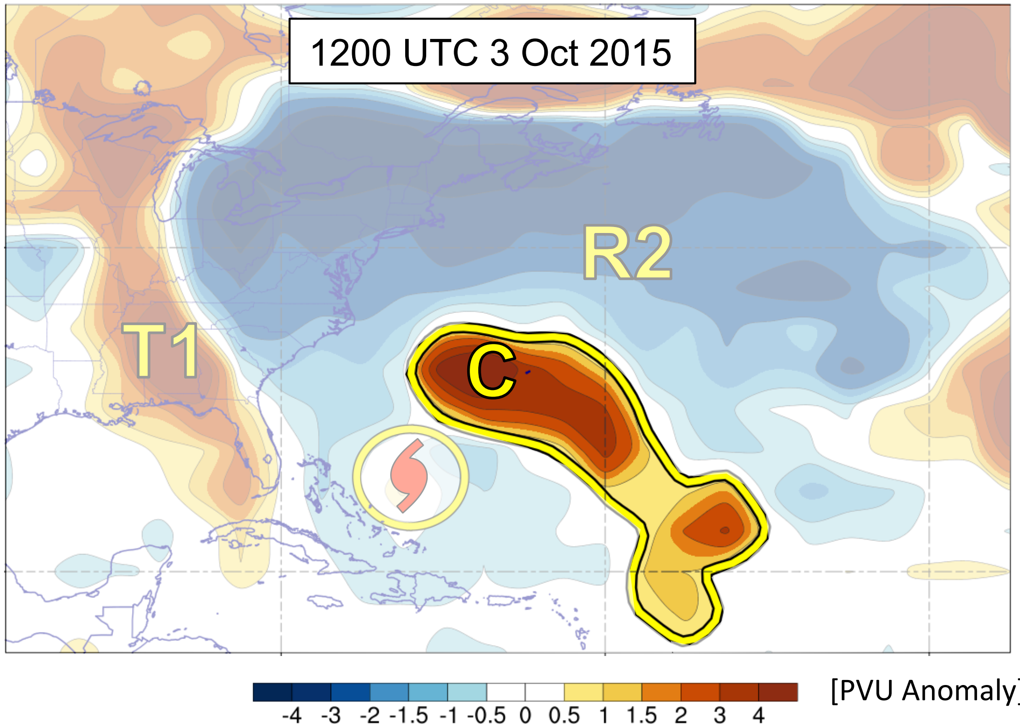
Test 2

- **Isolate steering from poleward upper-level ridge**

Piecewise Vorticity Inversion

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

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



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Nondivergent Winds **Irrotational Winds**

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

Total Wind

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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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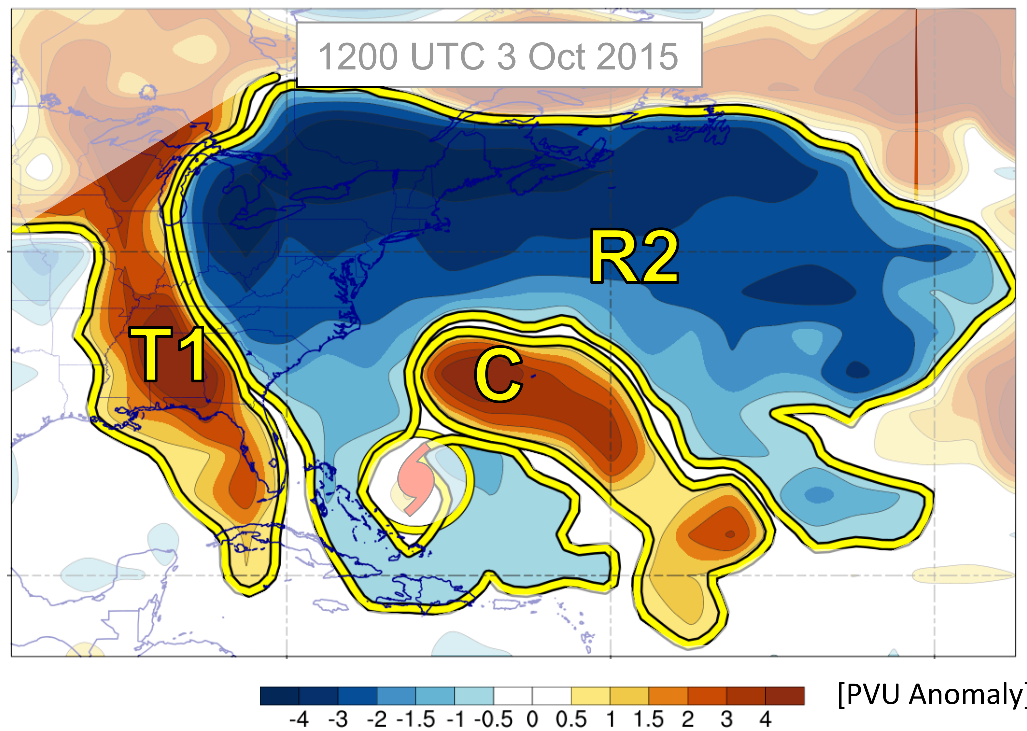
Nondivergent Winds — **Irrotational Winds**

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

Total Wind

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



- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**
- **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

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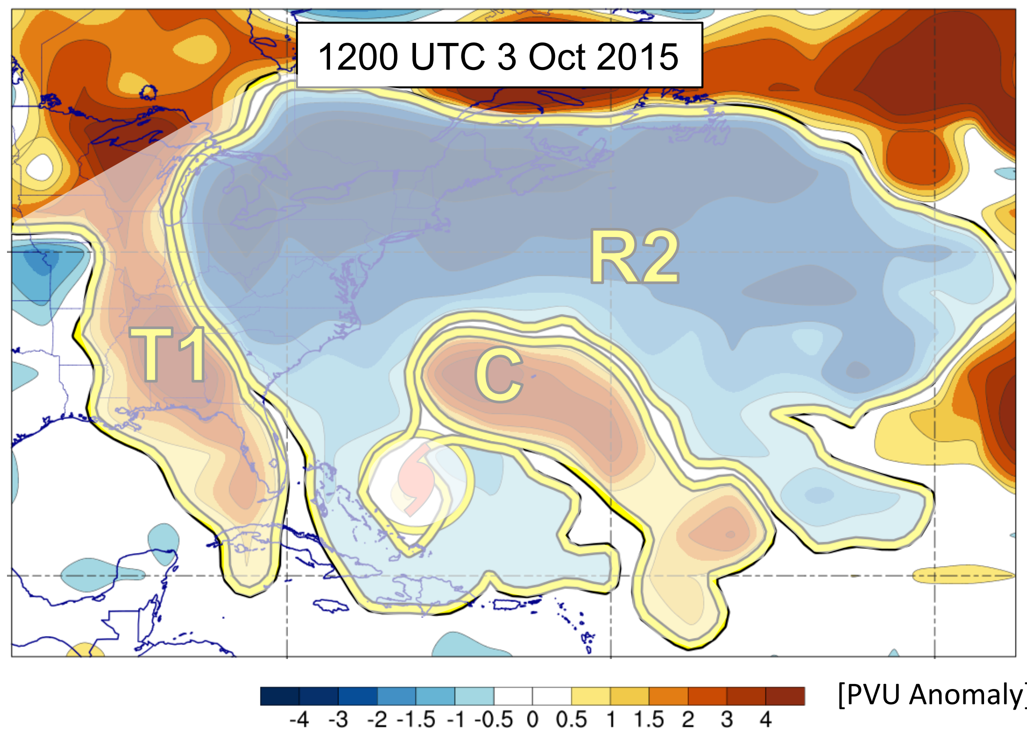
Nondivergent Winds — Irrotational Winds

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

Total Wind

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



- Remove TC Joaquin vortex
- $r_{Joaquin} \geq 3.0^o$
- 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

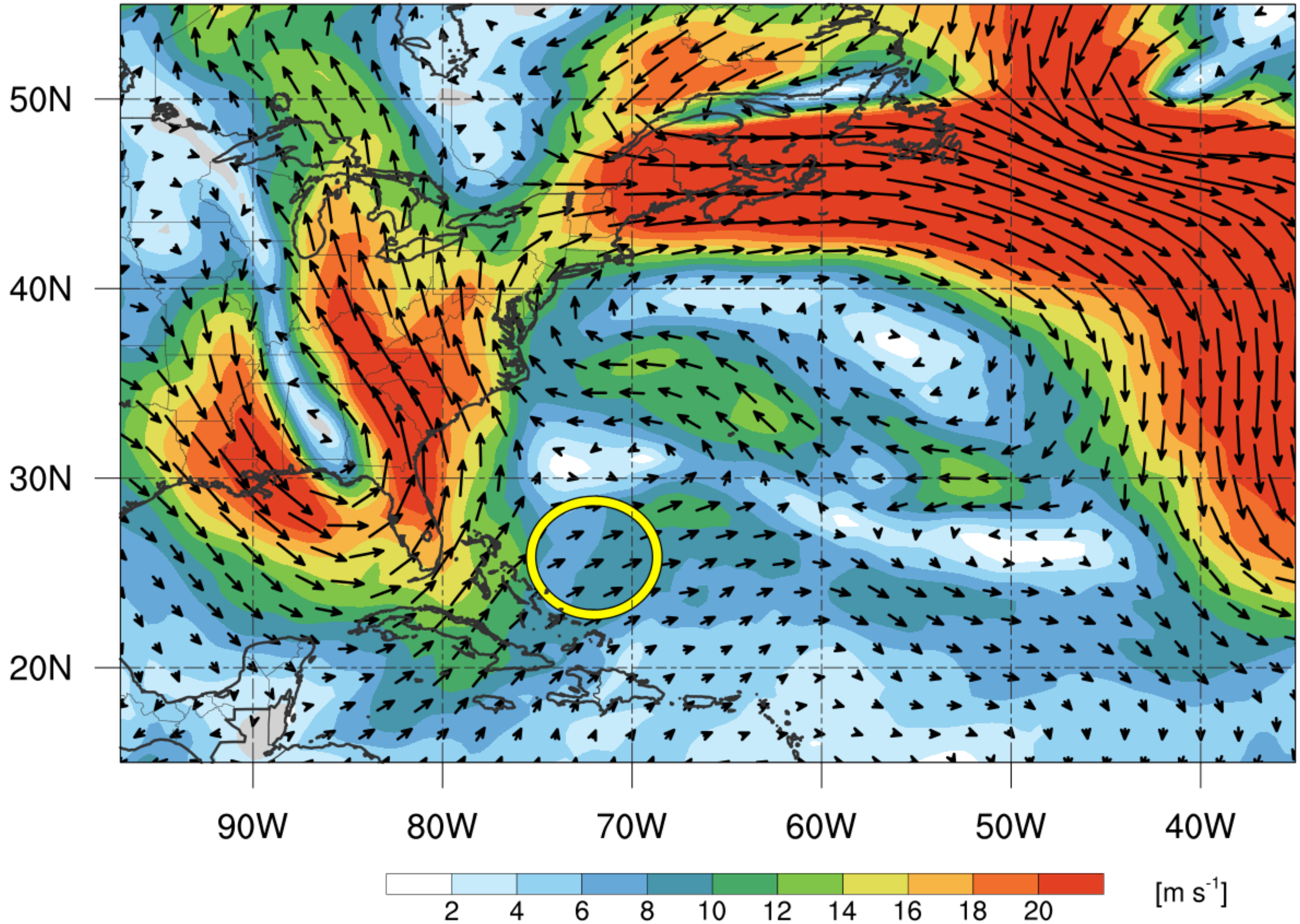
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Steering

Observations

- **CFSRv2 Steering**
  65º at 8.0 m s^{-1}
- **Actual TC Motion:**
  50º at 6.2 m s^{-1}



Steering Flow

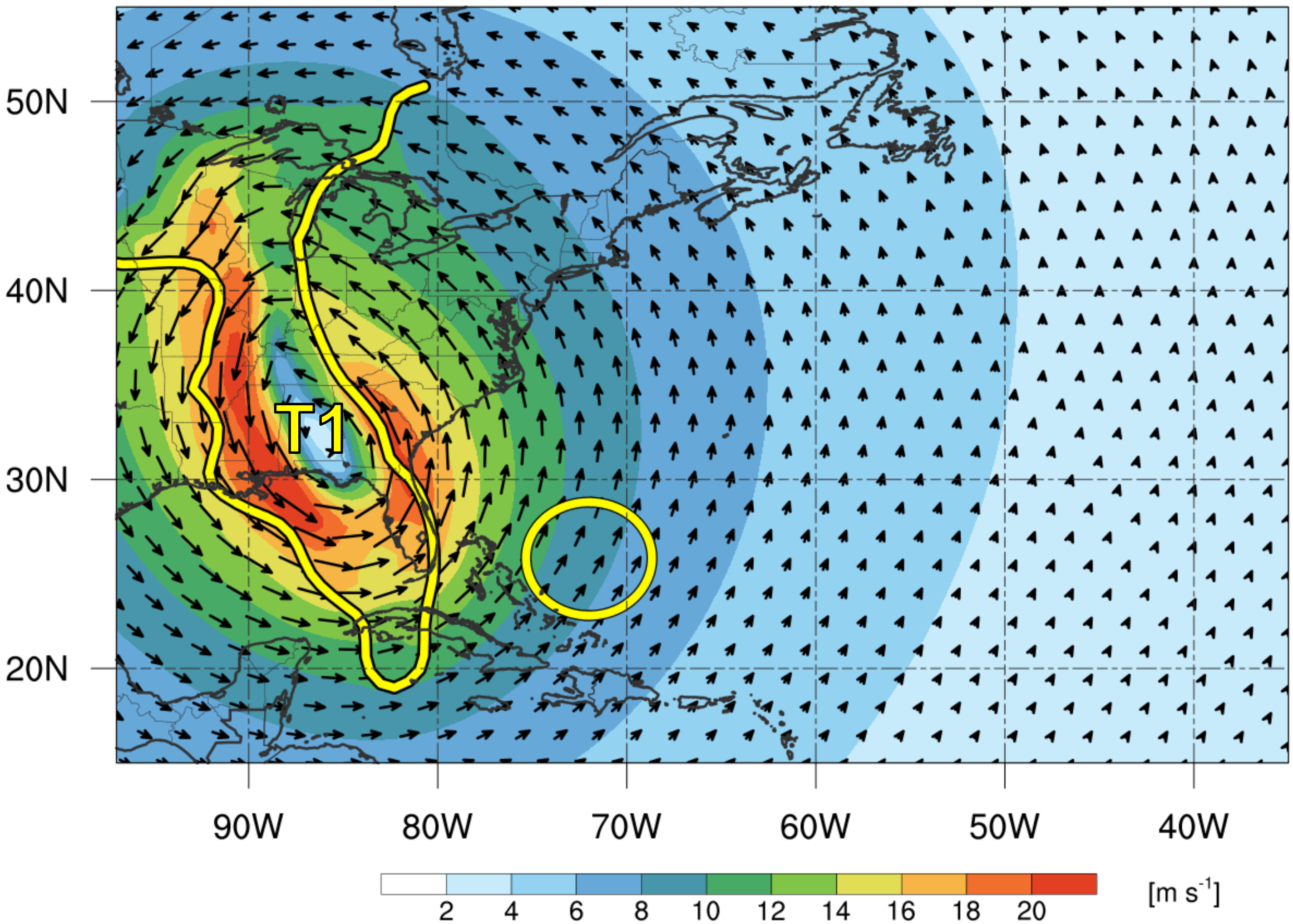
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 1

Observations

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



Steering Flow

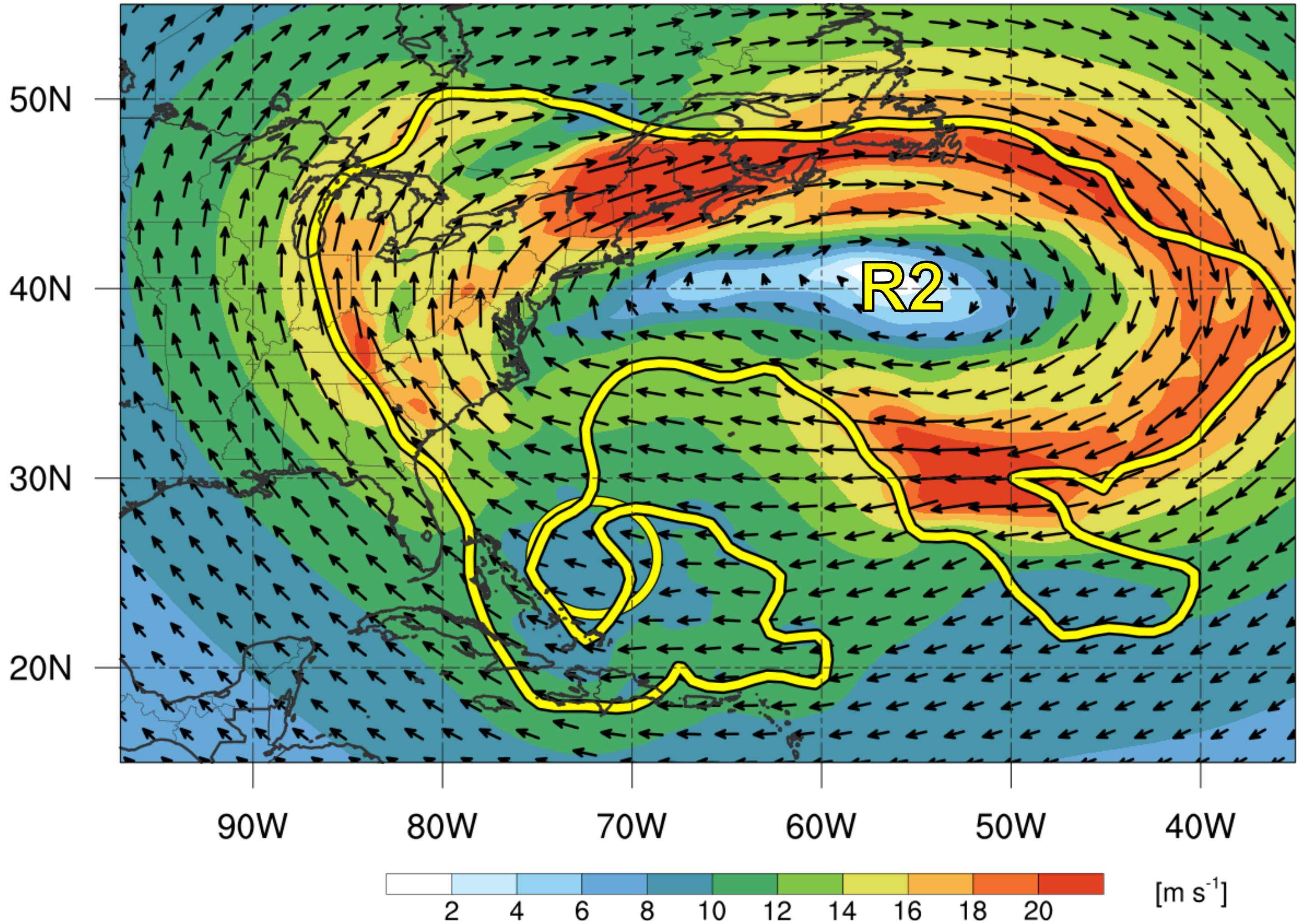
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 2

Observations

- **CFSRv2 Steering**
  286^o at 9.3 m s^{-1}
- **Actual TC Motion:**
  50^o at 6.2 m s^{-1}

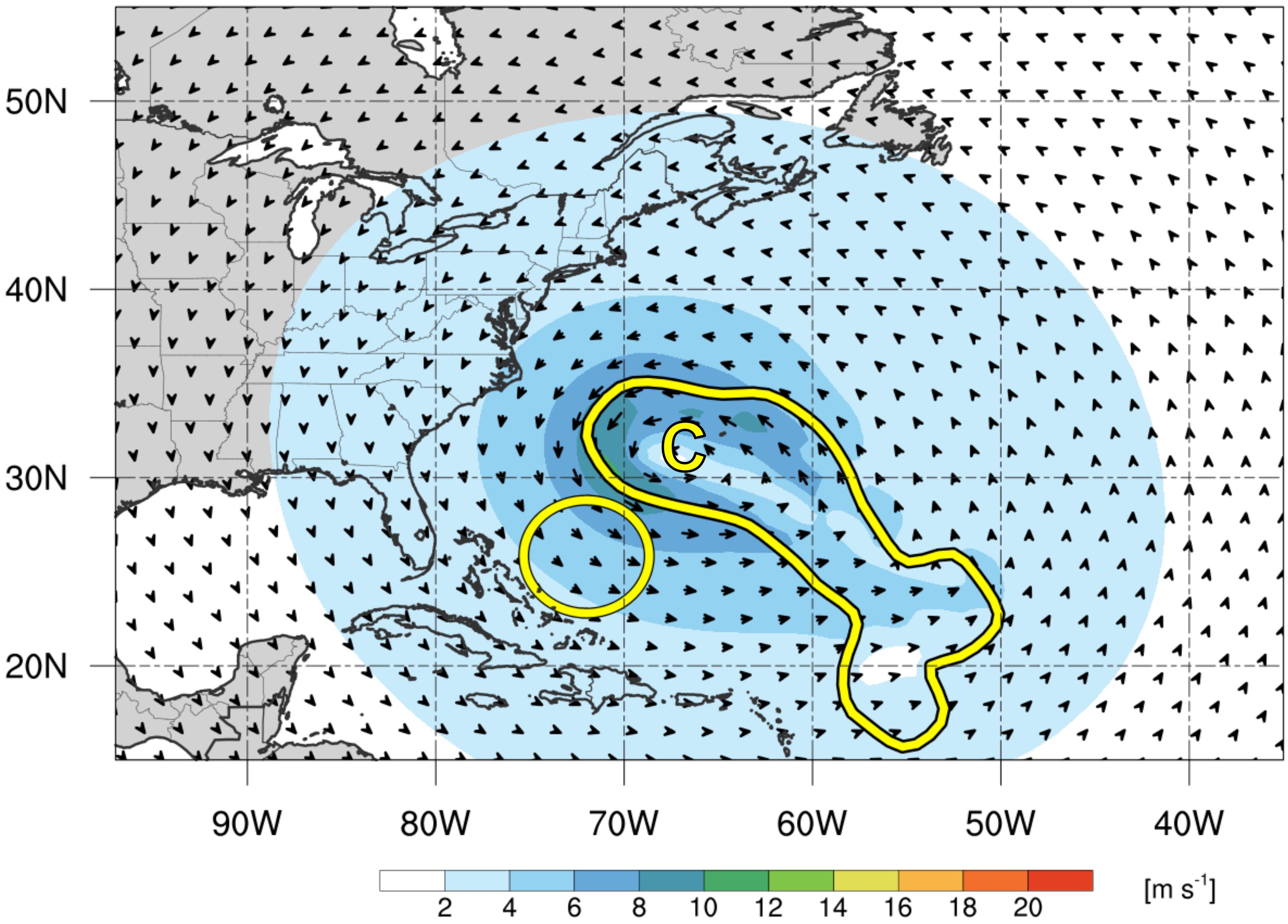


Steering Flow

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

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

Test 3



Observations

- **CFSRv2 Steering** **129° at 5.0 m s^{-1}**
- **Actual TC Motion:** **50° at 6.2 m s^{-1}**

Steering Flow

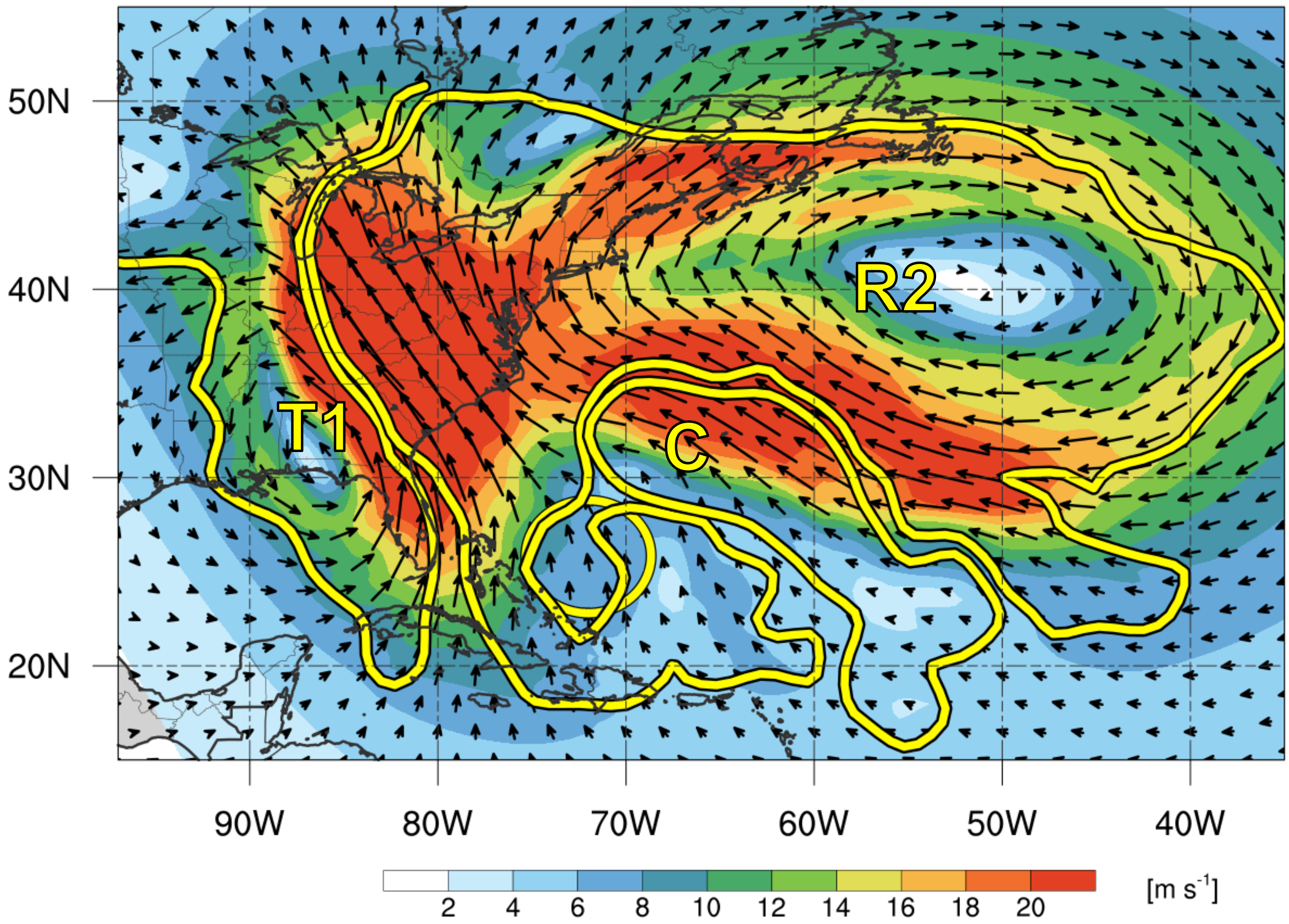
- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 3.0^o$**

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

Test 4

Observations

- **CFSRv2 Steering**
  350º at 7.2 m s^{-1}
- **Actual TC Motion:**
  50º at 6.2 m s^{-1}

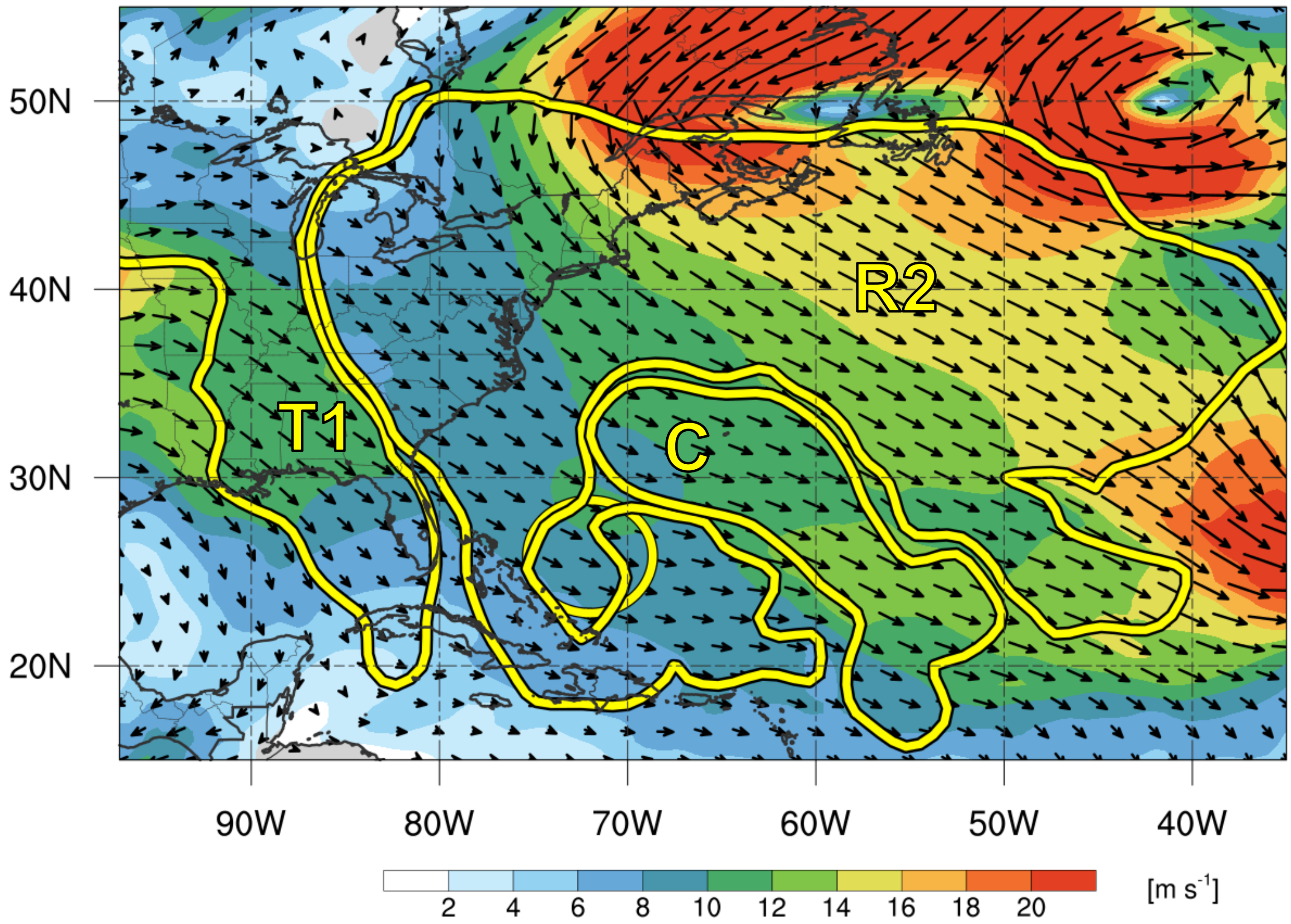


Steering Flow

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

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

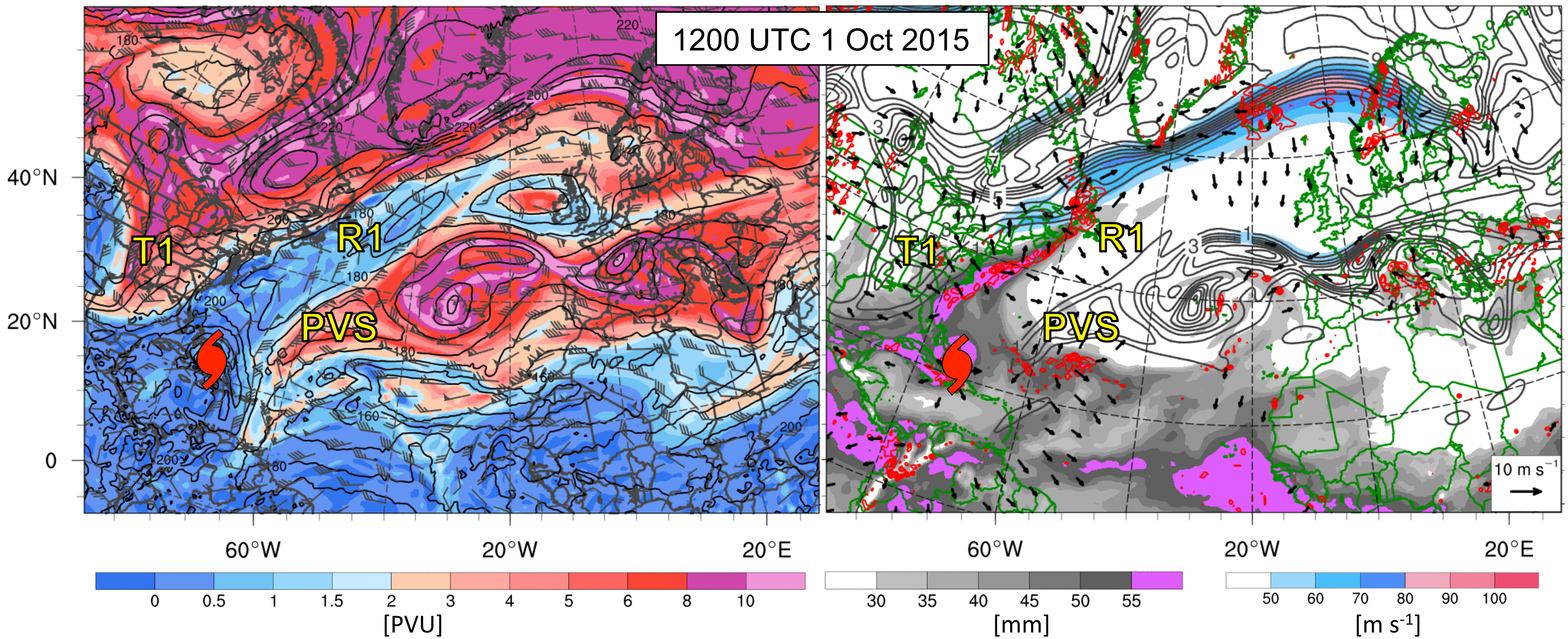
Test 5



Observations

- **CFSRv2 Steering**
  113^o at 9.3 m s^{-1}
- **Actual TC Motion:**
  50^o at 6.2 m s^{-1}

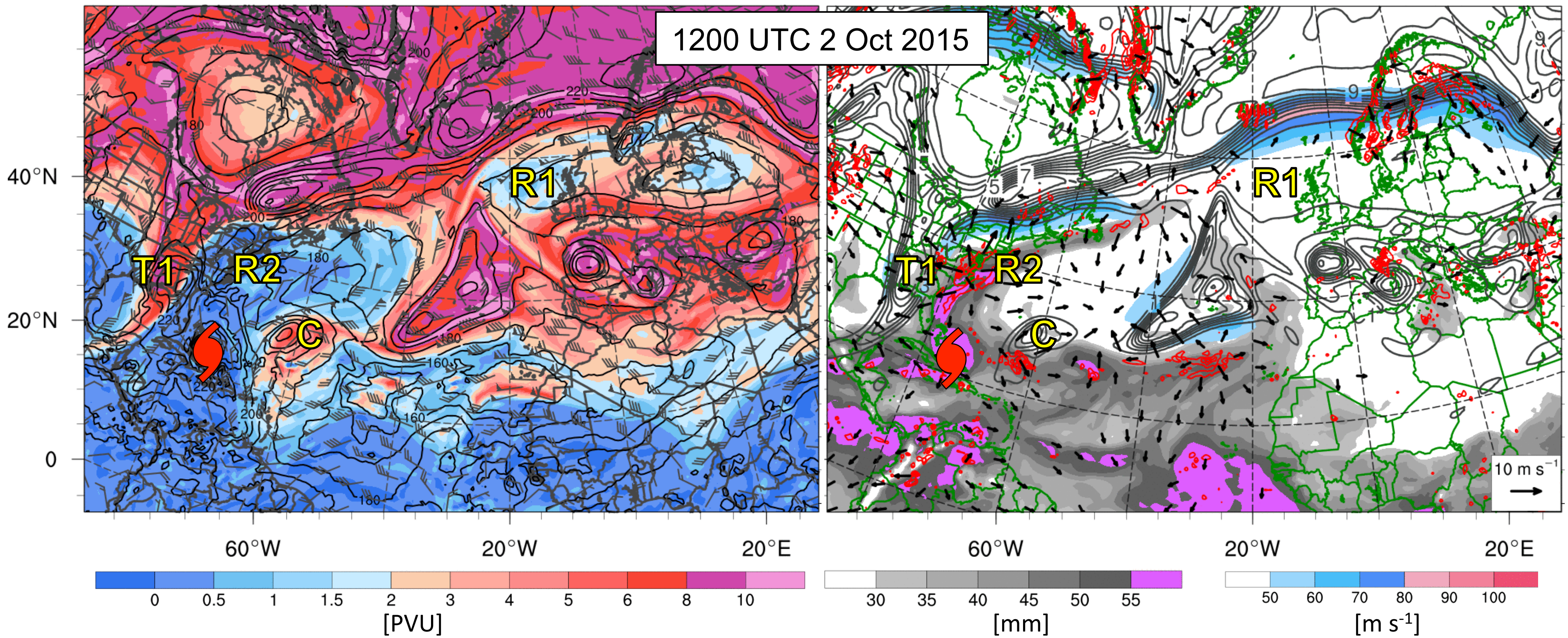
Synoptic Overview



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})

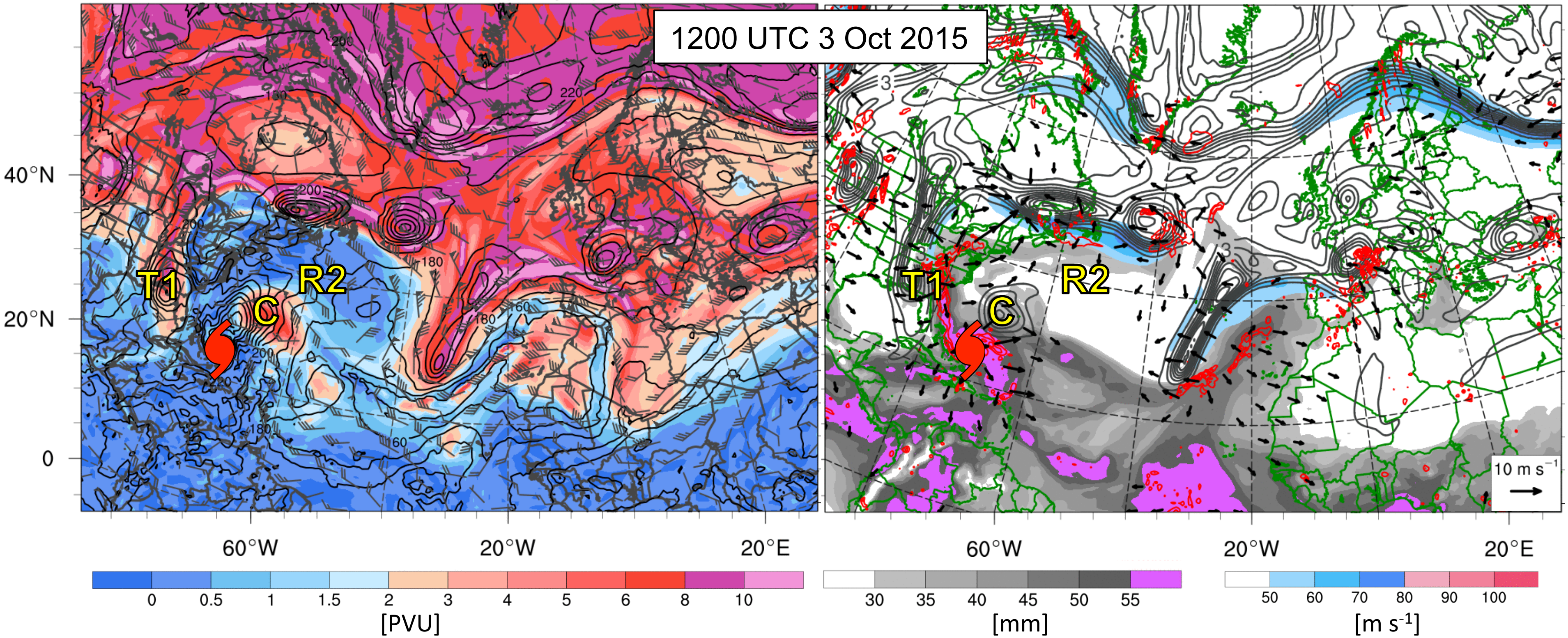
Synoptic Overview



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 x 10^{-3} hPa s^{-1})