An Analysis of Multiple Steering Influences on the Track of Tropical Cyclone Joaquin (2015)

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Motivation

- **TC Joaquin formed in the western Atlantic on 0000 UTC 28 September 2015**
- Synoptic track influences
  - Upstream deep-layer trough over the Eastern US
  - Poleward deep-layer ridge over northwest Atlantic
  - PV streamer northeast of Joaquin
- Track Results
  - Track forecast by the NHC took Joaquin inland
    - 1800 UTC 30 September 2015
  - Large spread in numerical guidance
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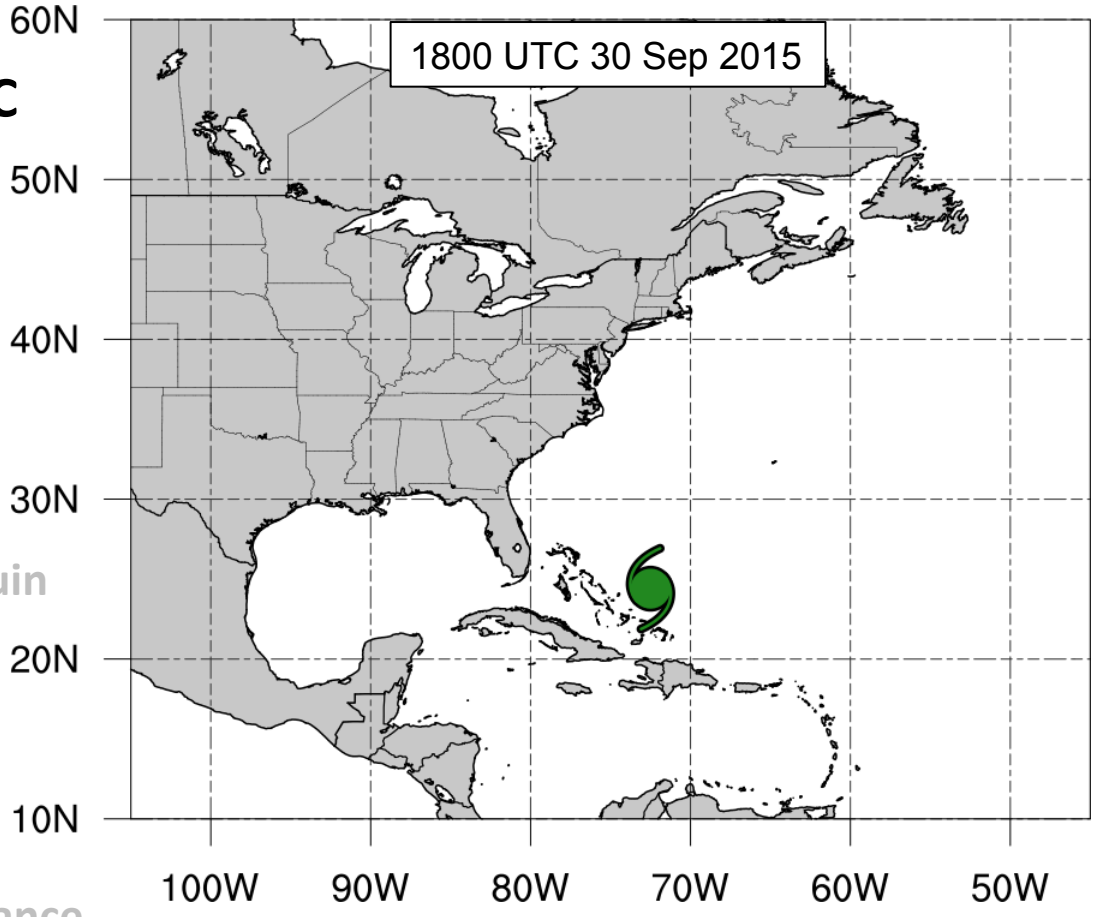

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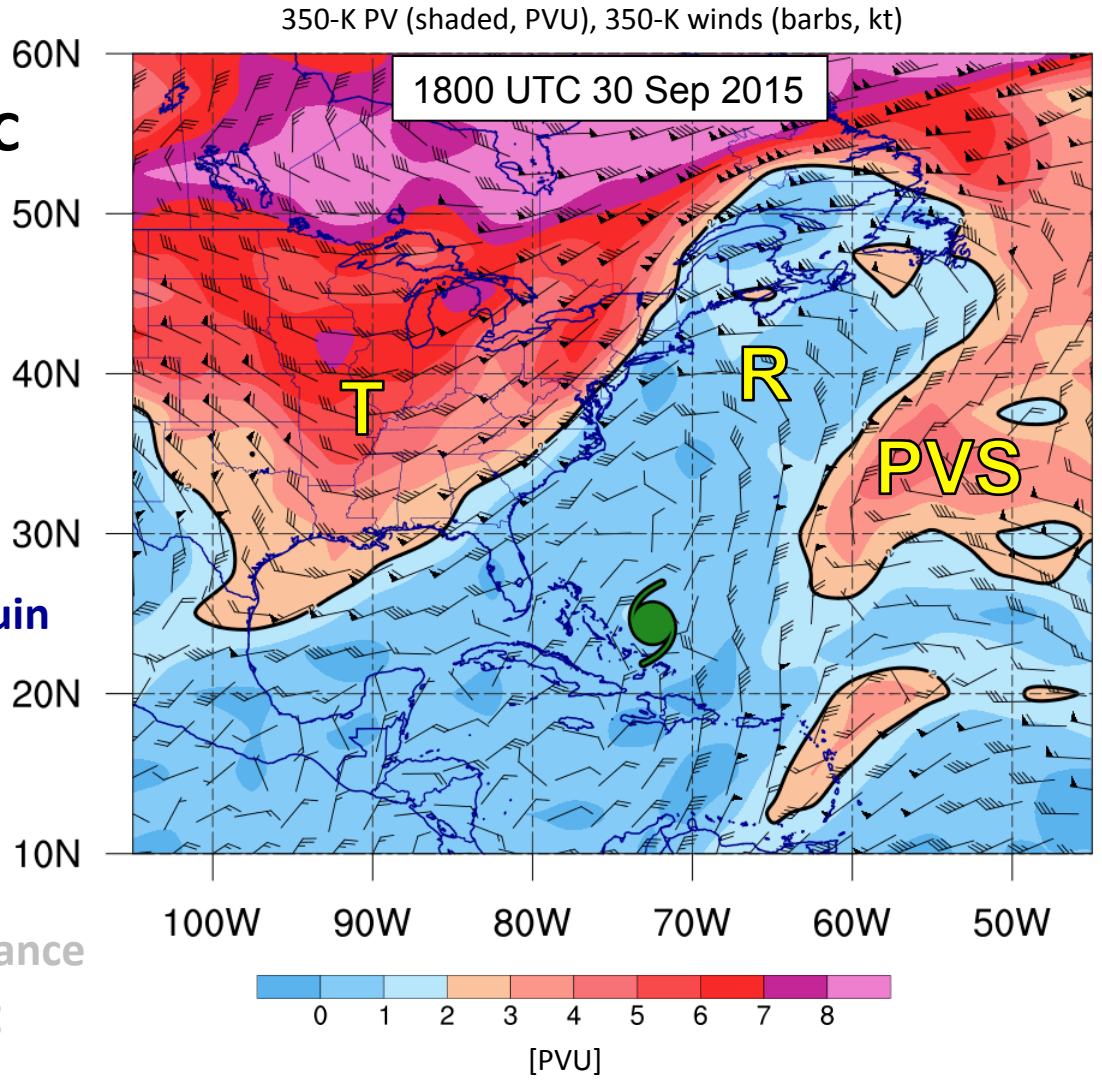

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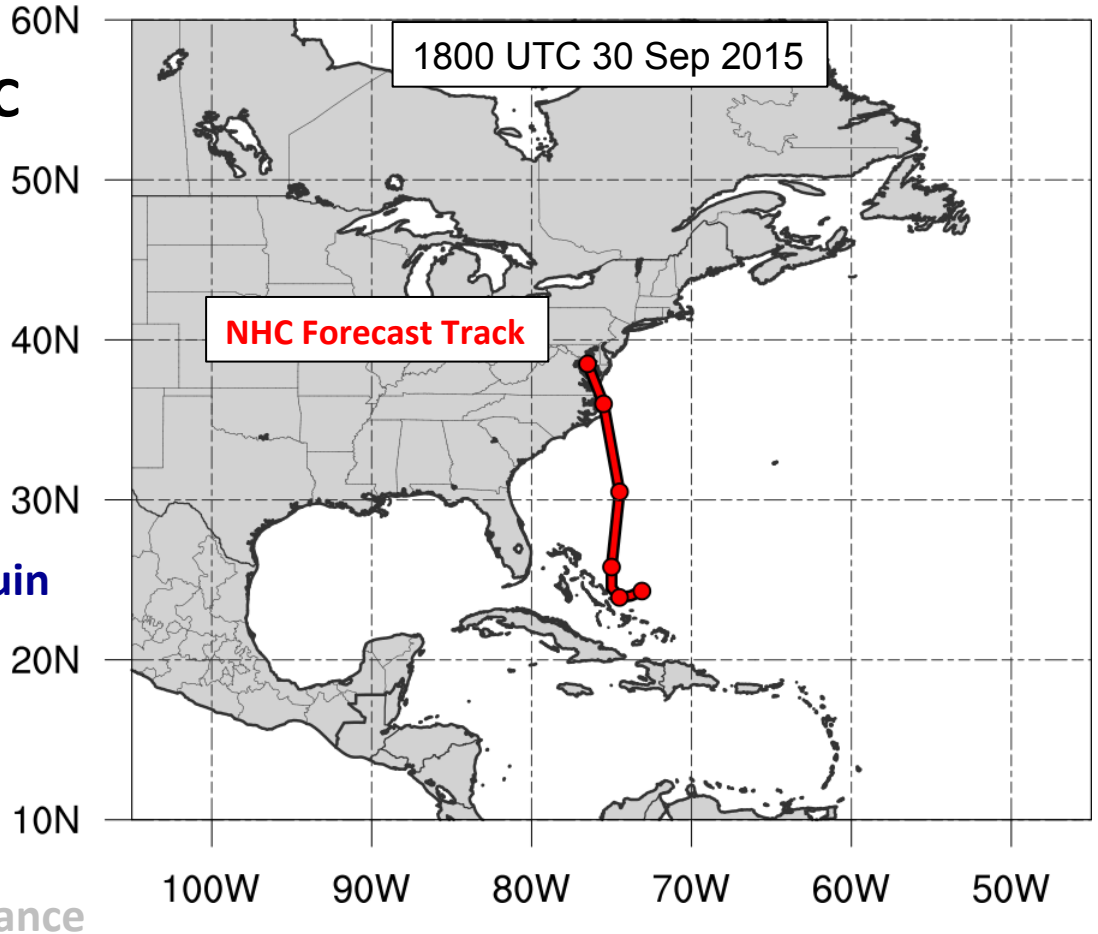

120-h NHC track (red line), 24-h forecast point (red circles)

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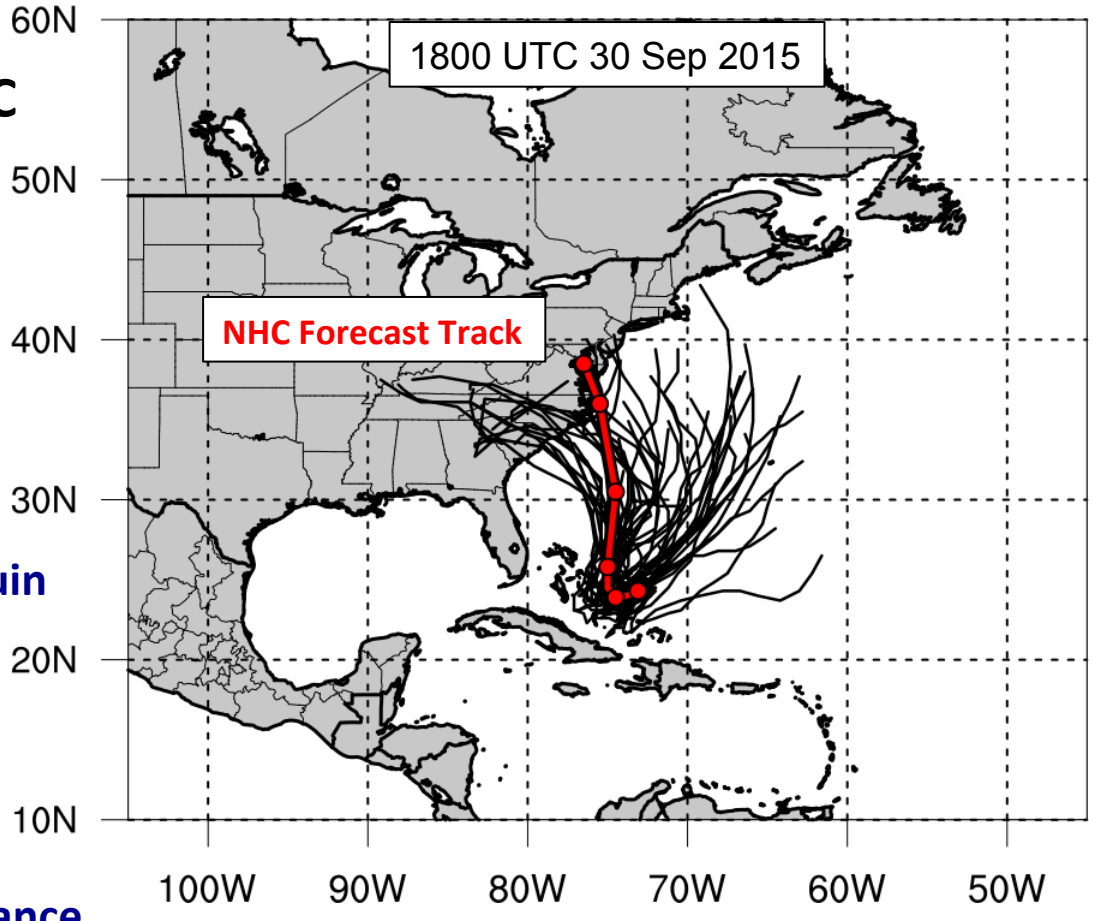

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120-h ECMWF Ensemble forecast tracks (black lines)

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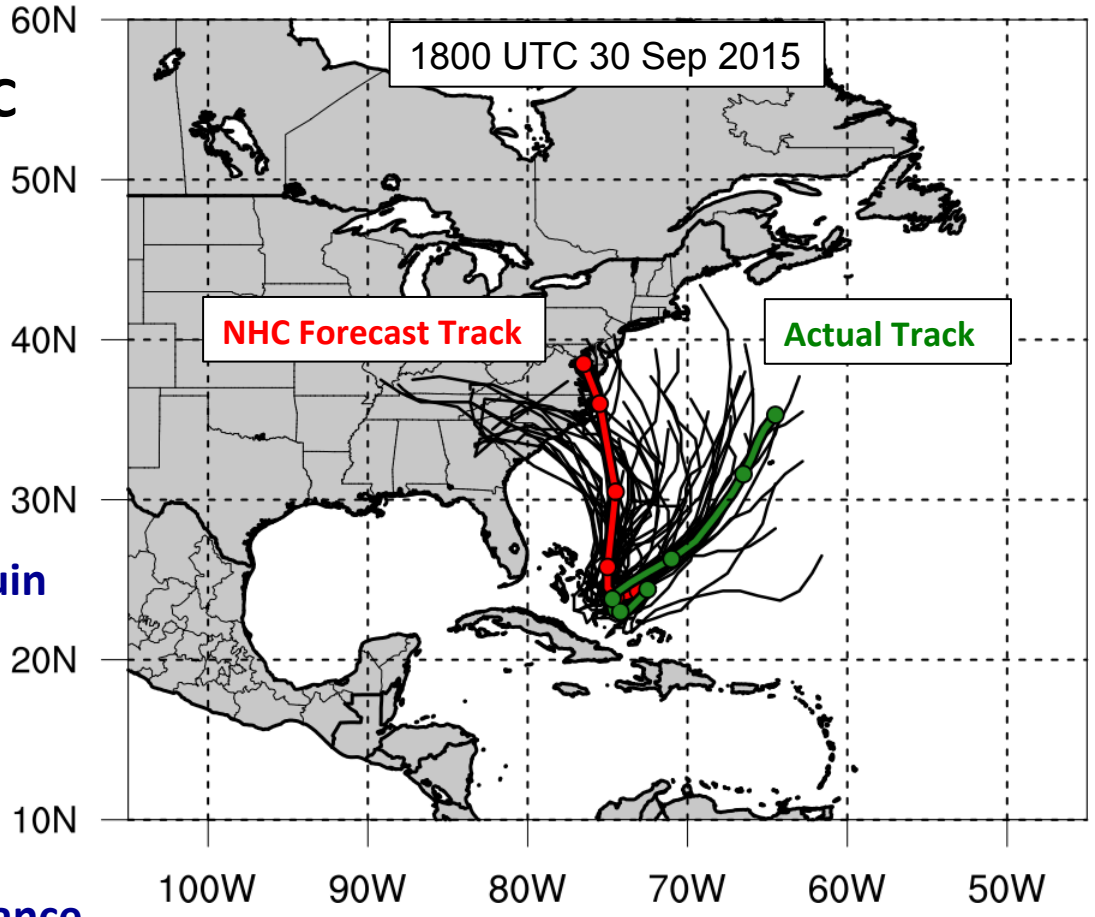

120-h NHC track (red line), 24-h forecast point (red circles)
120-h ECMWF Ensemble forecast tracks (black lines)
Best Track (green line), 24-h Best Track positions (green circles)

Which features were important for correct track?

Objectives

1) **Investigate the role that relevant synoptic features play on TC Joaquin's steering**
   - **Dataset: 0.5° Climate Forecast System Reanalysis (CFSR) v2**

2) **Investigate the forecast evolution of TC Joaquin's steering**
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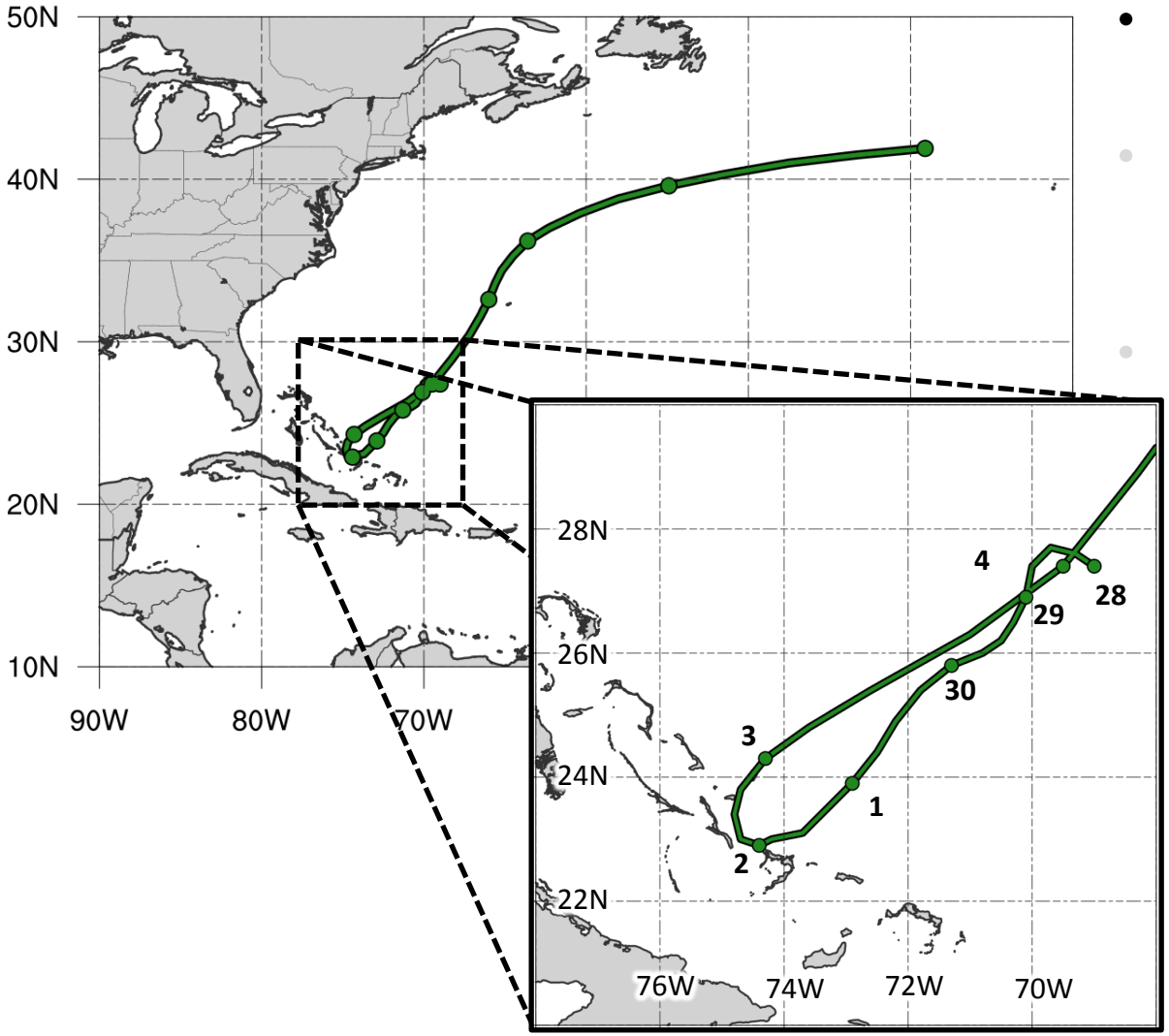

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- What synoptic features are responsible for unusual southwesterly motion?
- Investigate the individual pieces perceived to be responsible for southwesterly motion

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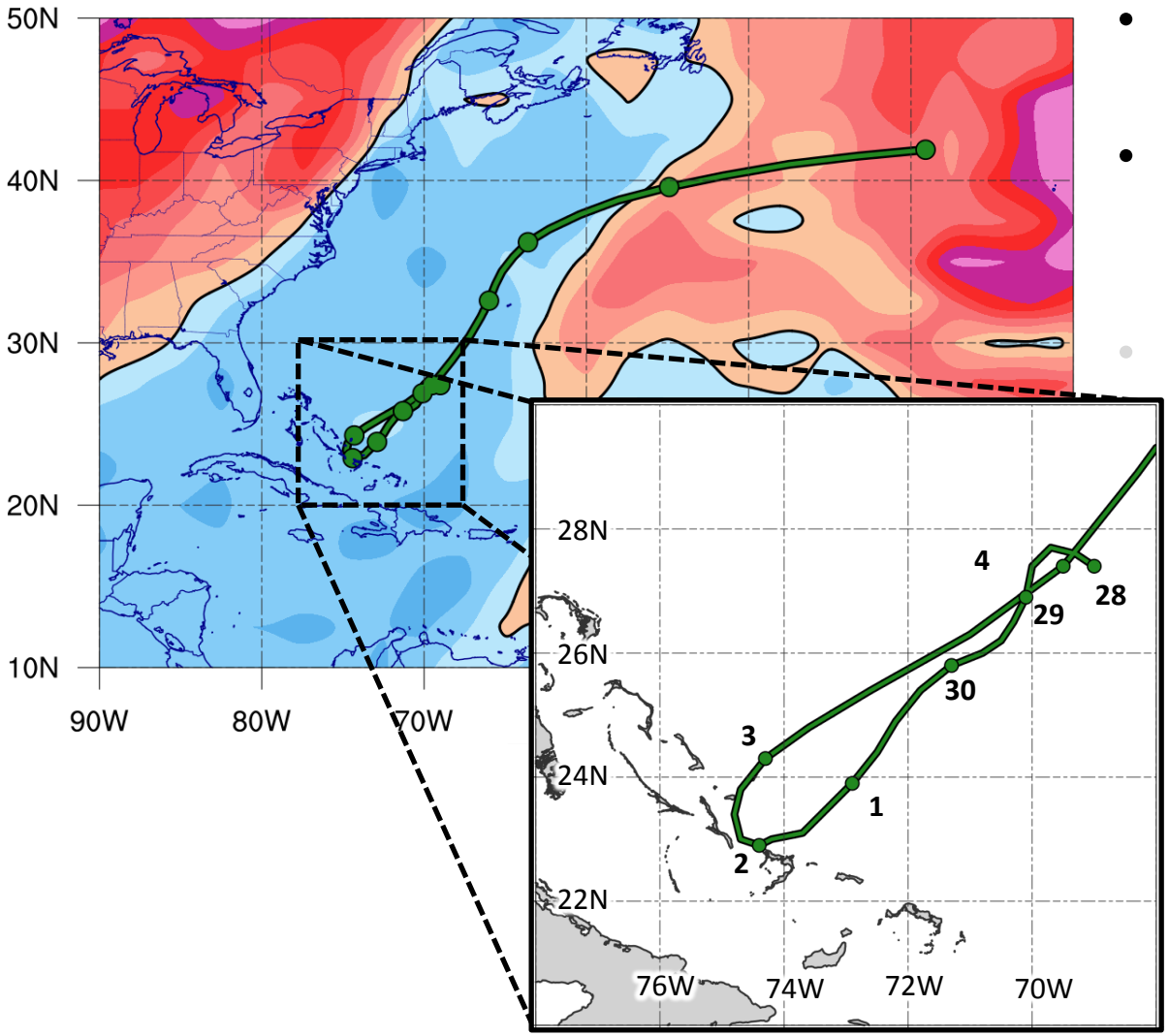

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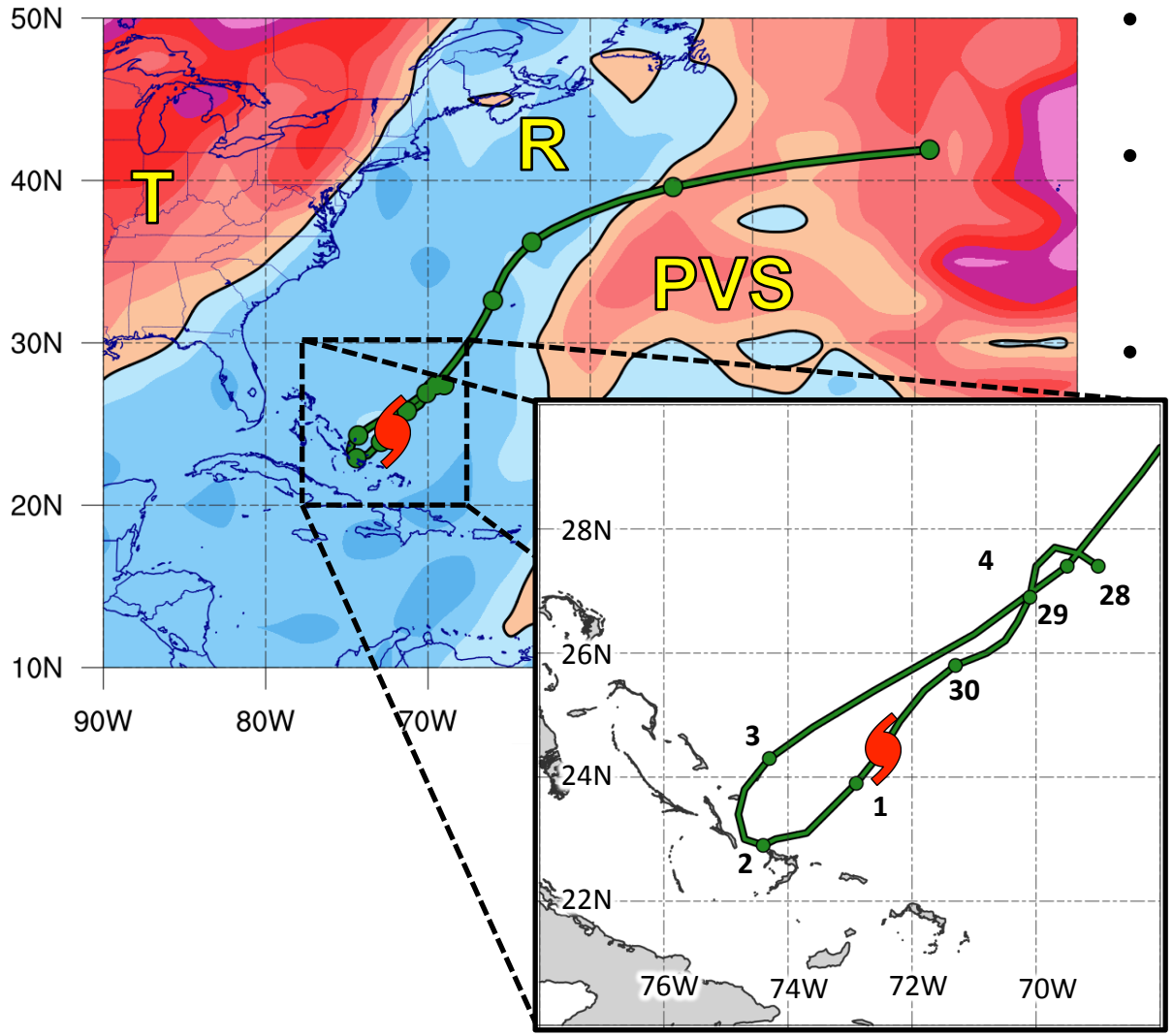

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Piecewise Vorticity Inversion

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

- **Adapted from Galarneau and Davis (2013)**

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

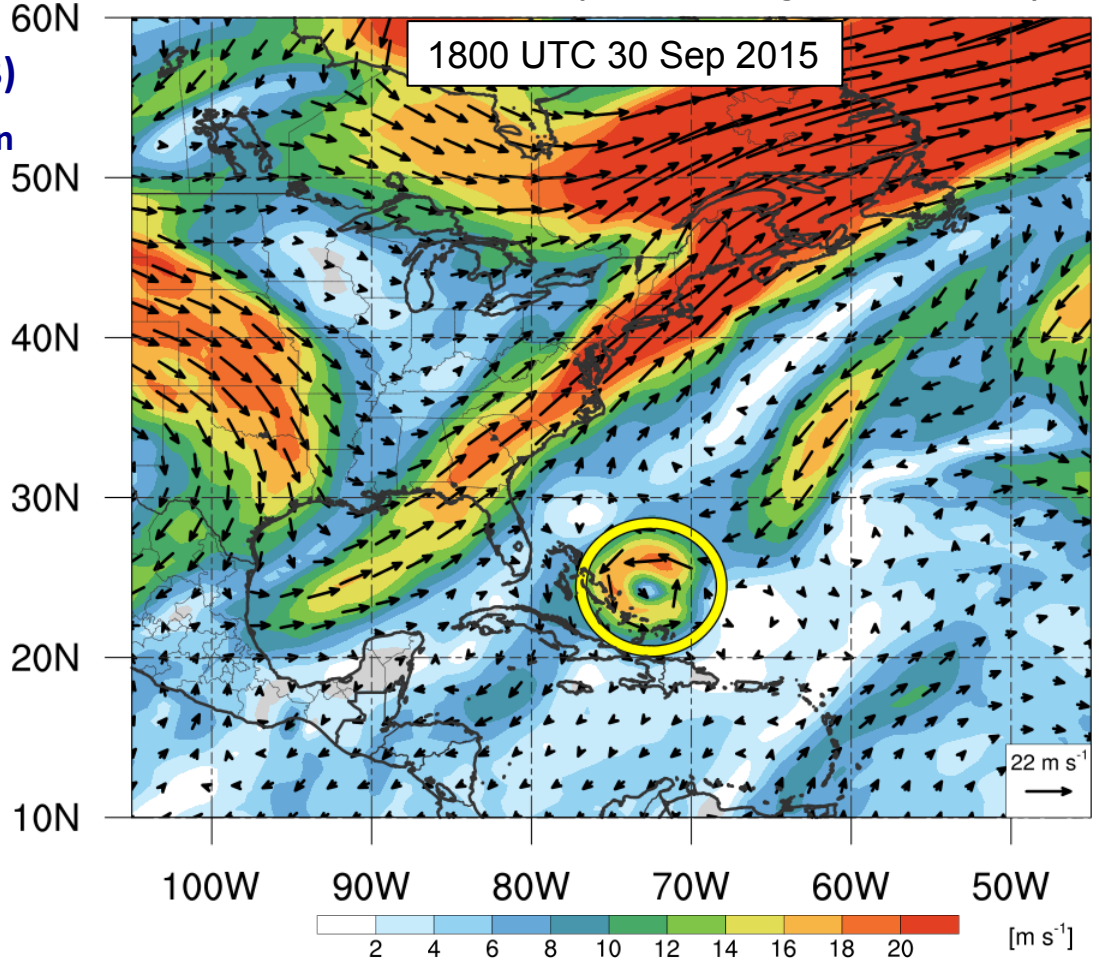
- Remove TC Joaquin vortex
- $r_{Joaquin} \leq 4.0^{o}$

- Assumption: Steering associated with deep-layer winds governs the motion of TC Joaquin

- CFSRv2 heading implied by layer mean flow:

- Actual best track heading:

850 – 250-hPa flow inverted (captures steering level for TC Joaquin)



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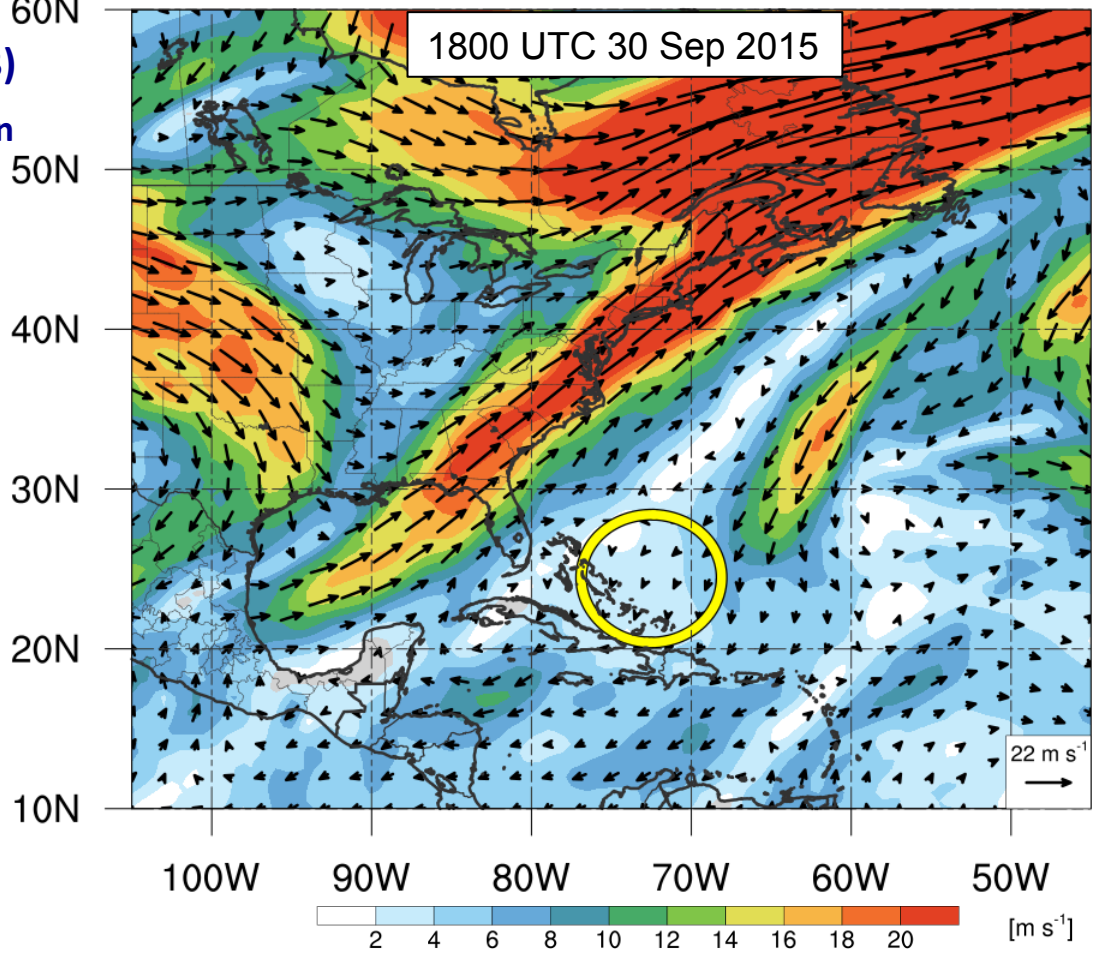

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- **CFSRv2 heading implied by layer mean flow:**

  208° at 2.9 m s^{-1}

- **Actual best track heading:**

  213° at 3.1 m s^{-1}

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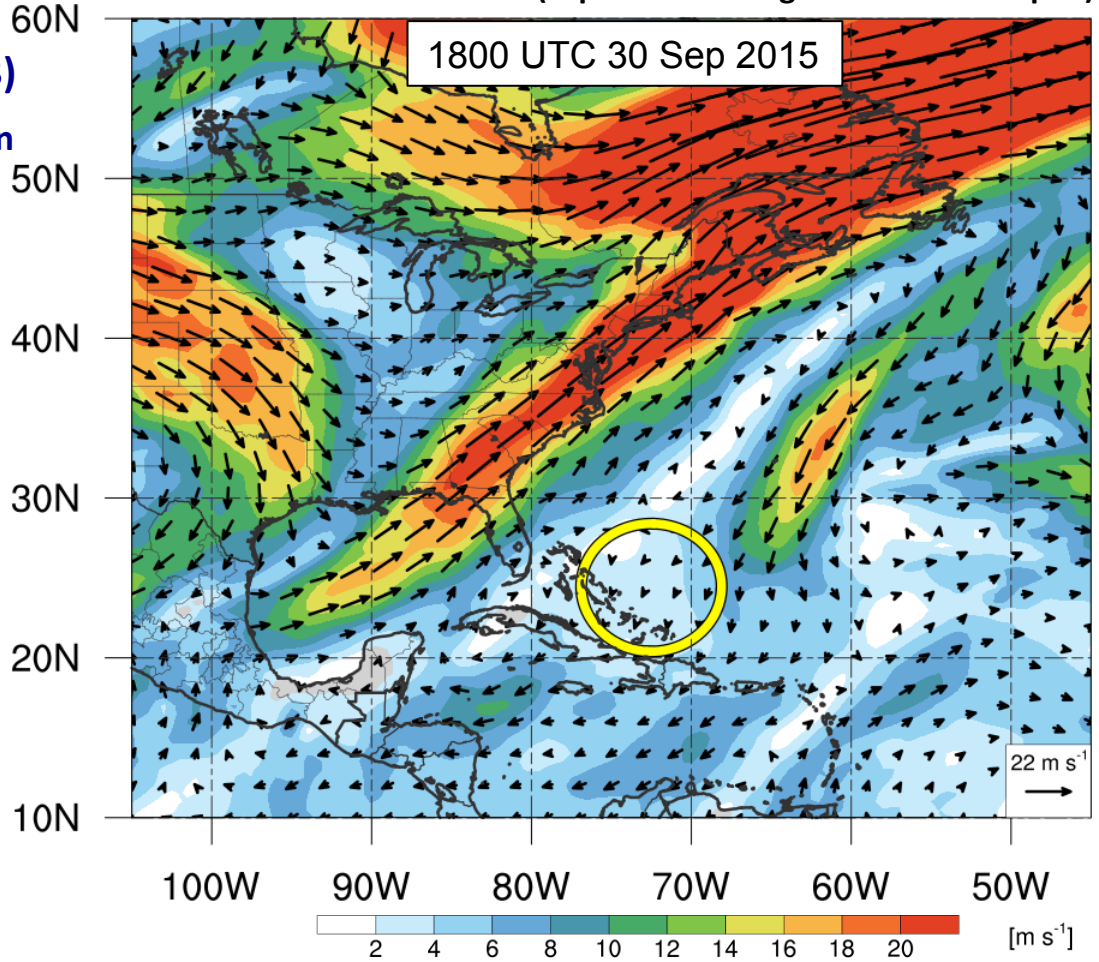

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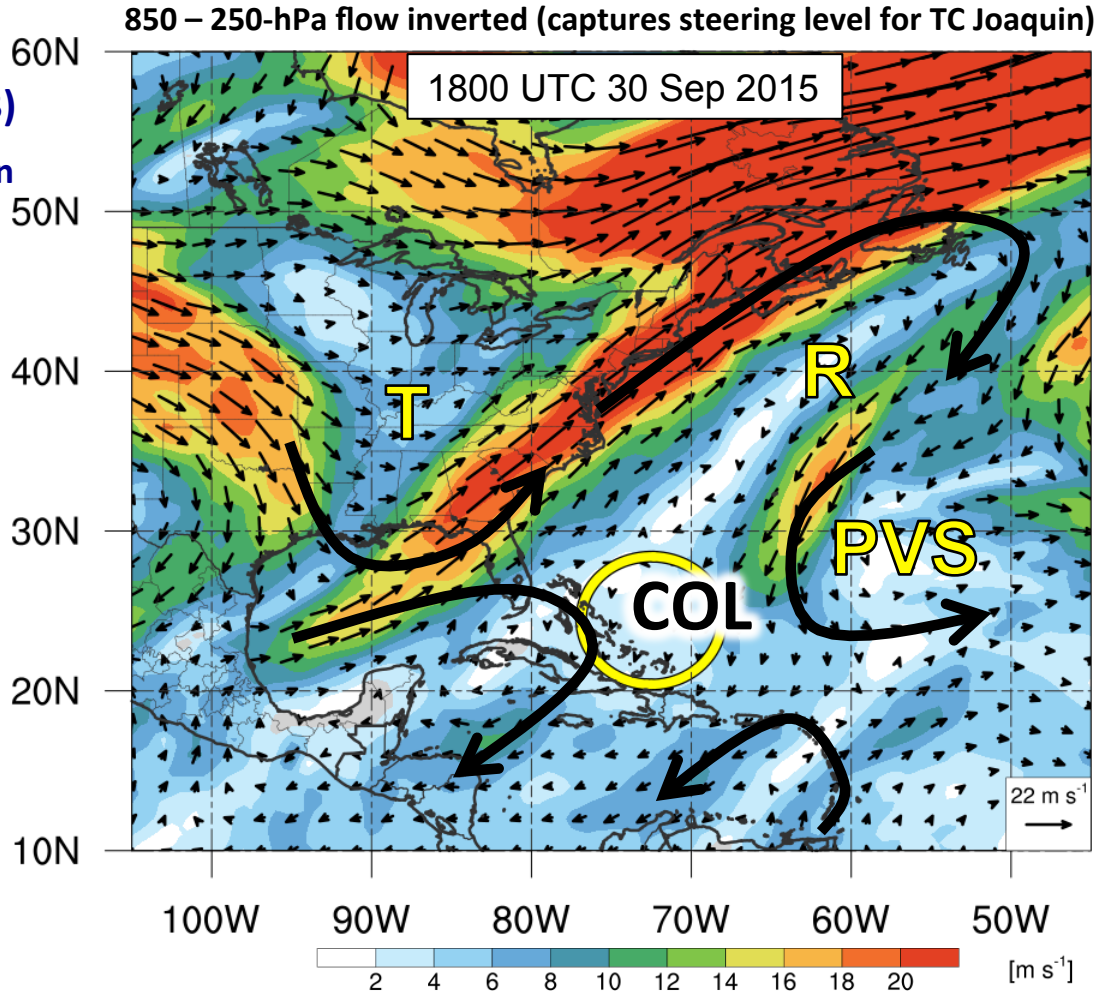
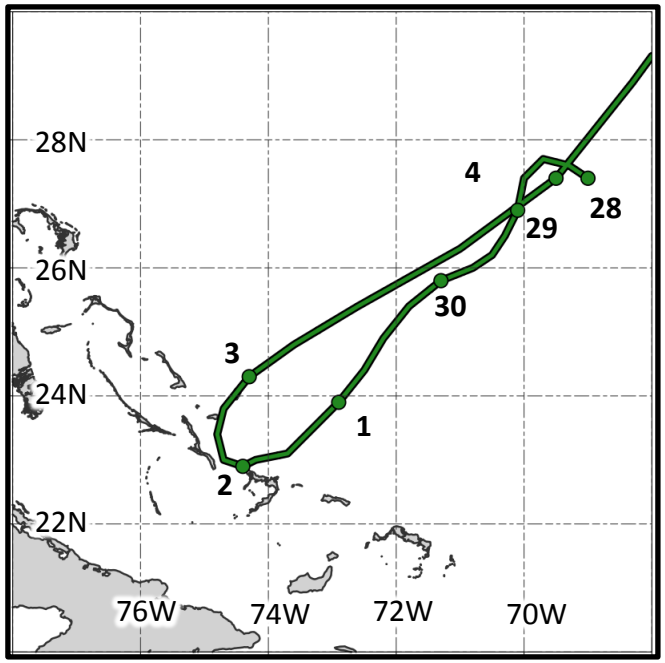
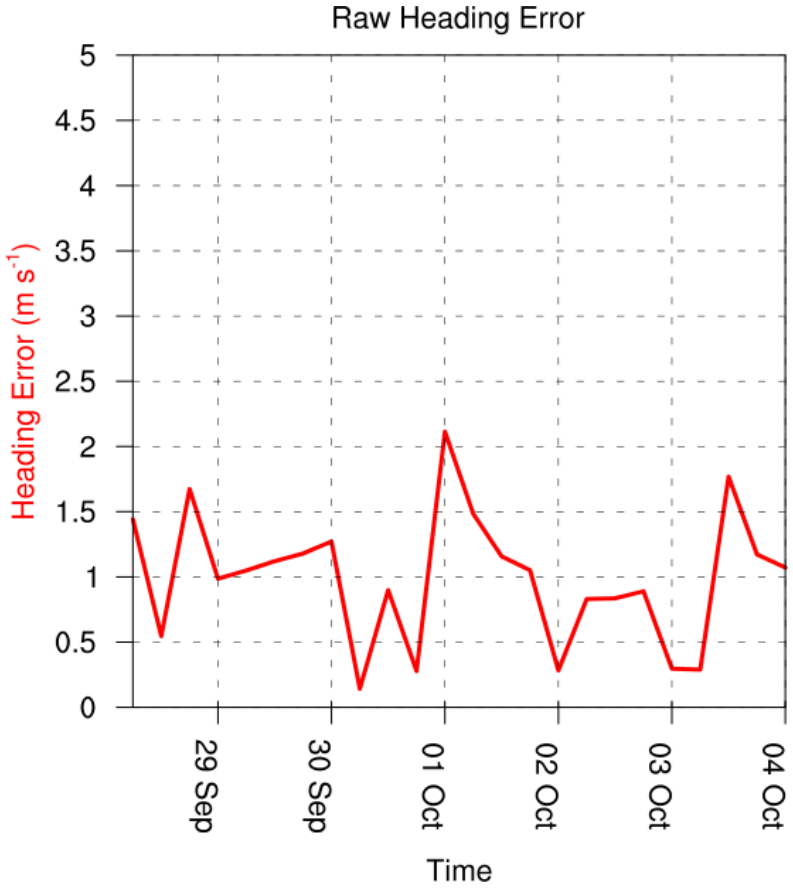


When does CFSR capture steering of Joaquin best?

CFSR Heading Error

CFSR heading$_{850-250\text{-}hPa}$ – Best Track heading = CFSR heading error





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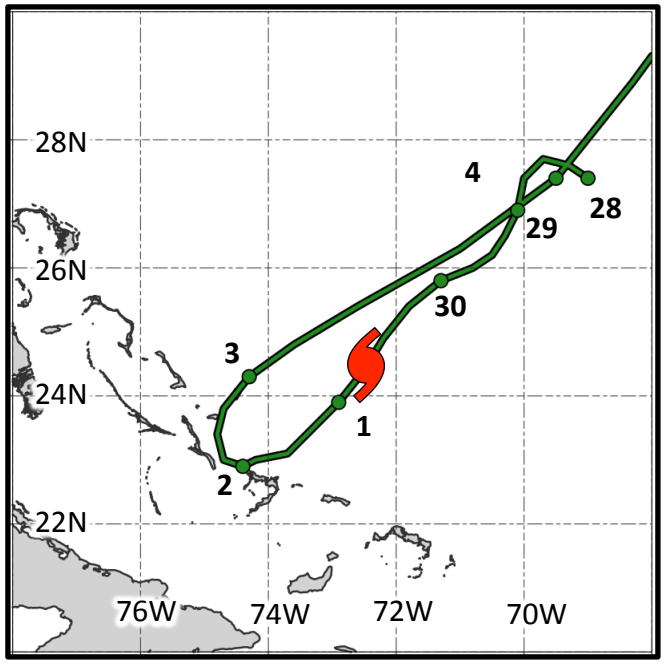

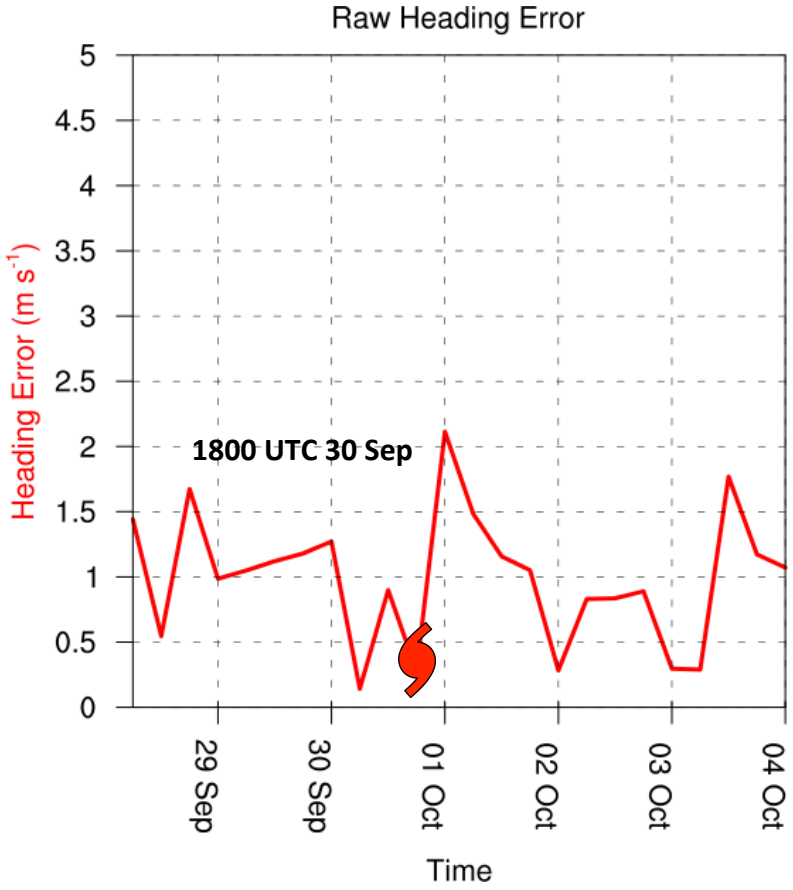

- **Pick period early in track evolution that had relatively low heading error**

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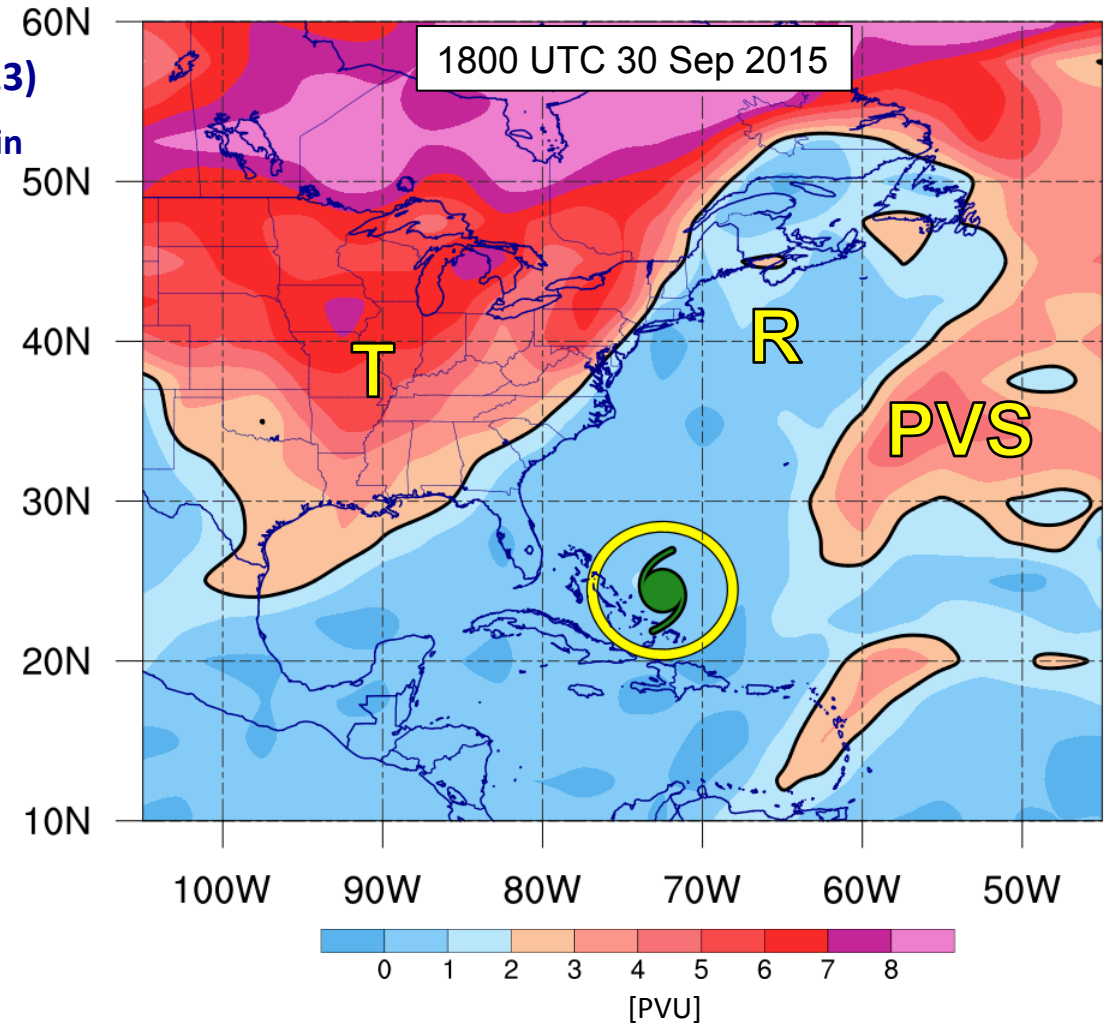
- **Use PV anomalies (+/- PVU) to diagnosis upper-tropospheric features related to steering of Joaquin**



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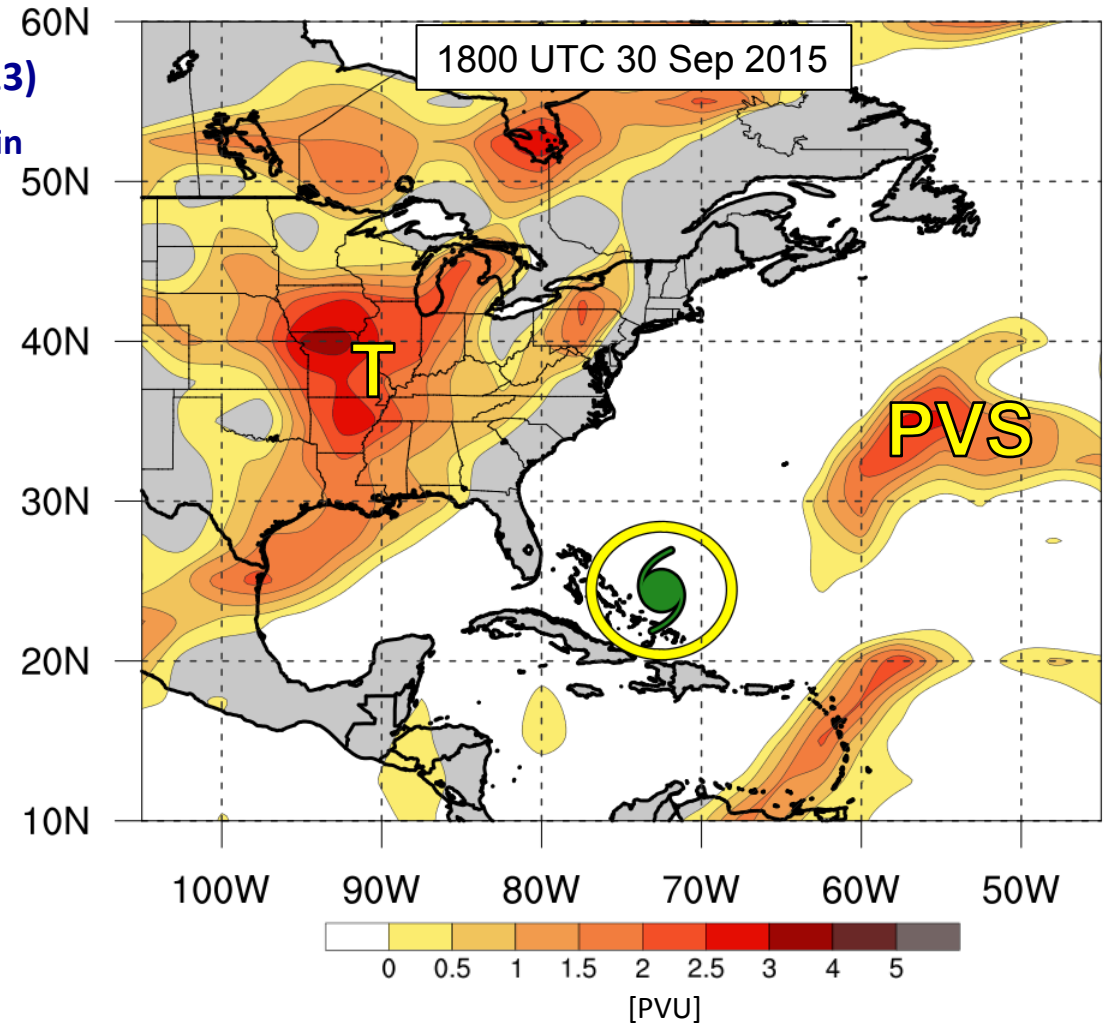

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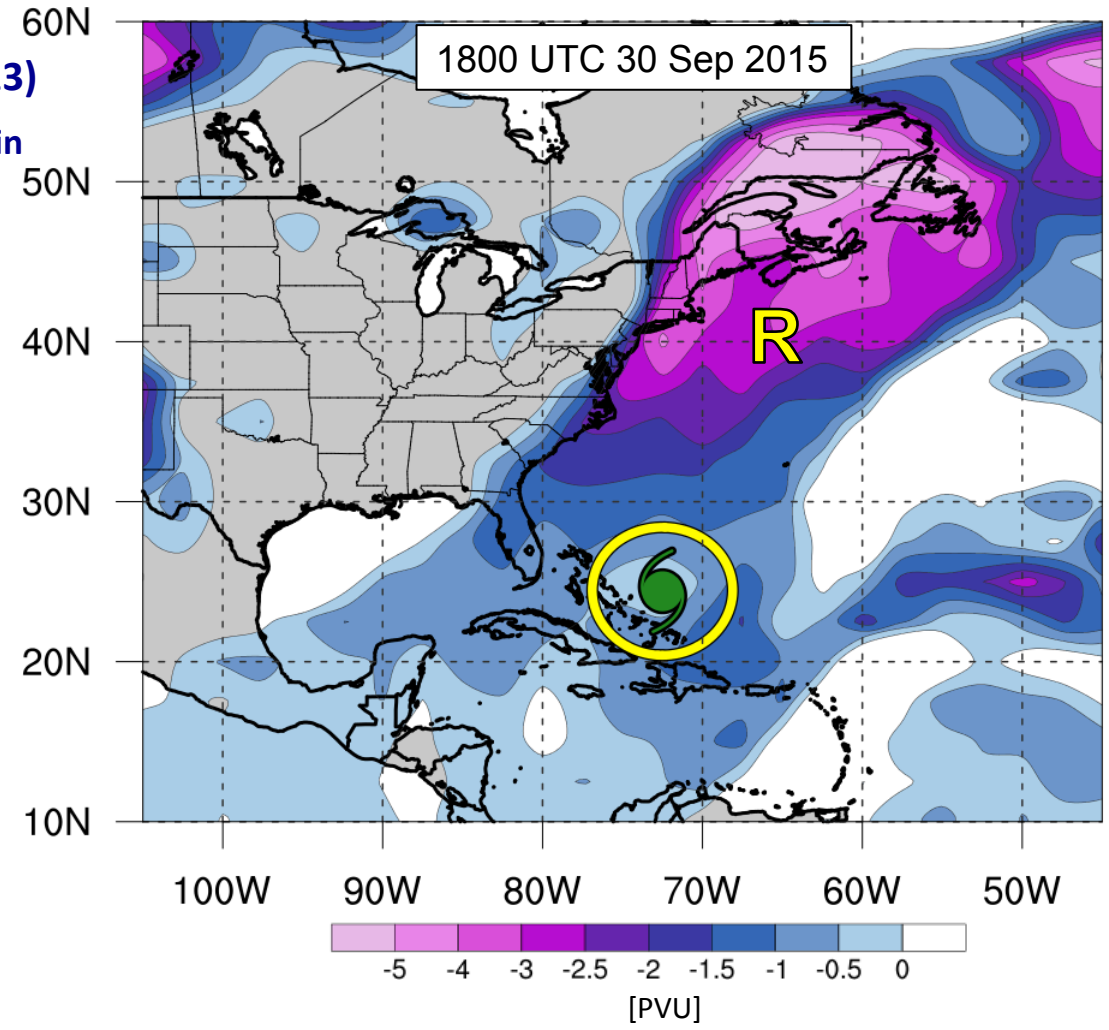
Test 2: **Negative PV Anomalies (isolates ridging)**



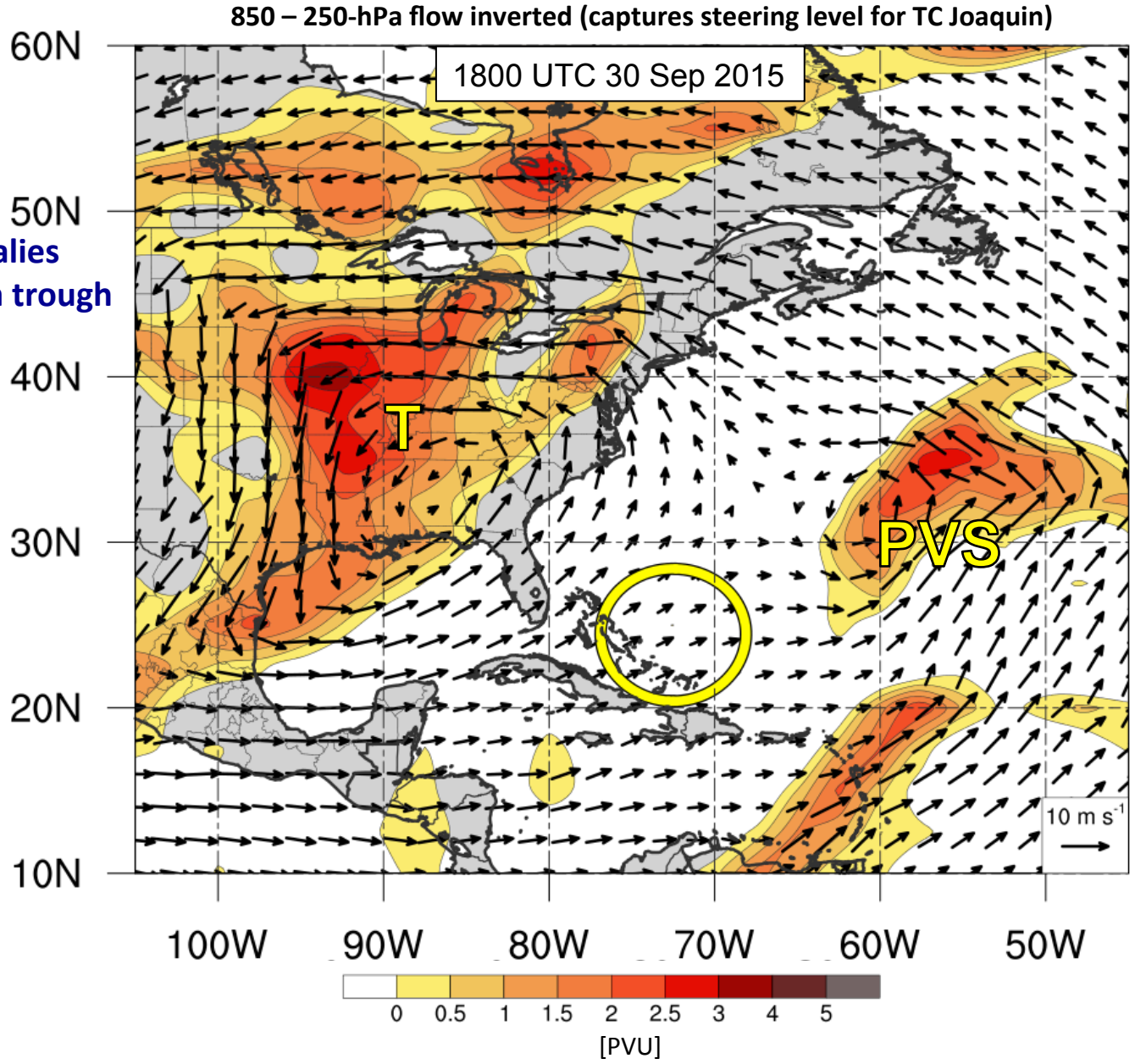
Steering Flow

- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \leq 4.0^{o}$**

Test 1 **Positive PV Anomalies (isolates upstream trough and PV streamer)**

Observations

- **CFSRv2 heading**
  61^{o} at 3.6 m s^{-1}
- **Actual TC motion:**
  213^{o} at 3.1 m s^{-1}



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Test 2 **Negative PV Anomalies (isolates ridging)**

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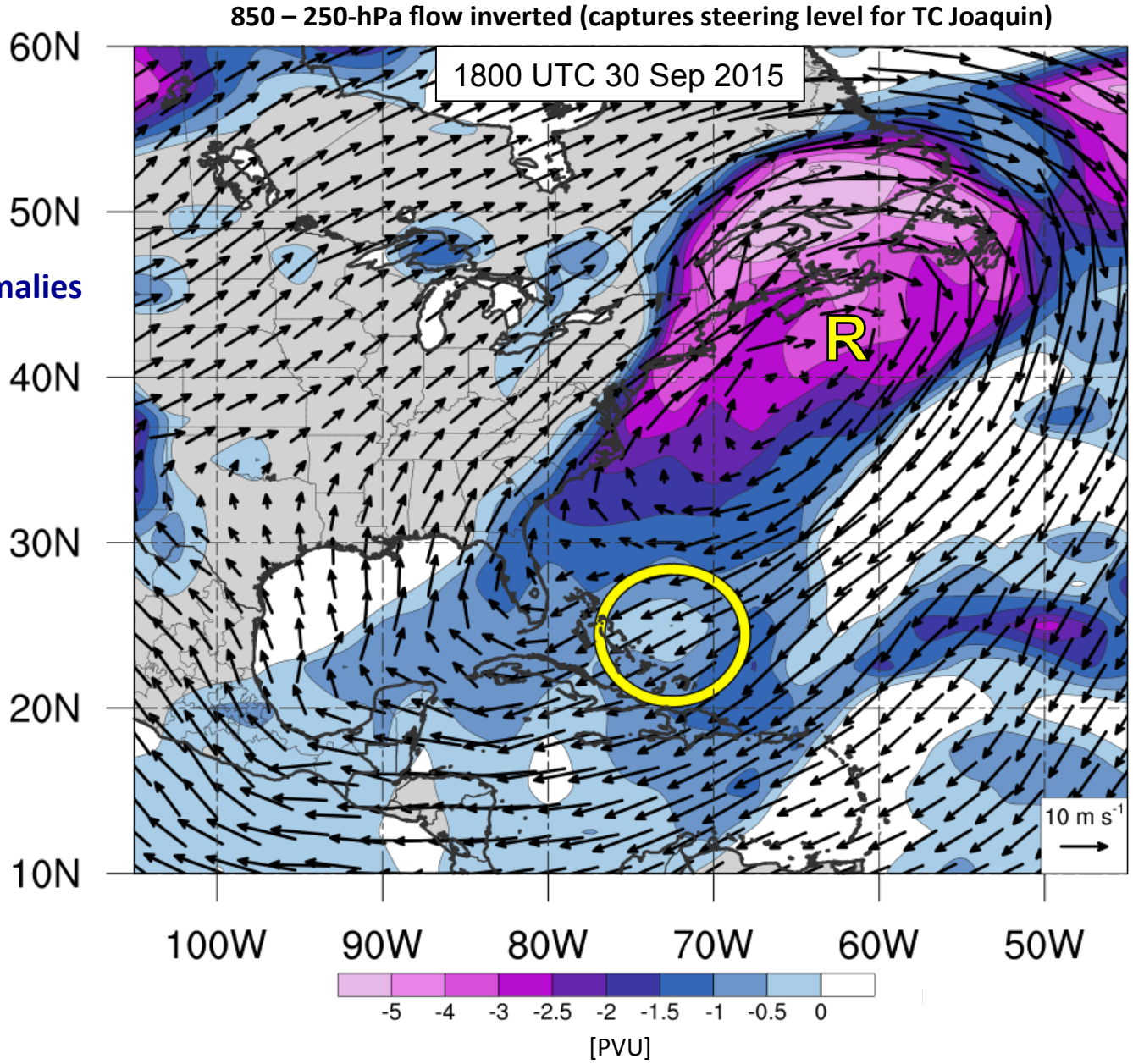
- **CFSRv2 heading 240^{o} at 10.2 m s^{-1}**
- **Actual TC motion: 213^{o} at 3.1 m s^{-1}**



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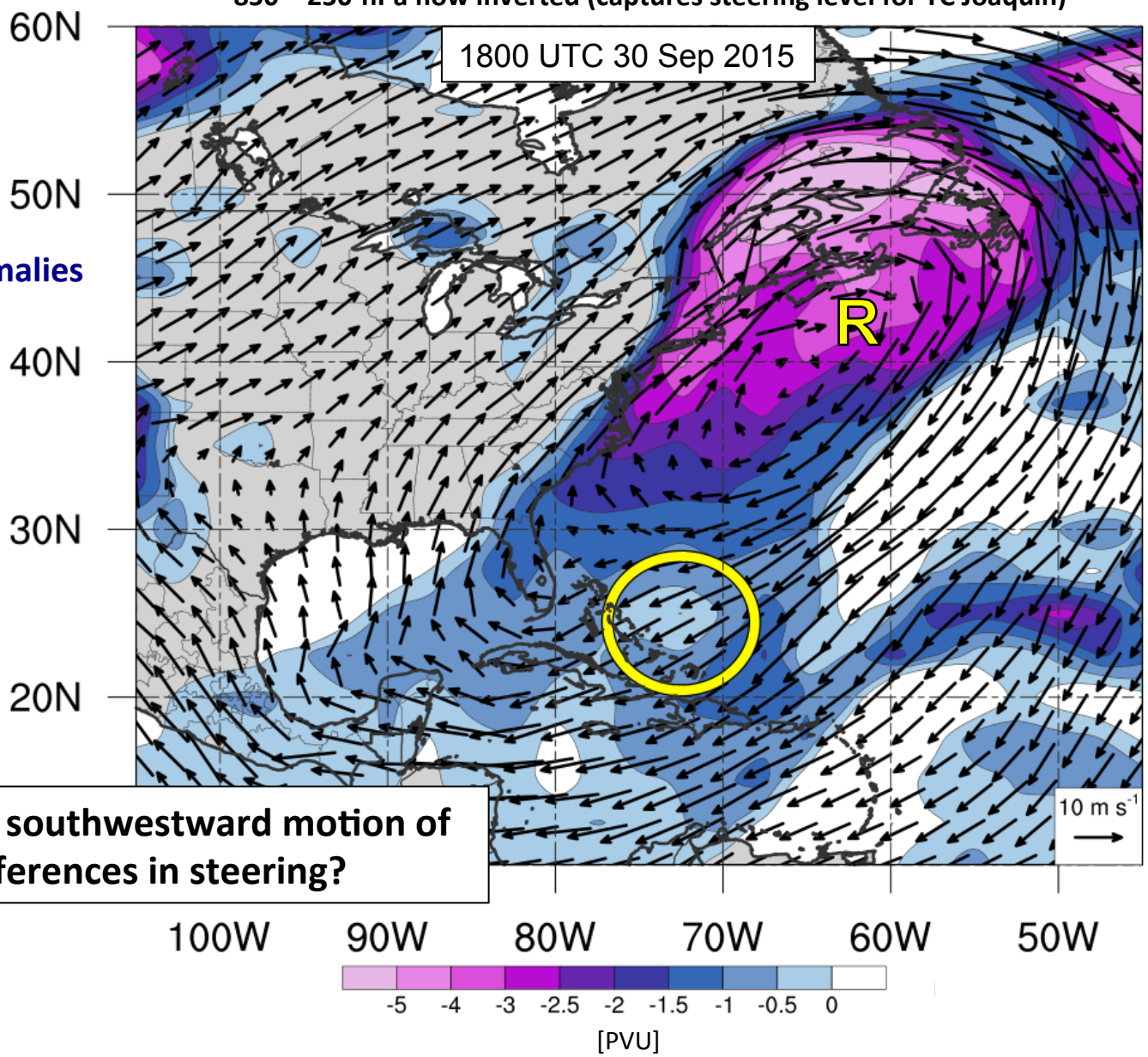

Are differences in the southwestward motion of Joaquin related to differences in steering?

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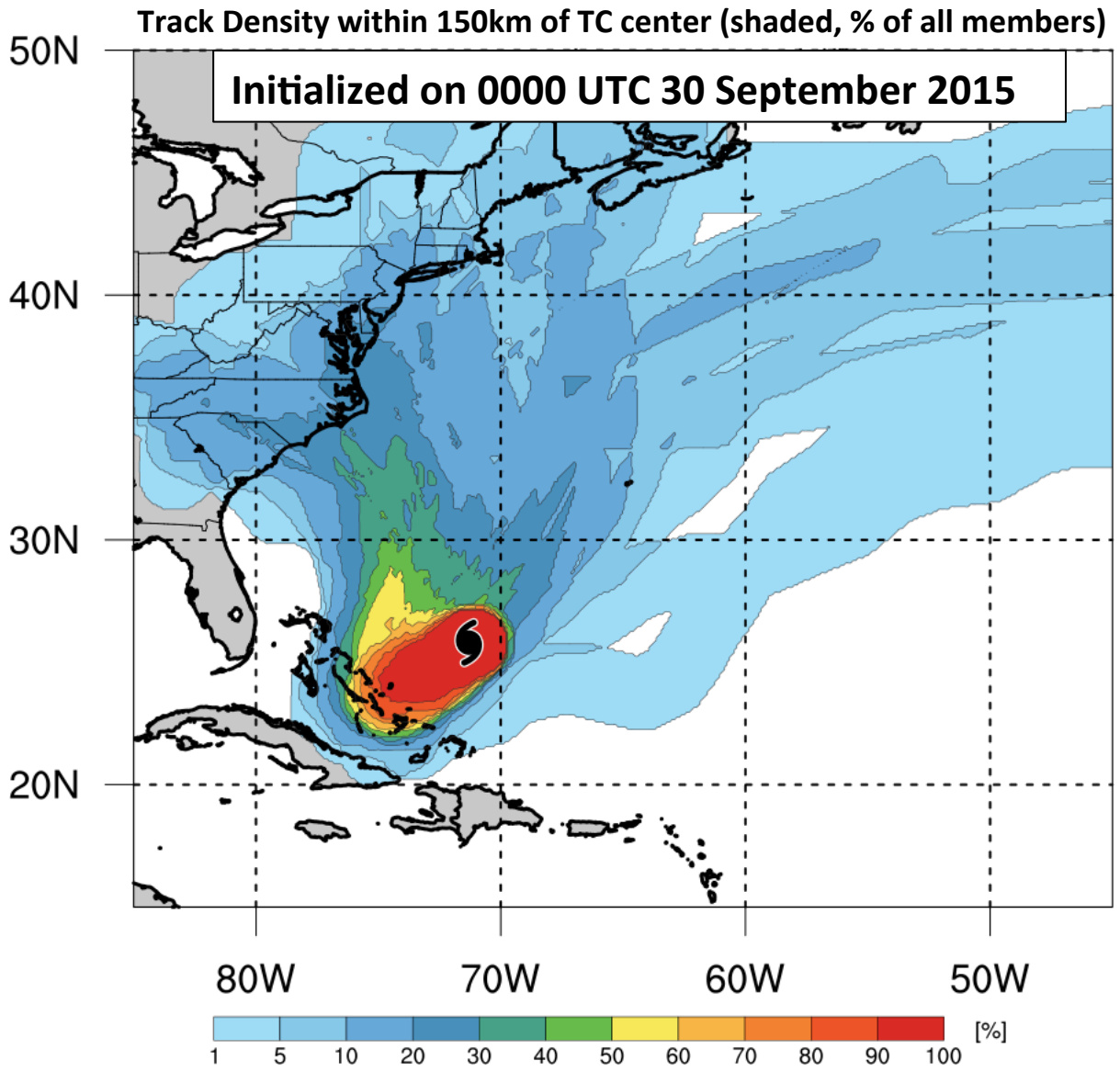
ECMWF Ensemble Prediction System (EPS)

- **Extreme spread in ensemble track forecast**
  - **Roughly equal probabilities of Joaquin striking South Carolina to Bermuda (10-30%)**
  - Verifying track on right side of guidance envelope
- Composite 10 rightmost tracks versus 10 leftmost tracks
  - Rightmost tracks best match actual Joaquin track



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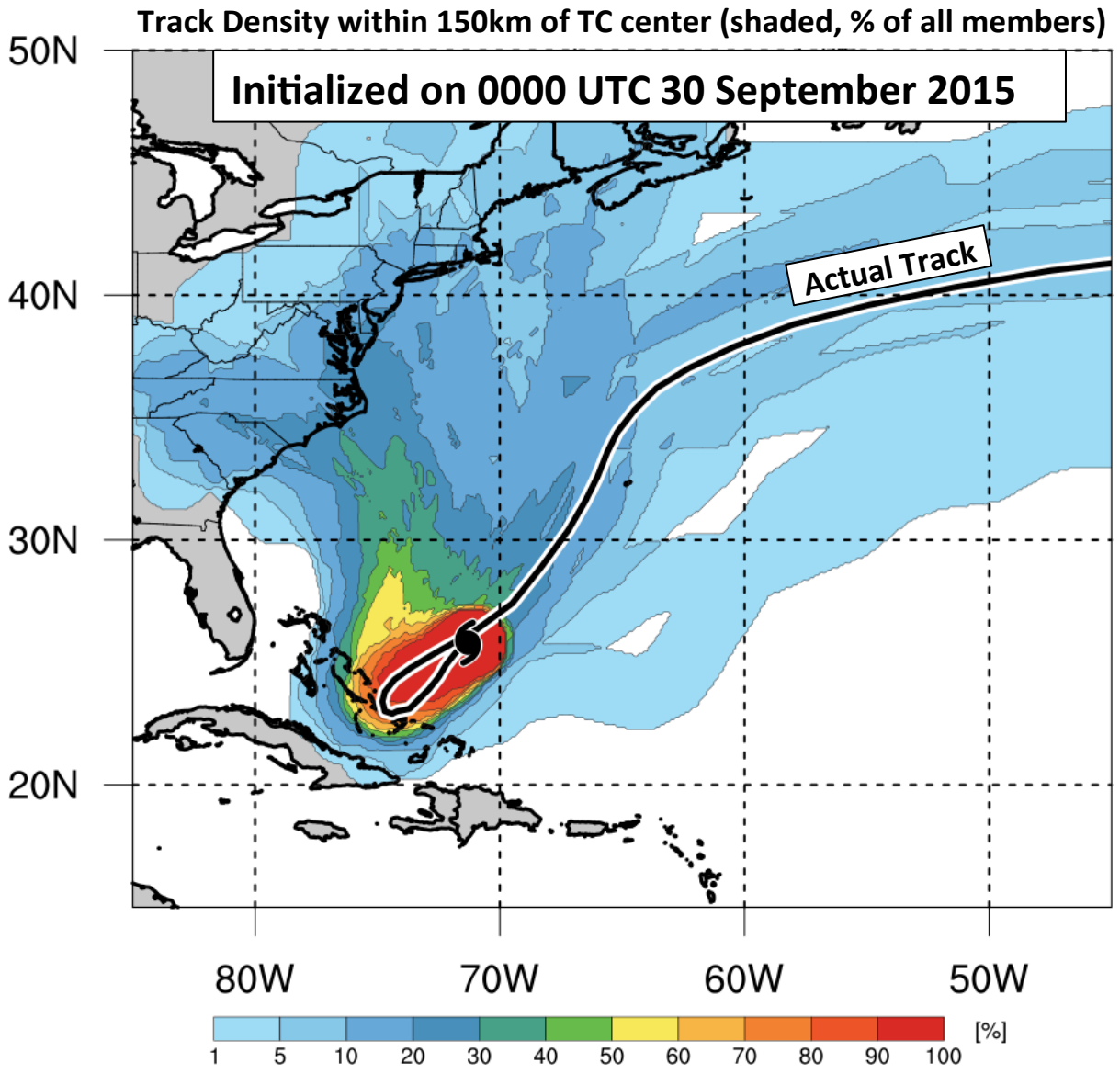

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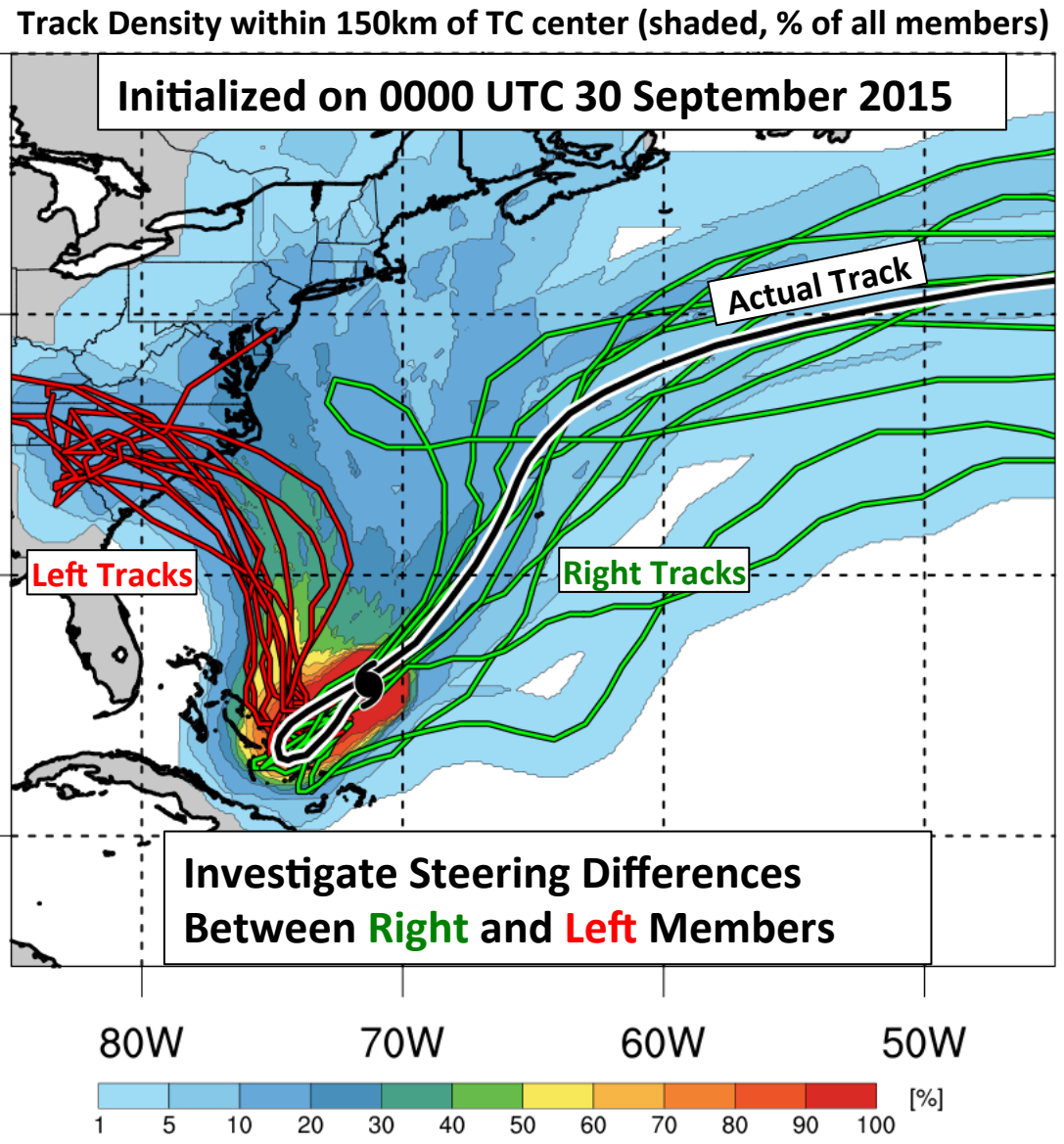


Ensemble Steering Differences

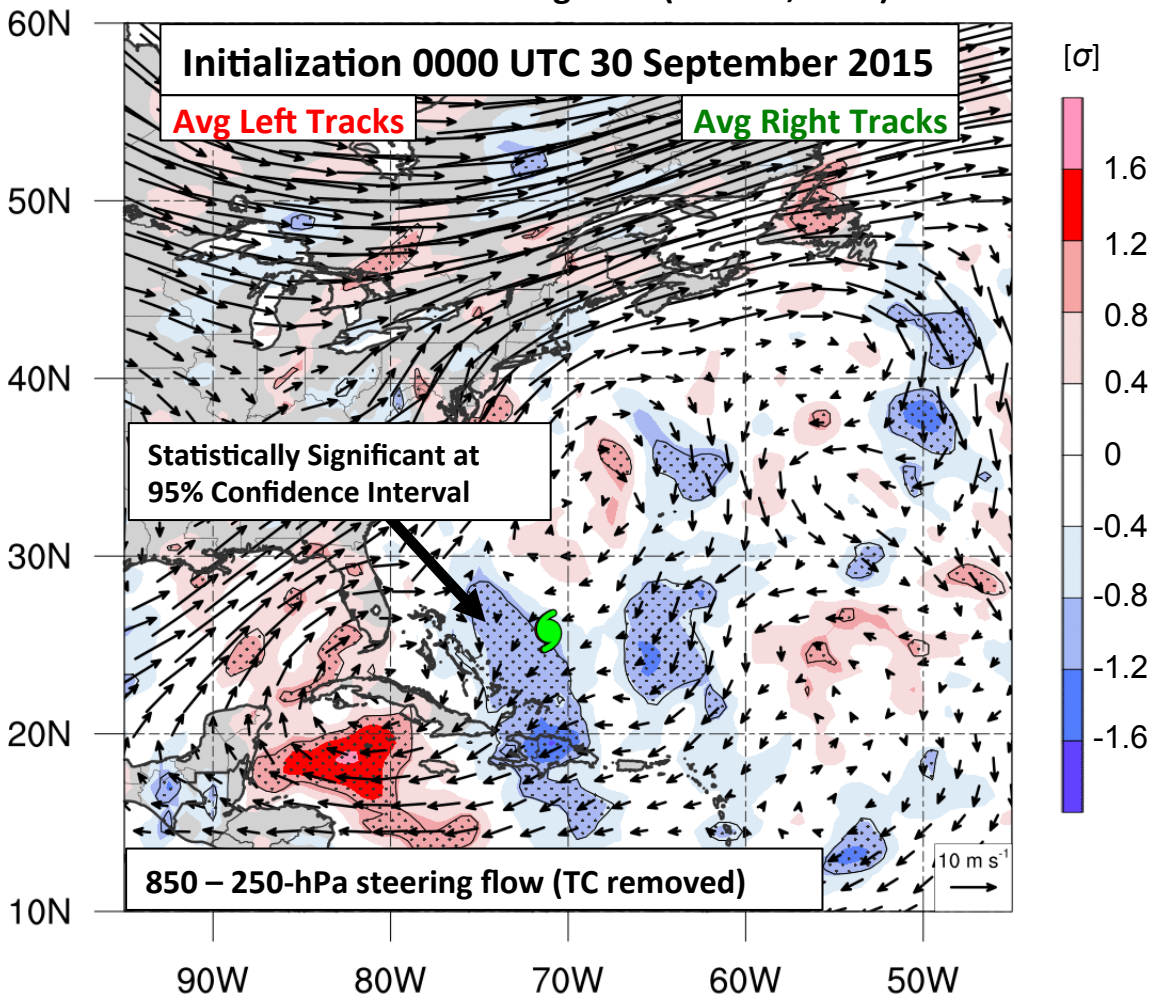
- **Standardized northerly meridional steering of right tracking members guides Joaquin further south first 24-36 hours**
  - **Statistically significant**
- **Standardized flow differences weaken by 48 hours**
  - **Perturbations no longer significant compared to ensemble mean**
  - **However, Joaquin's track is irreversibly altered**

$$\Delta x_i = \frac{\bar{x}_i^{Right} - \bar{x}_i^{Left}}{\sigma_{x_i}}$$

Difference between Right Mean and Left Mean

Standard Deviation of Entire EPS

Meridional Steering Wind Standardized Ensemble Difference (shaded), Ensemble Mean Steering Flow (vectors, m s^{-1})



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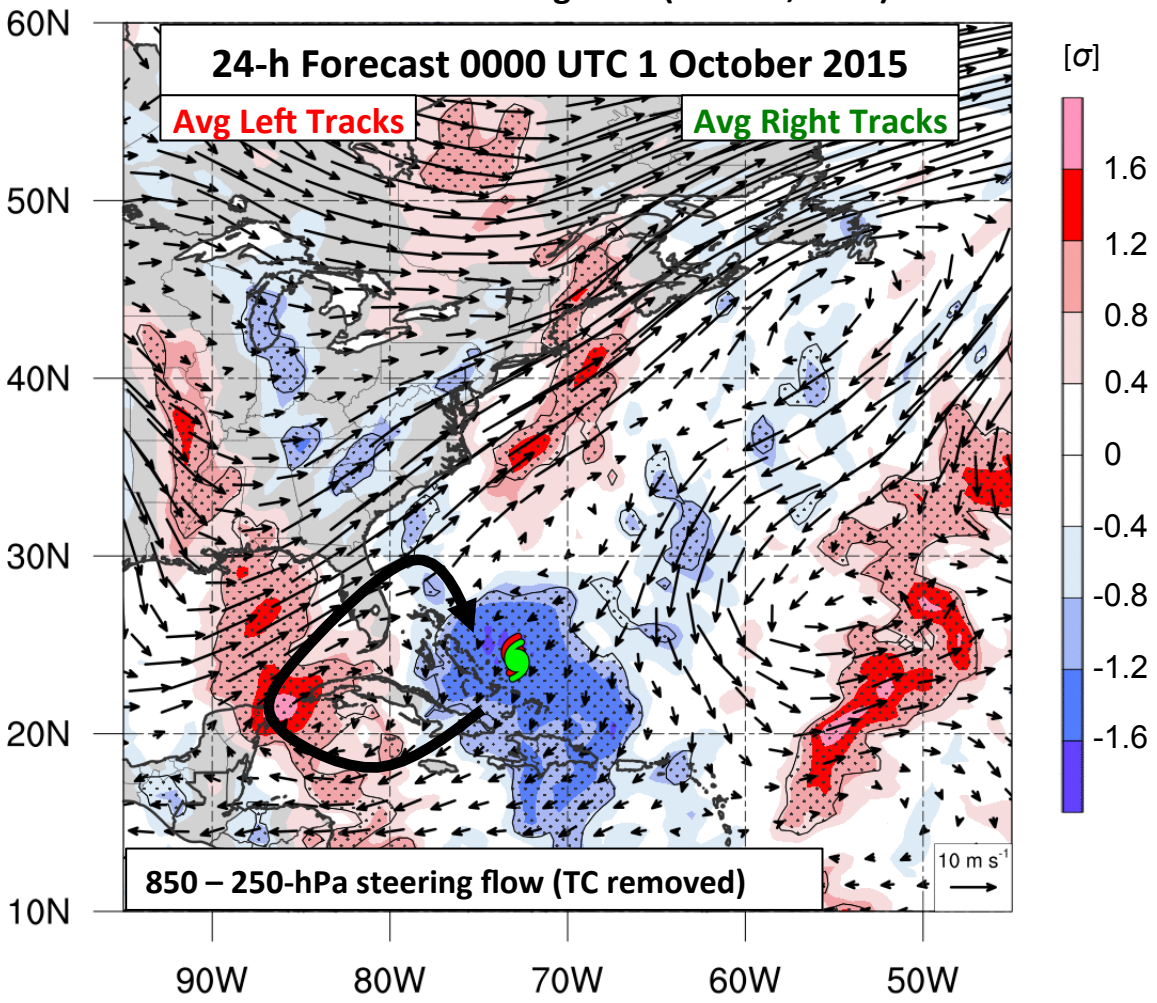

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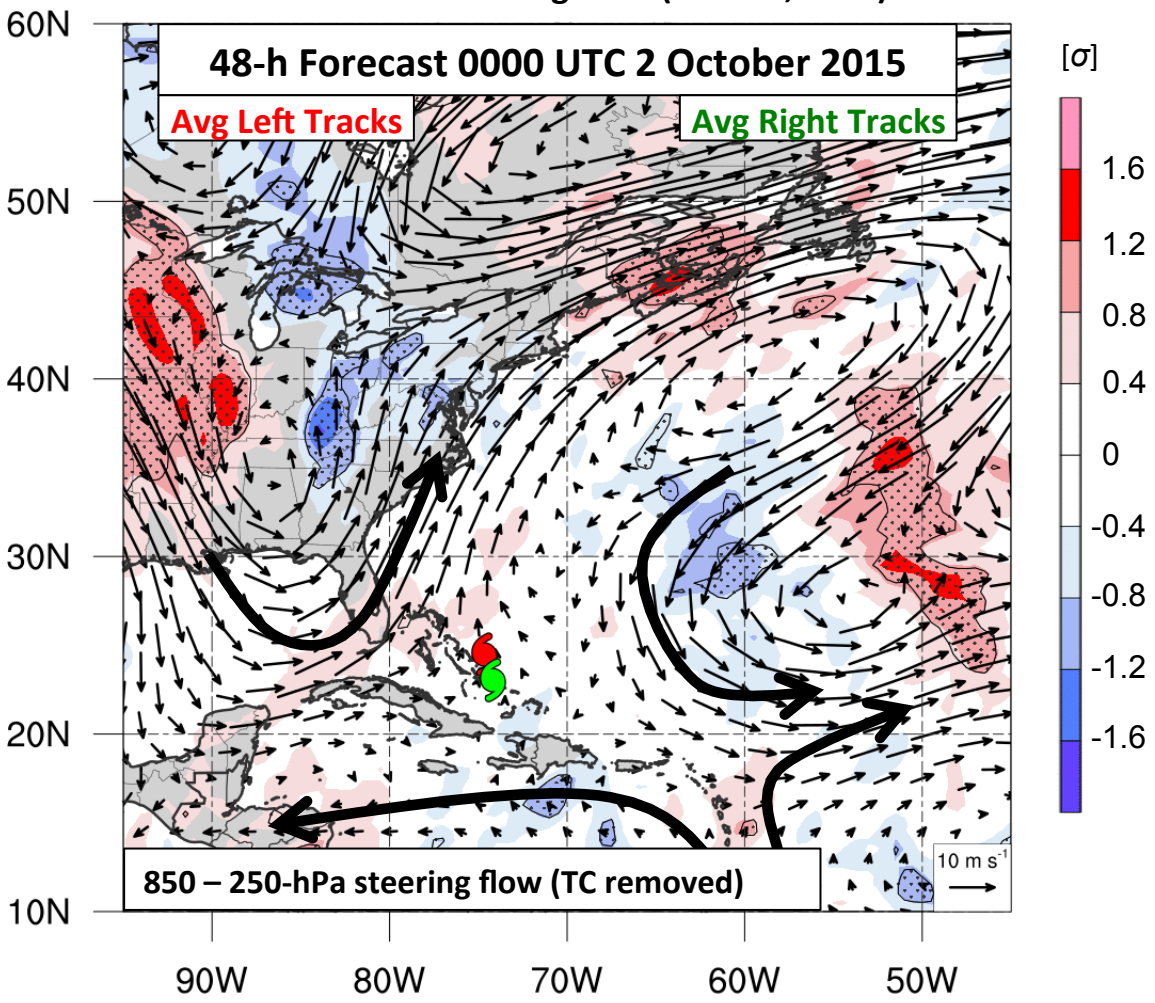

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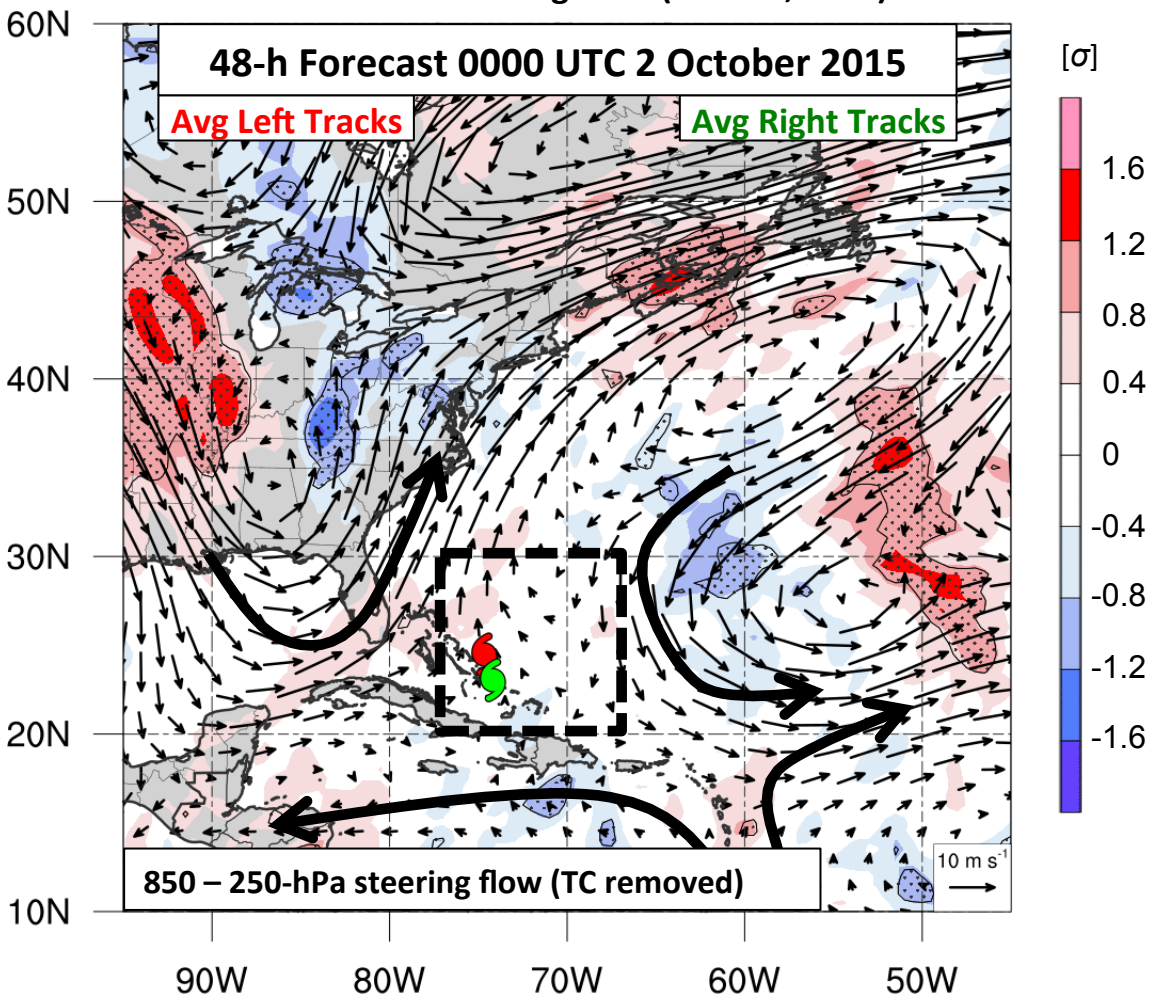
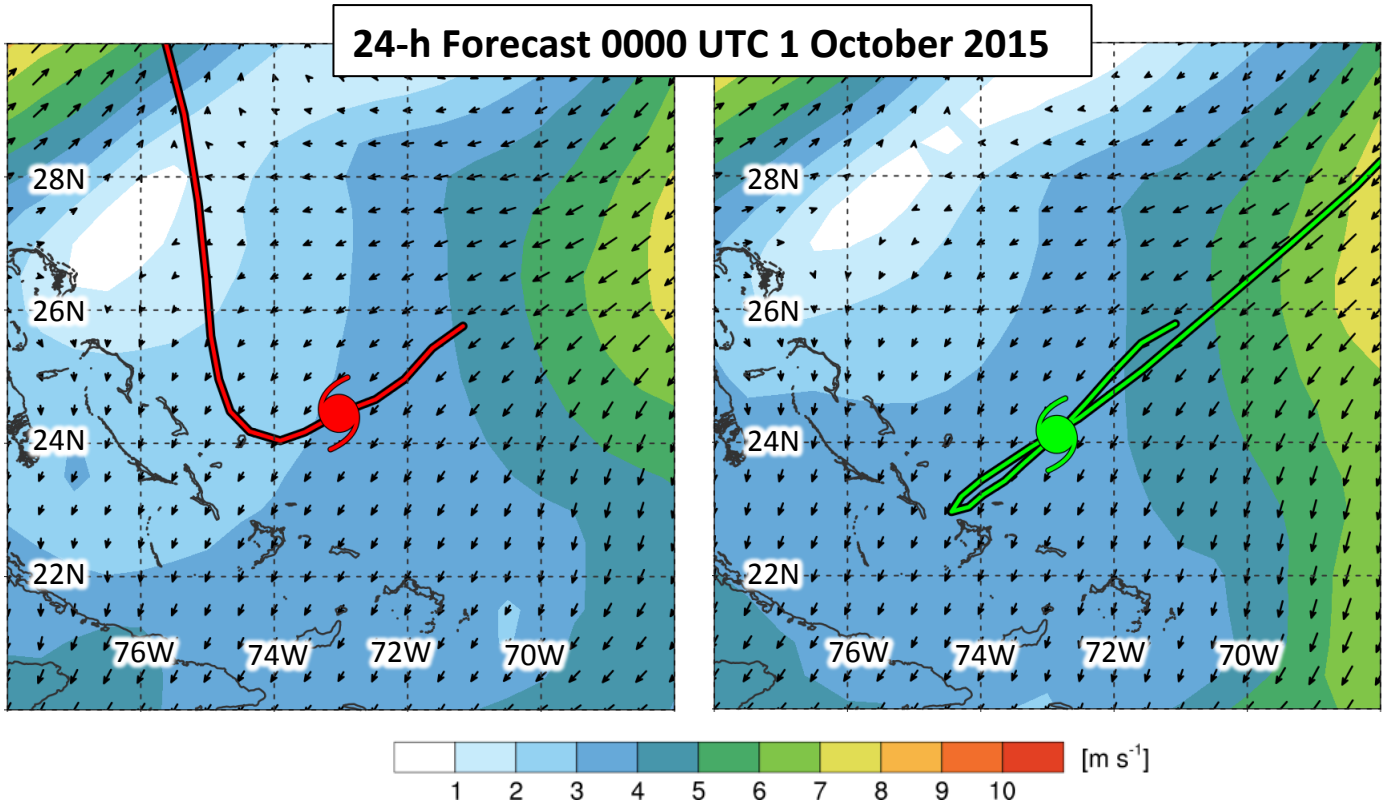


Ensemble Steering Differences

Composite Mean Steering Flow Magnitude (shaded, m s^{-1}), and direction (vectors)

Left Tracking Members **Right Tracking Members**



- **Stronger northerly meridional flow initially steers right members south**
- **Weaker northerly meridional flow keeps left members north of COL**
- **Right members end up south of COL, on an out to sea track**

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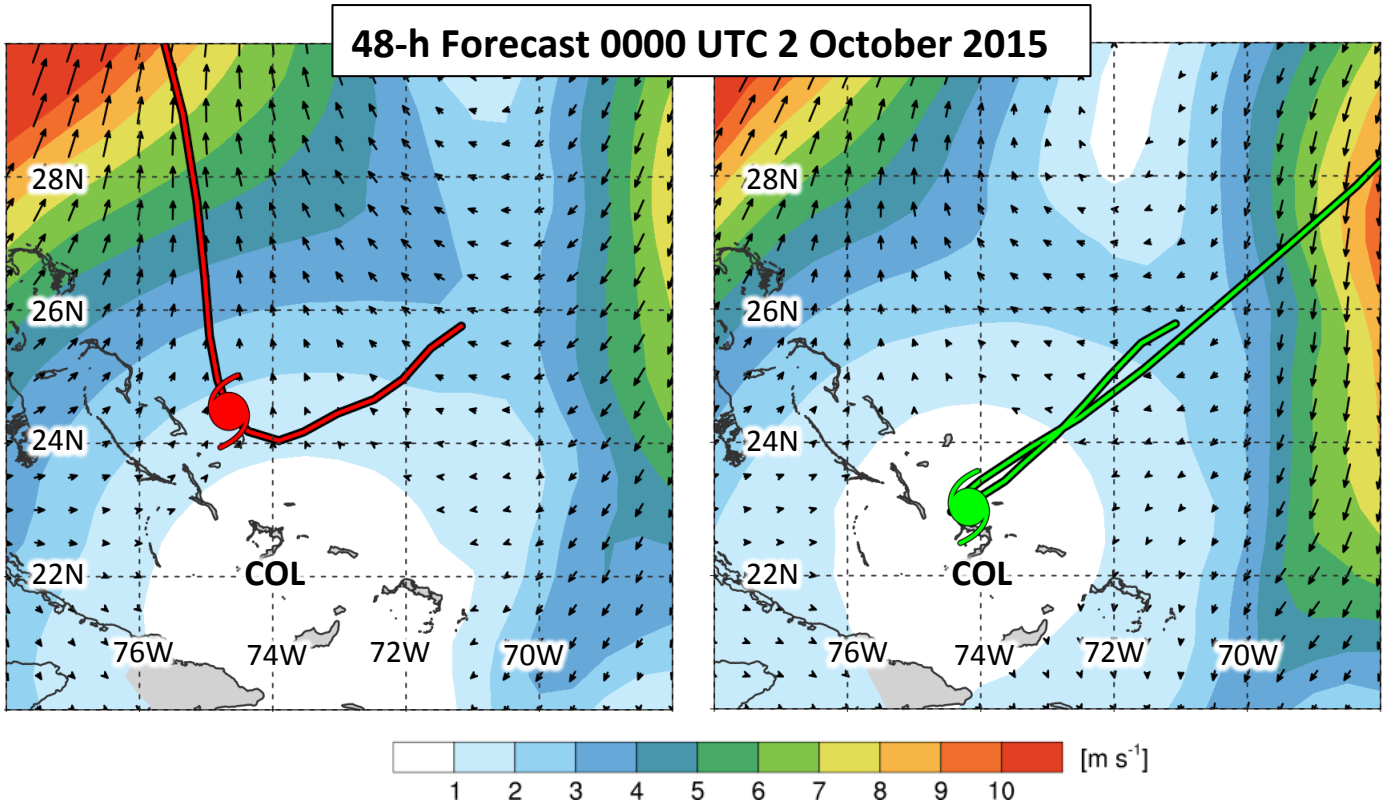

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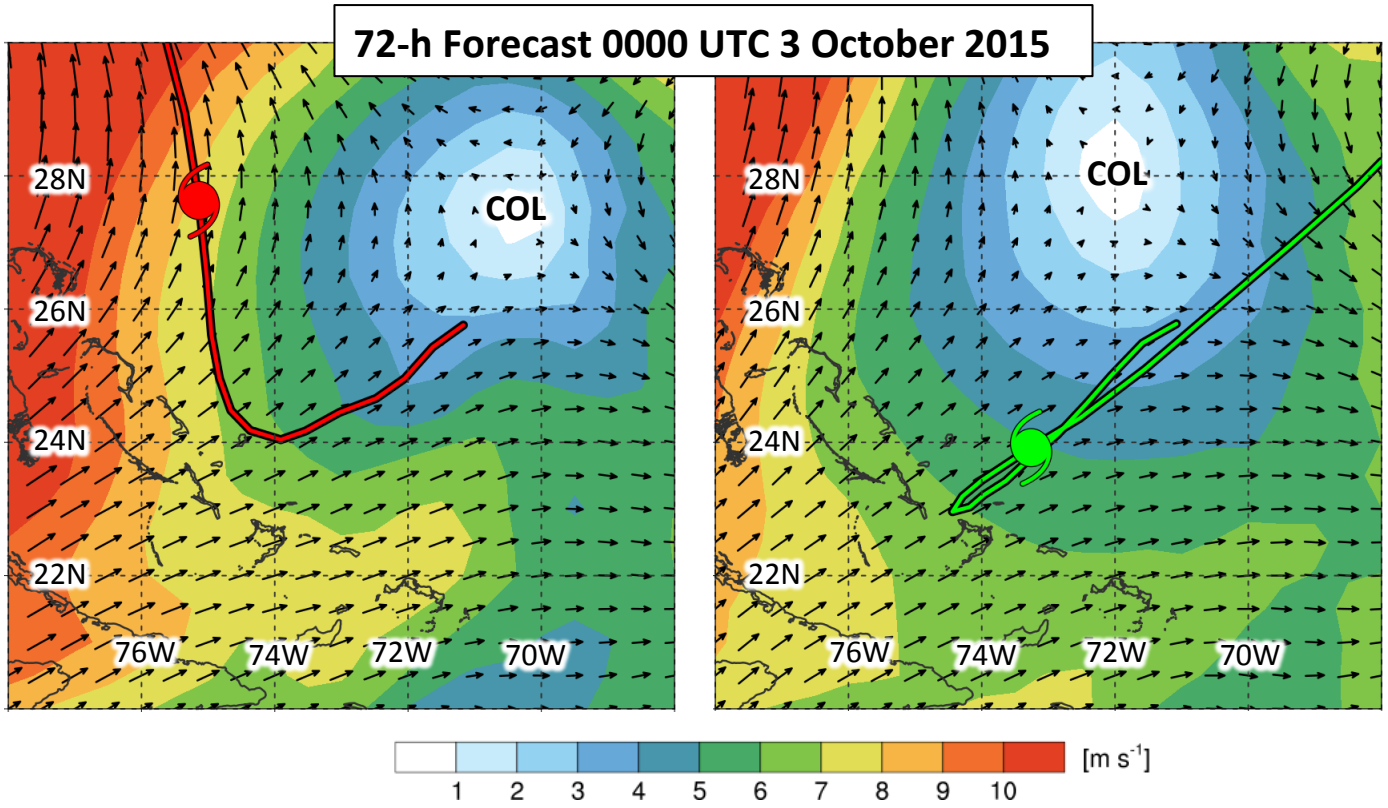
Composite Mean Steering Flow Magnitude (shaded, m s^{-1}), and direction (vectors)

Left Tracking Members **Right Tracking Members**



- Stronger northerly meridional flow initially steers right members south
- Weaker northerly meridional flow keeps left members north of COL
- Right members end up south of COL, on an out to sea track

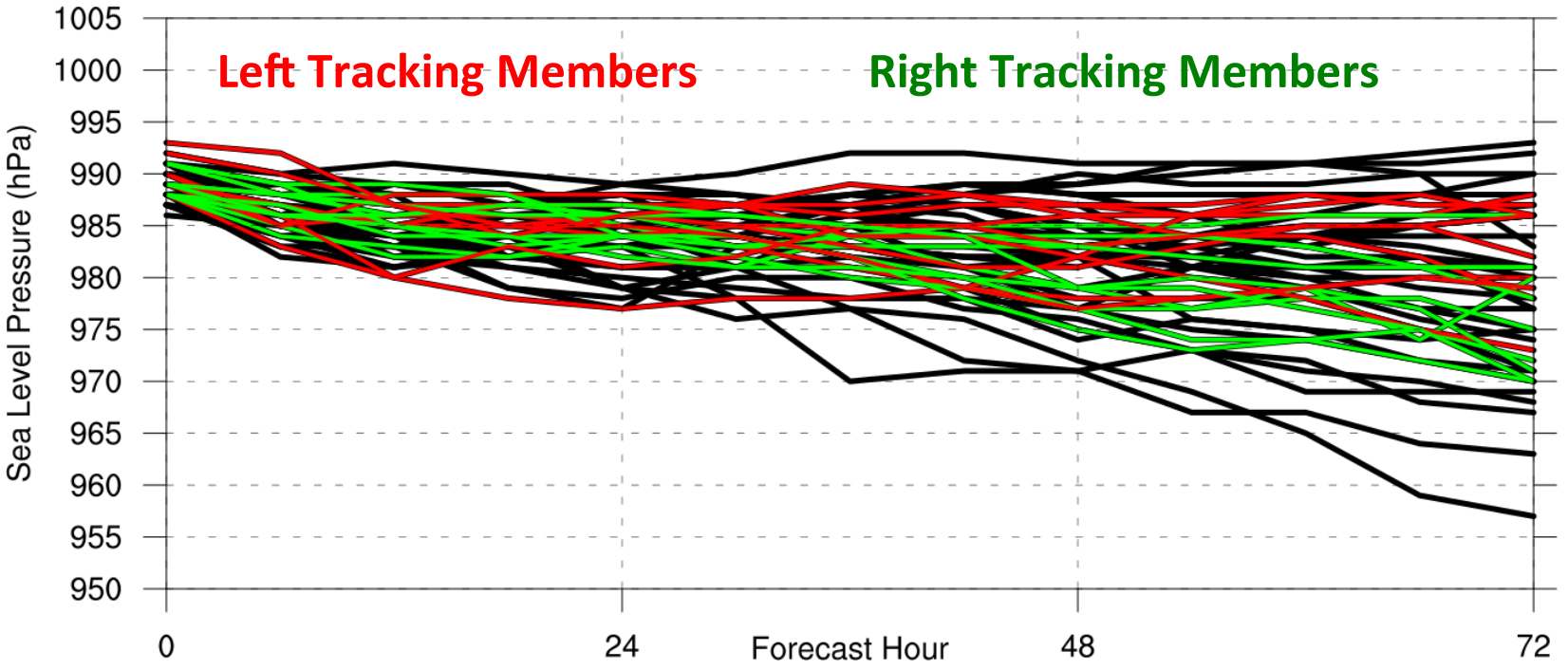
Conclusions

- **Steering of Joaquin at 0000 UTC 1 October from CFSR:**
  - **Southwest motion of Joaquin driven primarily by deep-layer ridge**
  - **Partially offset from PV streamer and upstream trough**
  - **Joaquin embedded in region of relatively light flow (COL)**
- **Differences in Joaquin's steering from 0000 UTC 30 September ECMWF EPS**
  - **Compared 10 leftmost members versus 10 rightmost members**
  - **Stronger northerly meridional steering flow pushes Joaquin southward in right tracking members**
  - **Track differences first 24-36 hours place Joaquin on opposite sides of COL, leading to track divergence**
- **Future Work**
  - **Investigate steering differences by synoptic feature**
  - **Investigate dynamical reasons for steering perturbations between left and right tracking members**

Extra Slides

Left/Right Intensity Differences

Using sea level pressure (hPa)

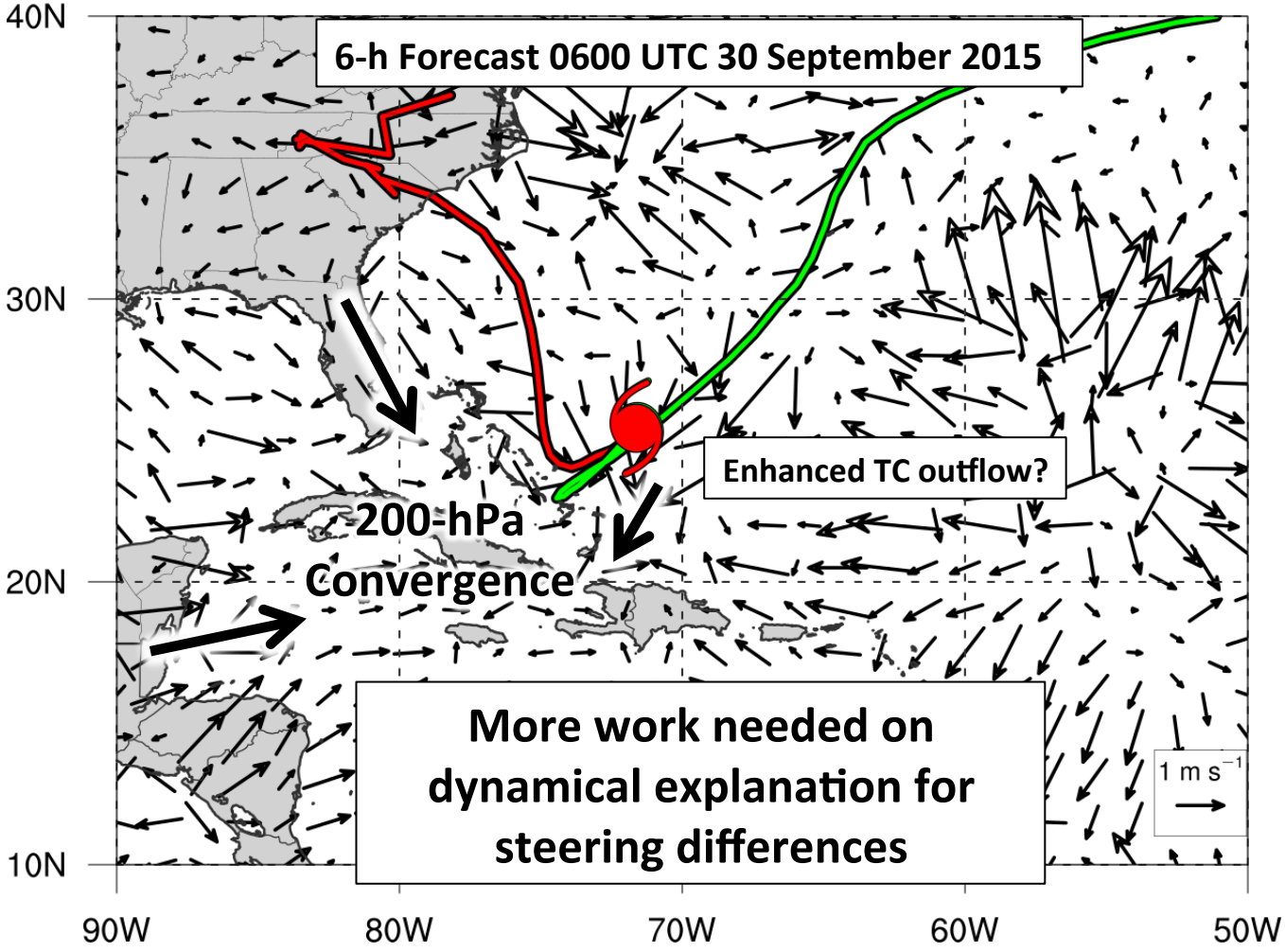


0000 UTC 30 Sep **0000 UTC 1 Oct** **0000 UTC 2 Oct** **0000 UTC 3 Oct**

Left/Right Divergent Wind Differences

Irrotational flow differences between Right and Left members

$$\bar{\chi}_i^{Right} - \bar{\chi}_i^{Left}$$



Piecewise Vorticity Inversion

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

- **Adapted from Galarneau and Davis (2013)**

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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

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

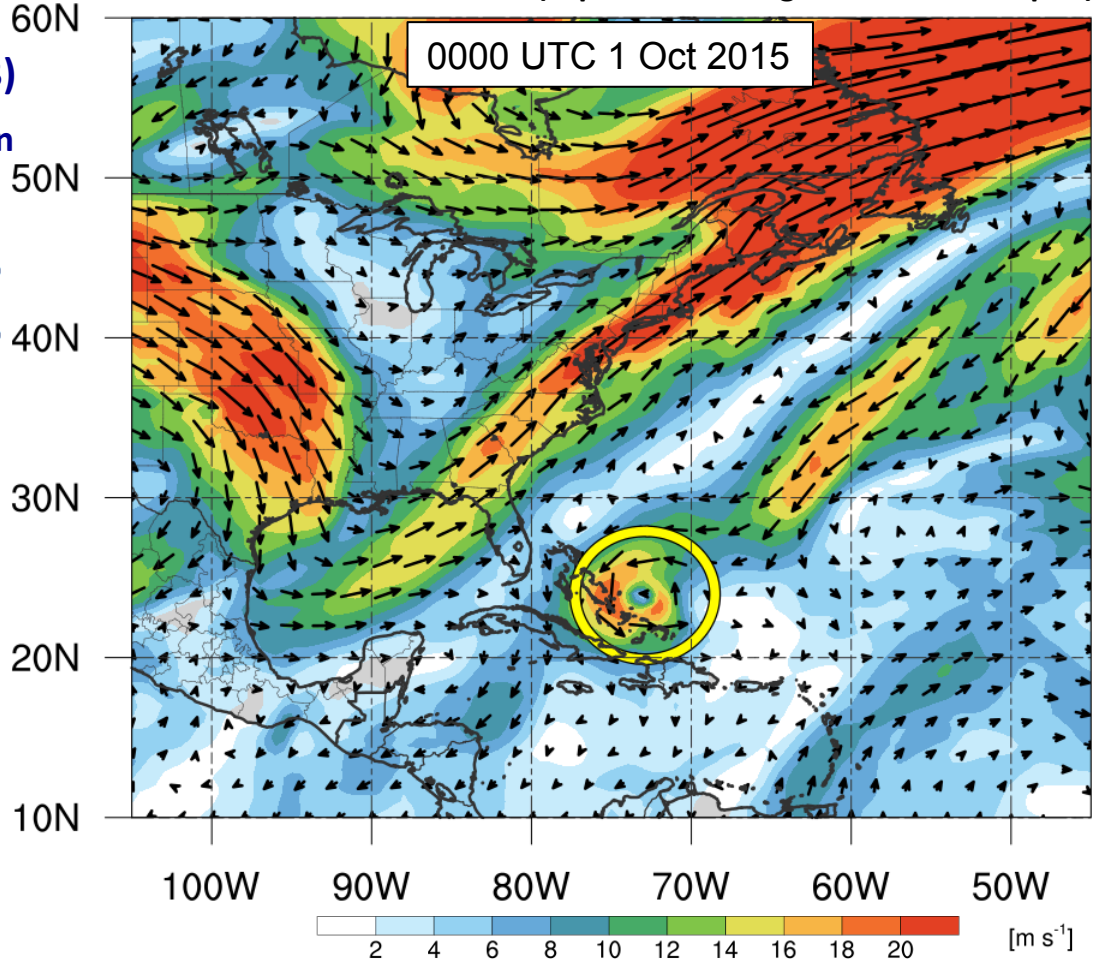
Nondivergent Winds — **Irrotational Winds**

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

Total Wind

- Remove TC Joaquin vortex
- $r_{Joaquin} \geq 4.0^o$
- Calculate heading imparted by CFSRv2 layer mean flow
- Compare to actual heading from NHC track

850 – 250-hPa flow inverted (captures steering level for TC Joaquin)



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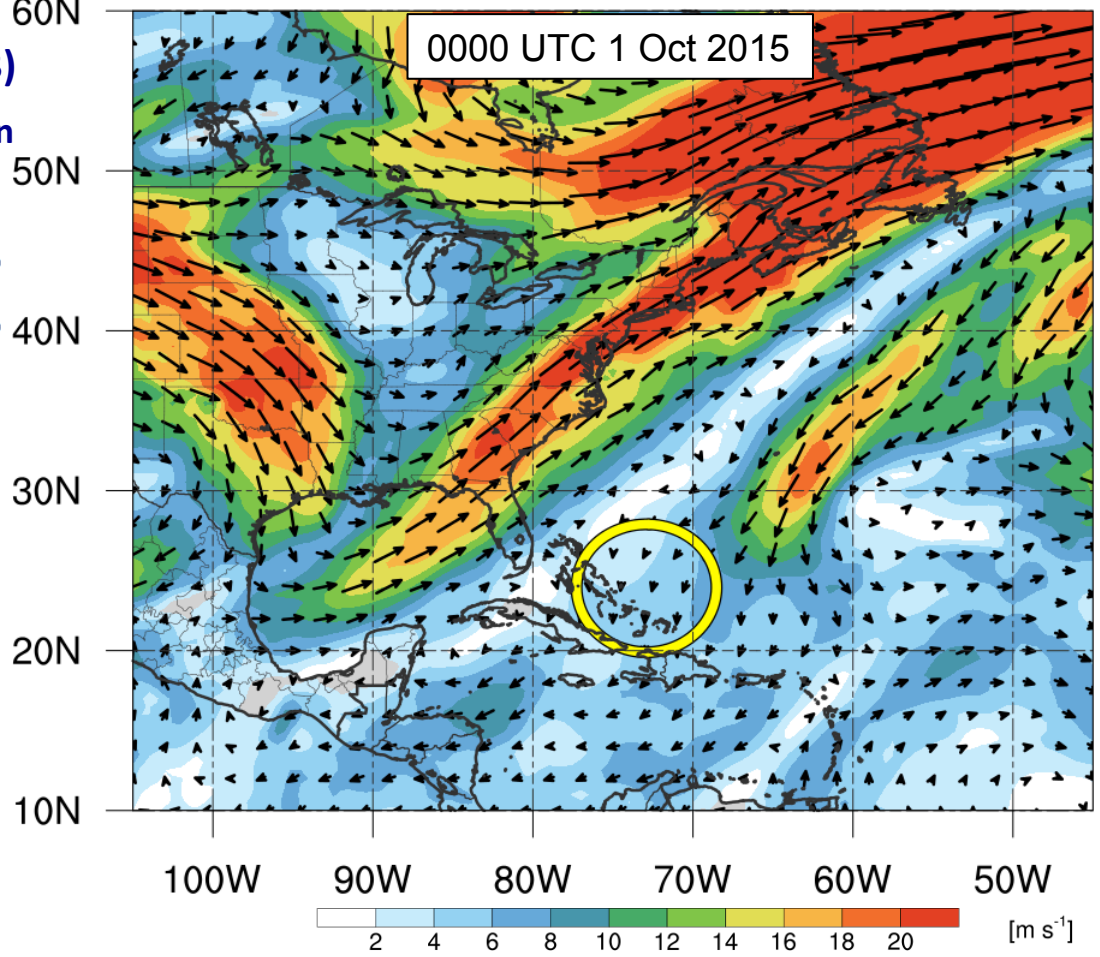

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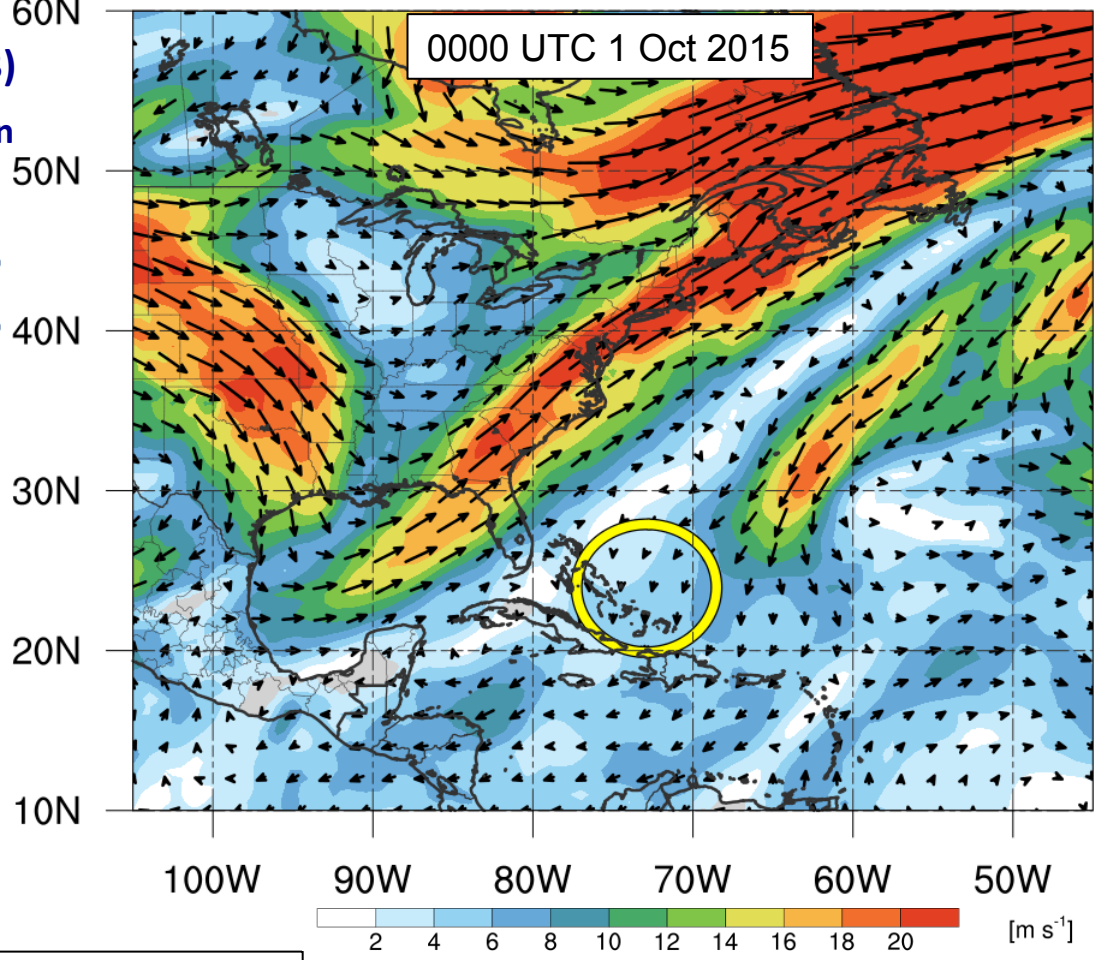
Nondivergent Winds — **Irrotational Winds**

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

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**

850 – 250-hPa flow inverted (captures steering level for TC Joaquin)



12.4° at 4.3 m s^{-1}

39.1° at 3.0 m s^{-1}

When does CFSR capture steering of Joaquin best?

Piecewise Vorticity Inversion

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

- **Adapted from Galarneau and Davis (2013)**

Inverted vorticity and divergence used to obtain nondivergent and irrotational winds

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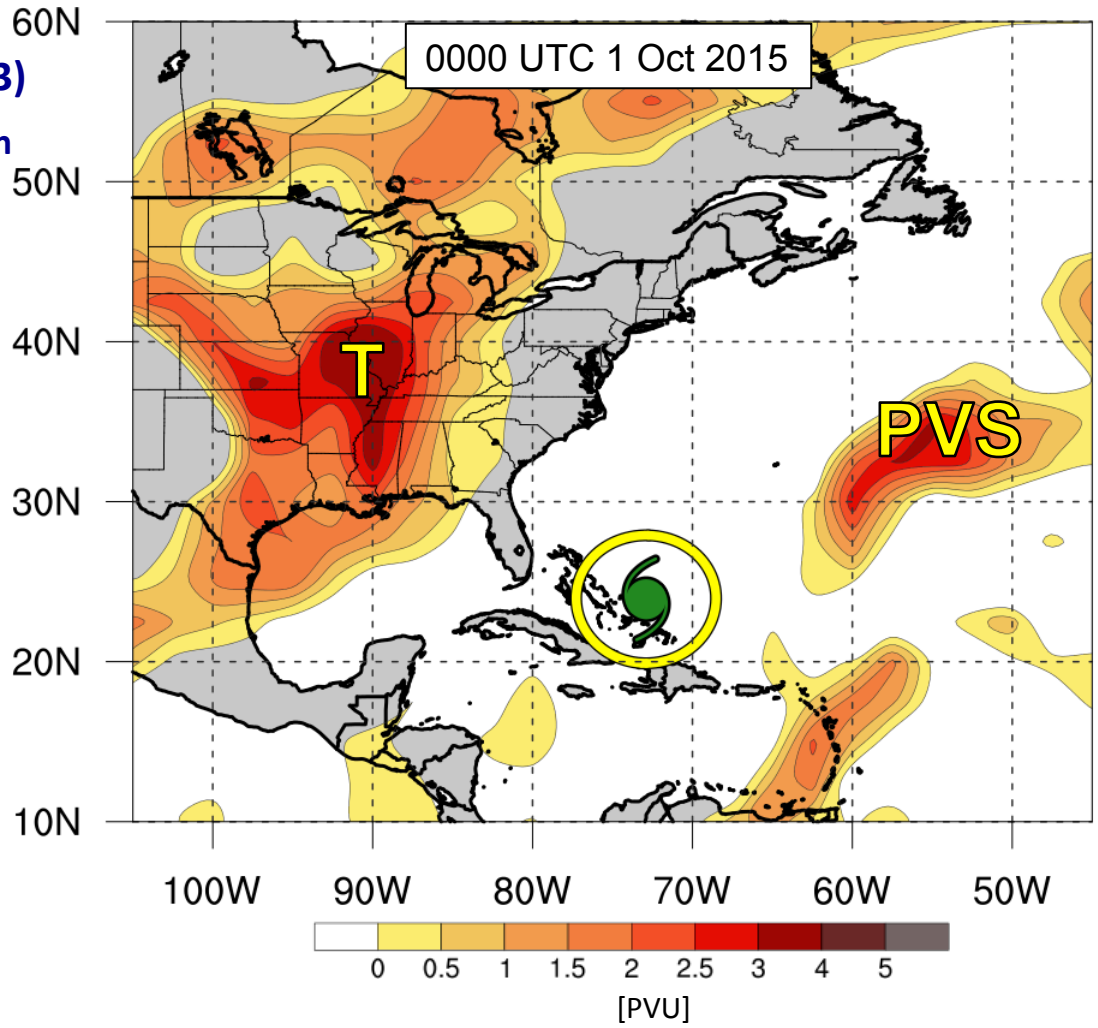
Nondivergent Winds — **Irrotational Winds**

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

Total Wind

- **Remove TC Joaquin vortex**
- **$r_{Joaquin} \geq 4.0^o$**
- **Use PV anomalies (+/- PVU) to diagnosis upper-tropospheric features related to steering of Joaquin**



Test 1 **Positive PV Anomalies (isolates upstream trough and PV streamer)**

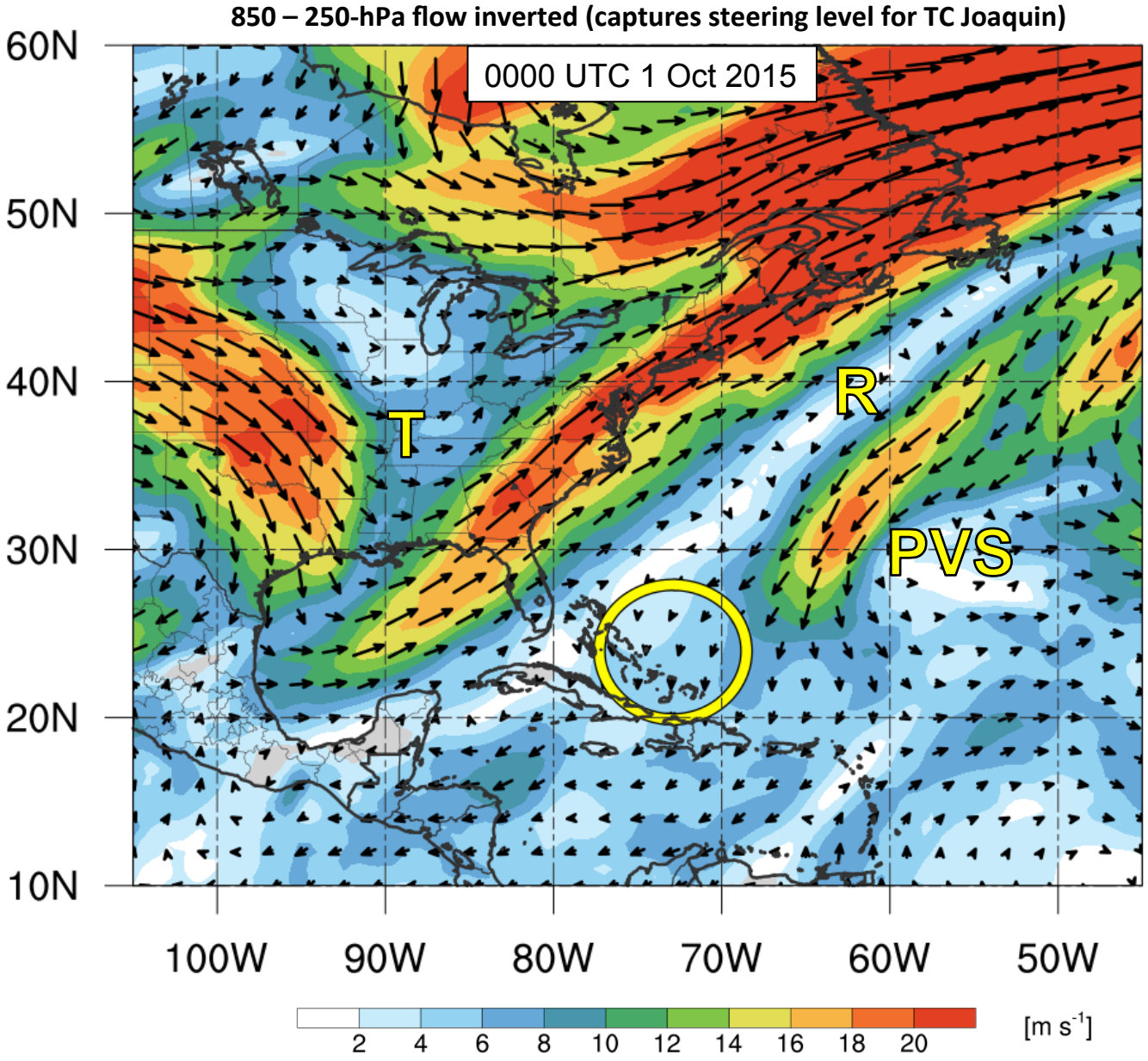
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 4.0^{o}$

Steering

Observations

- CFSRv2 heading 12^{o} at 4.3 m s^{-1}
- Actual TC motion: 39^{o} at 3.0 m s^{-1}



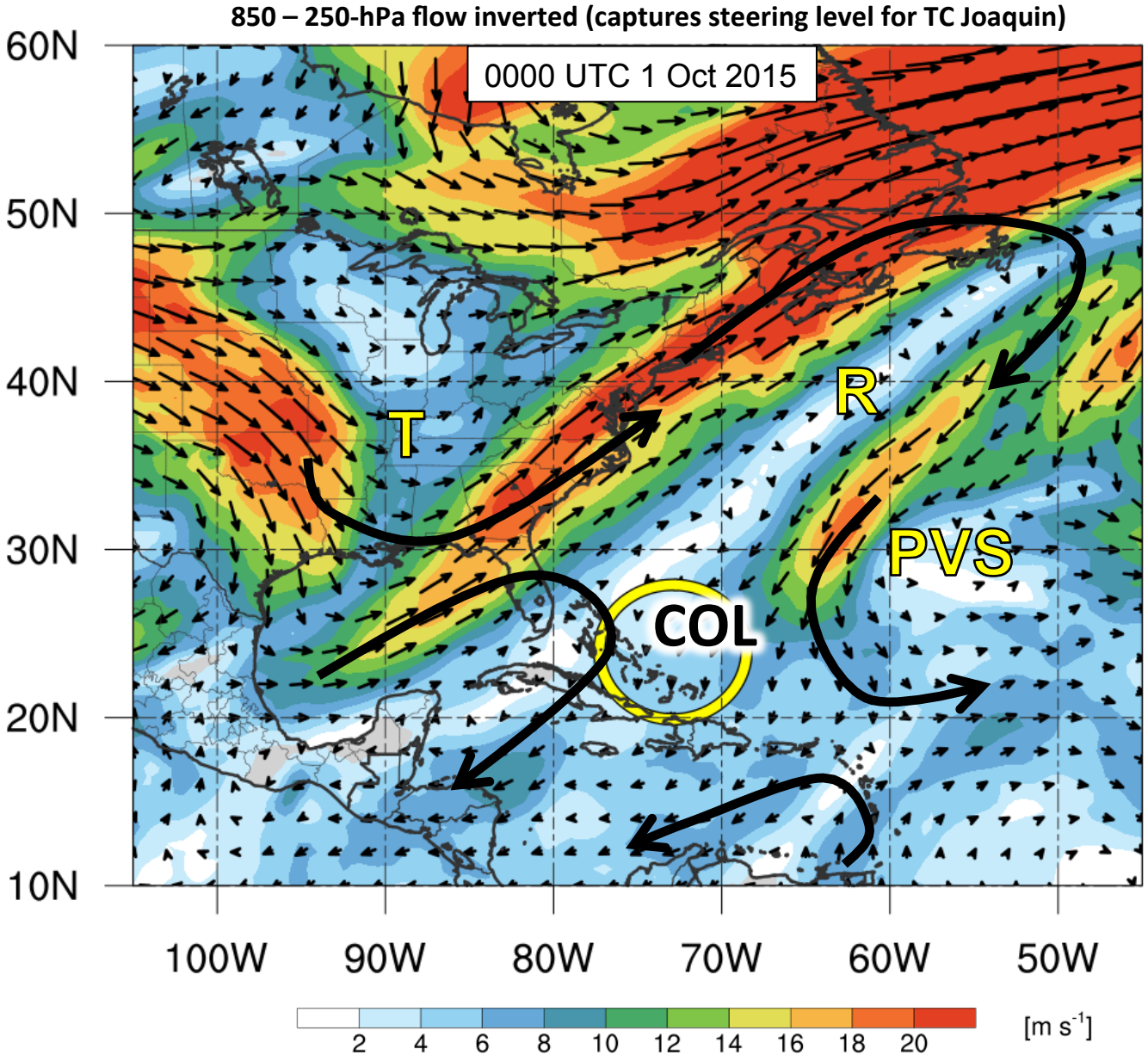
Steering Flow

- Removal of TC Joaquin vortex
- $r_{Joaquin} \geq 4.0^{o}$

Steering

Observations

- CFSRv2 heading 12^{o} at 4.3 m s^{-1}
- Actual TC motion: 39^{o} at 3.0 m s^{-1}



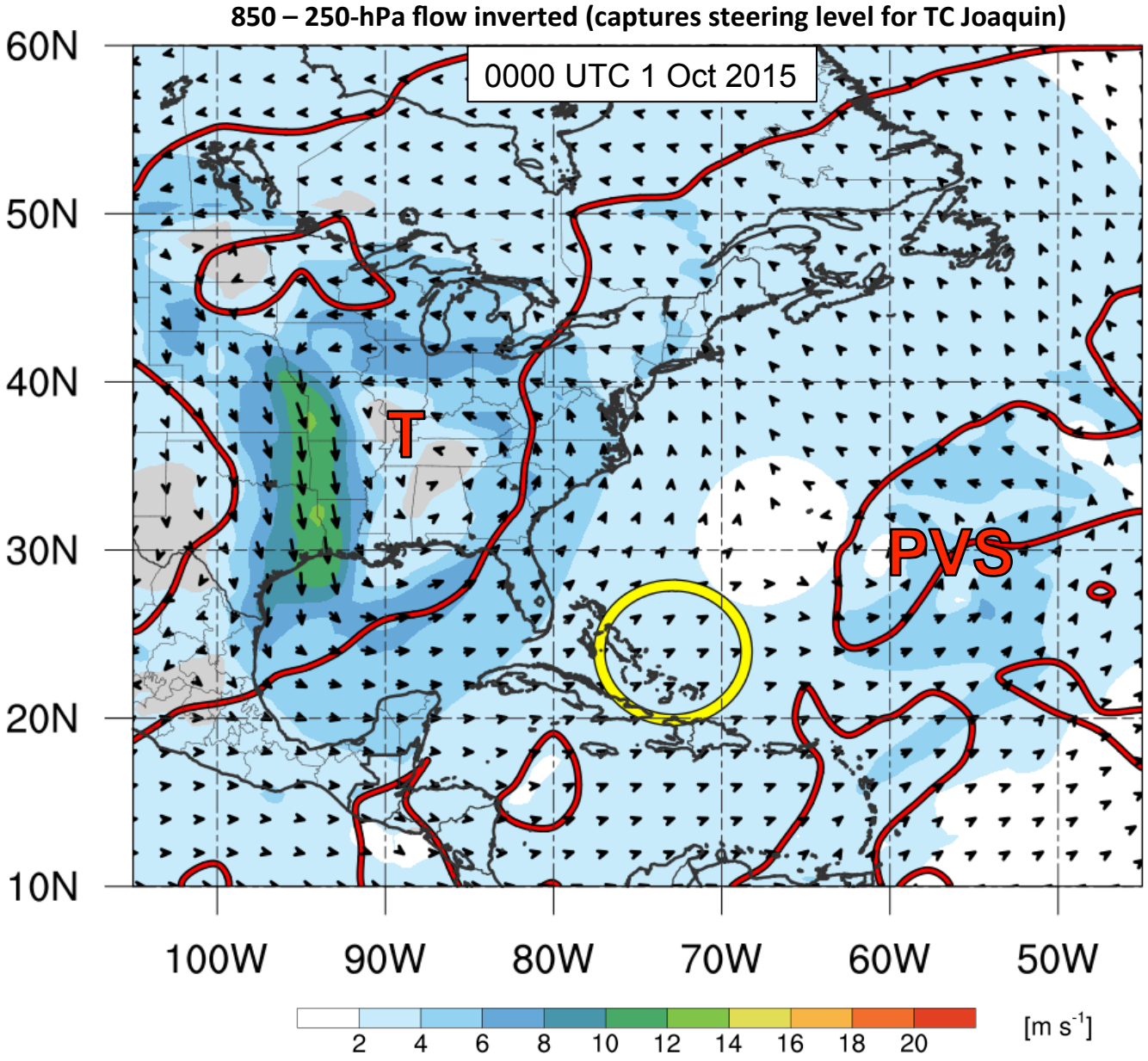
Steering Flow

- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 4.0^{o}$**

Test 1

Observations

- **CFSRv2 heading 241^{o} at 2.7 m s^{-1}**
- **Actual TC motion: 39^{o} at 3.0 m s^{-1}**

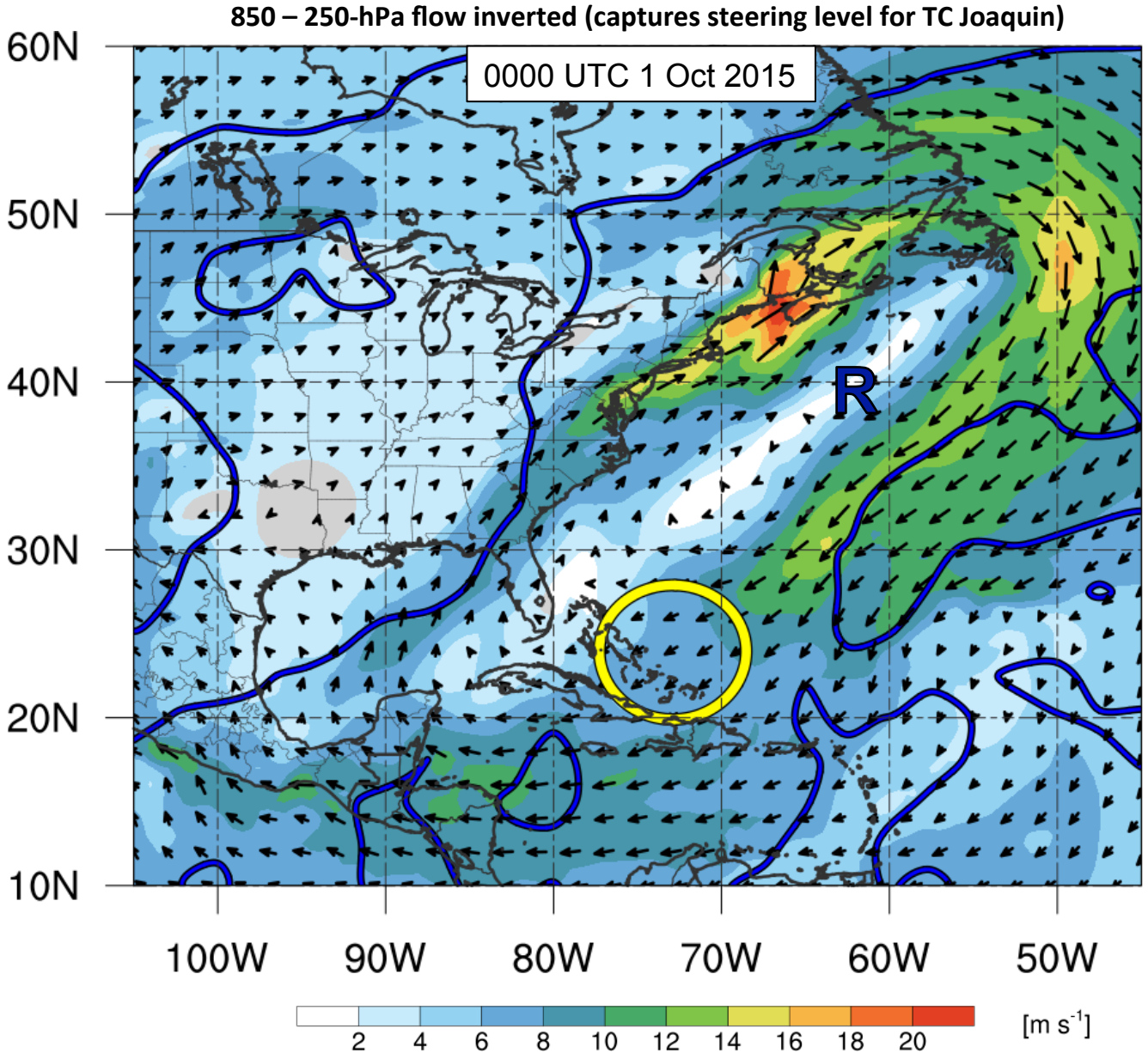


- **Removal of TC Joaquin vortex**
- **$r_{Joaquin} \geq 4.0^{o}$**

Test 2

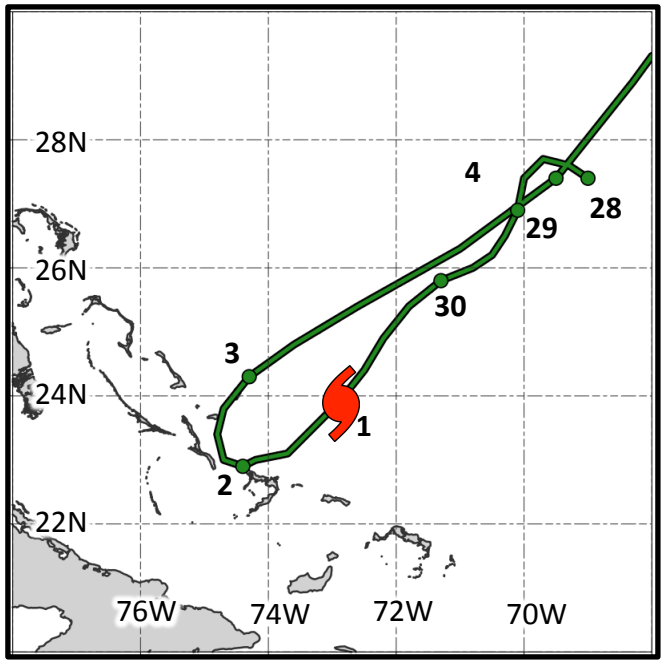
Observations

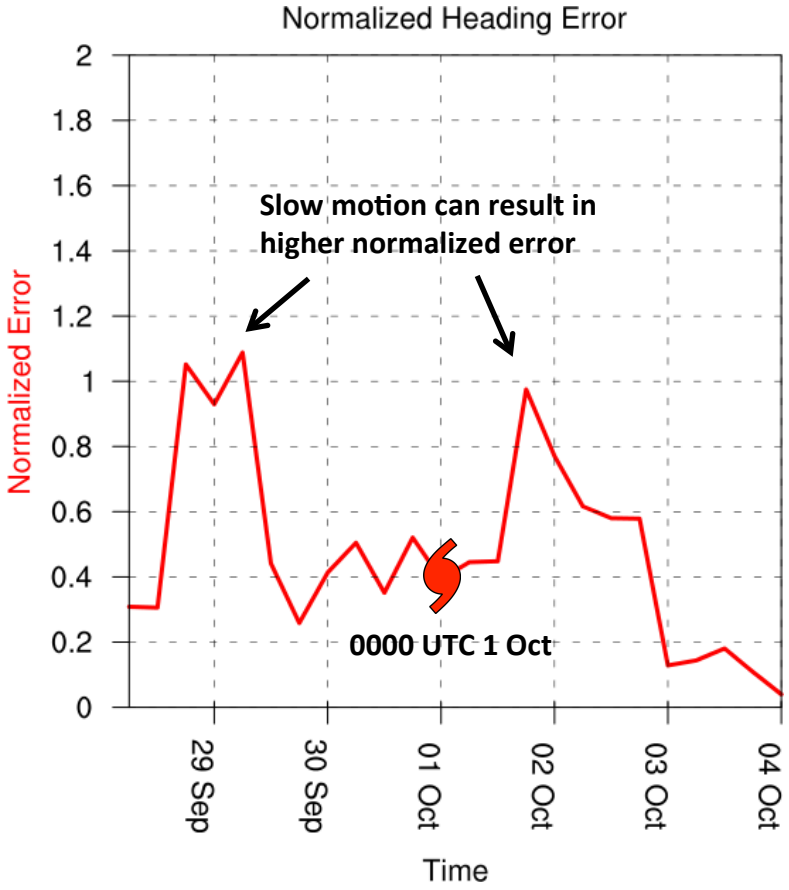
- **CFSRv2 heading 56^{o} at 6.7 m s^{-1}**
- **Actual TC motion: 39^{o} at 3.0 m s^{-1}**



CFSR Normalized Error

CFSR heading$_{850-250\text{-hPa}}$ – Best Track heading = CFSR heading error





- **Pick period early in track evolution that had relatively low heading error**