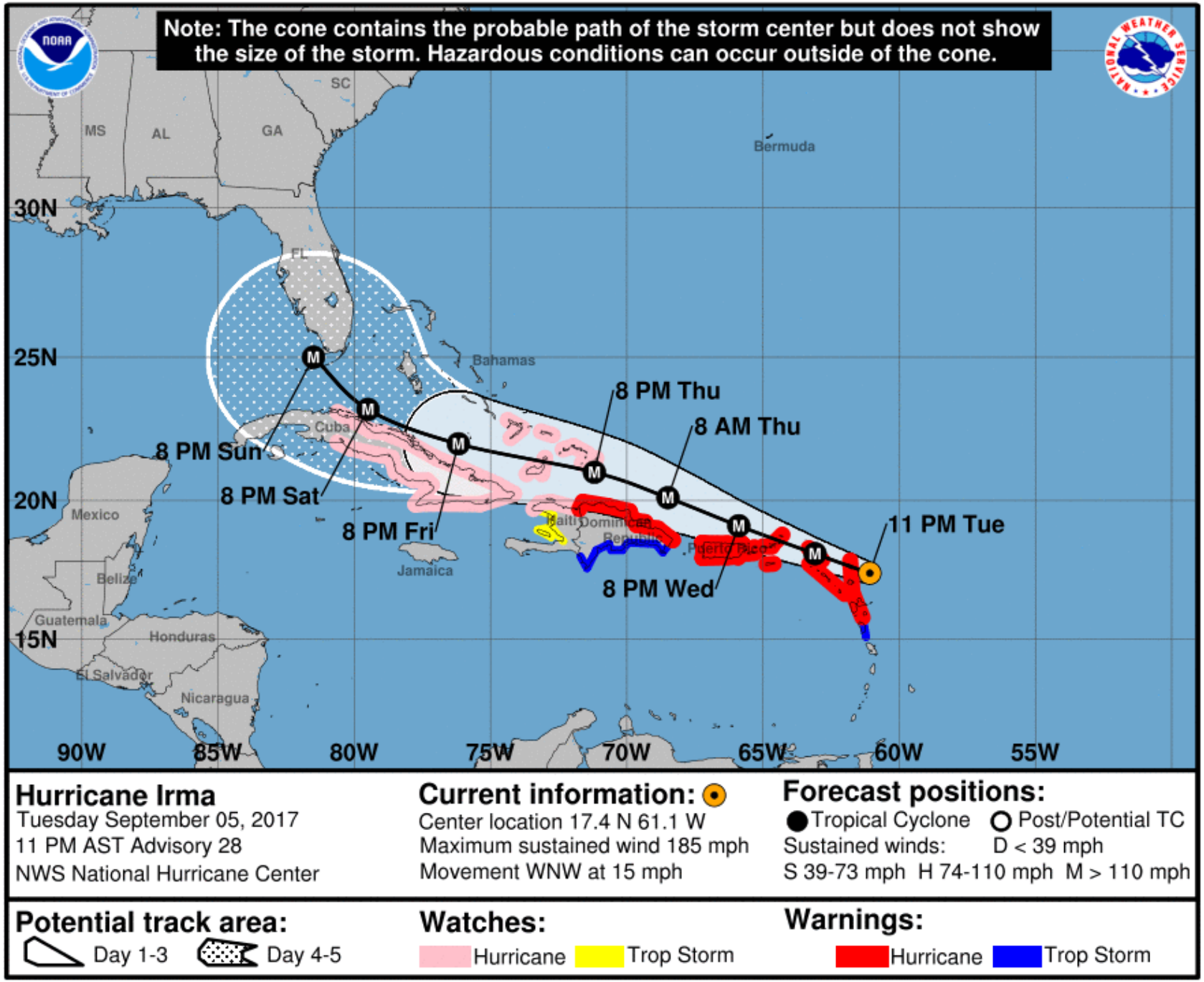
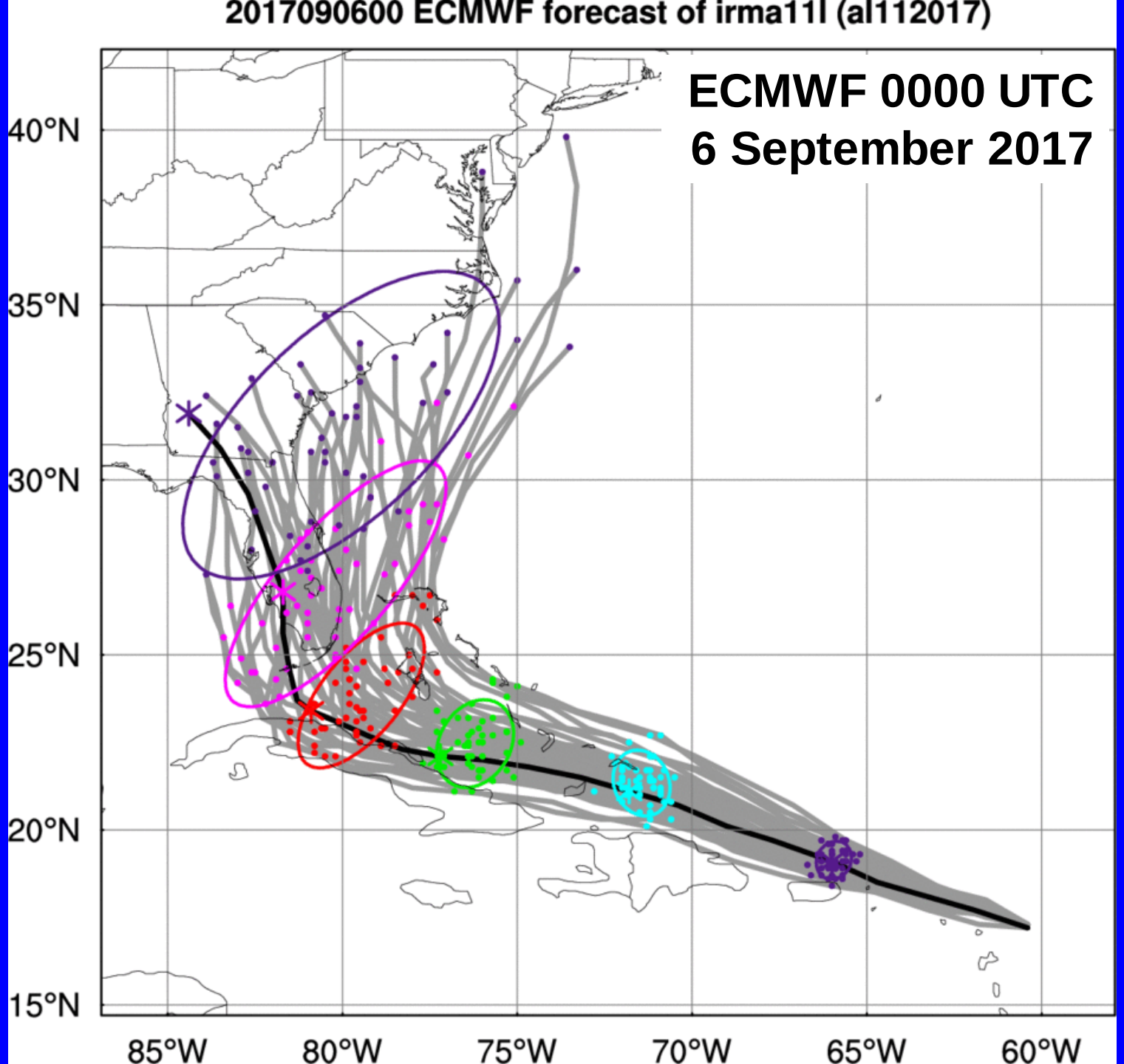
TC Track Ensemble Sensitivity

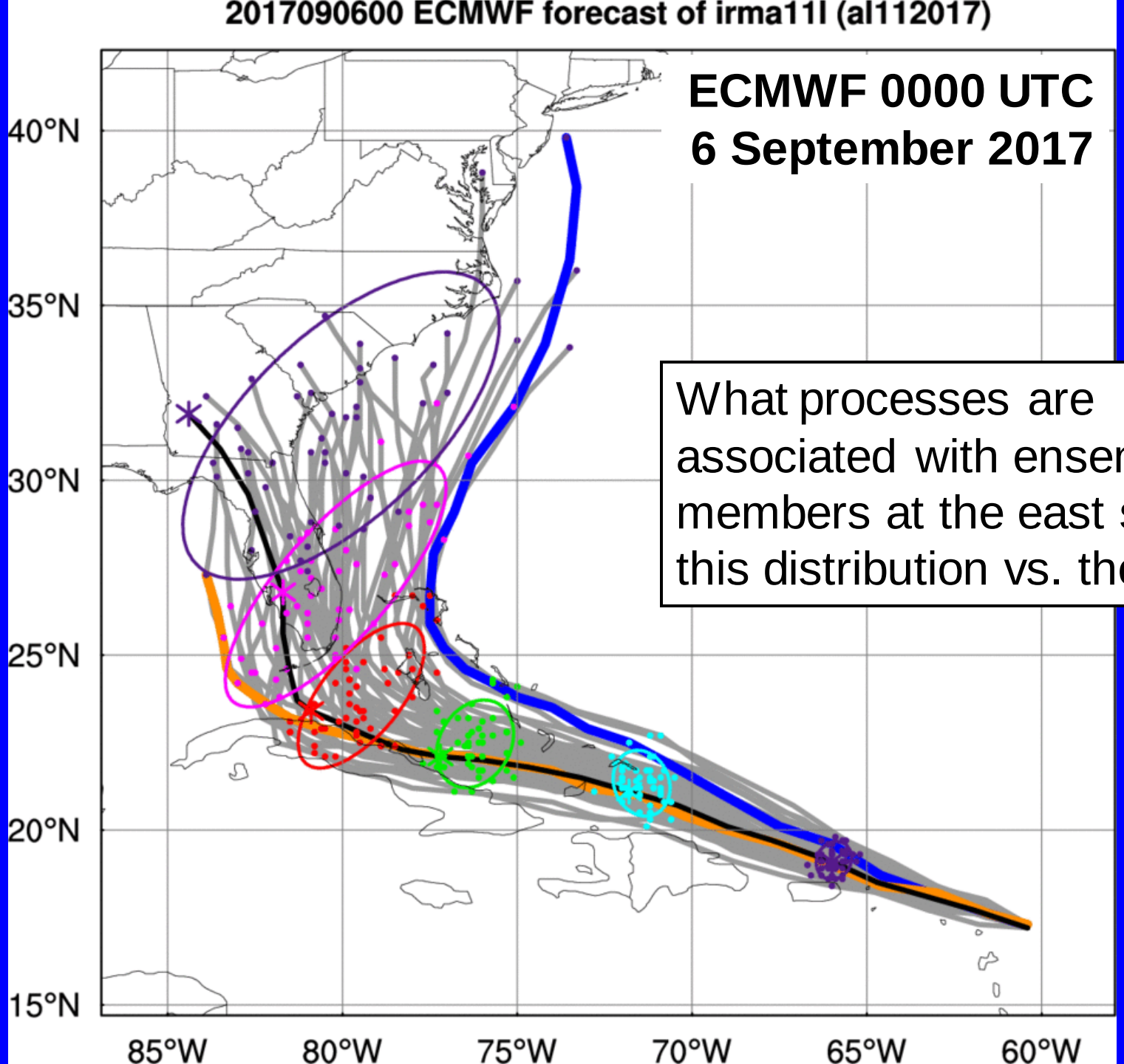
Ryan D. Torn
University at Albany, SUNY

Support From NOAA Awards:
NA16NWS4680025
NA18NWS4680060
NA19OAR4590129
NA22OAR4590528

- **Outline:**
  - Introduction to Sensitivity Analysis
  - Application to TC Track forecasts
  - Examples of TC Track Sensitivity for Recent Storms
  - Exercise with Sensitivity Analysis
  - Future Directions
- **Learning Objective:** Understand how ensemble-based sensitivity analysis can be used to diagnose the aspects of the forecast that yield track forecast uncertainty and to identify locations that would benefit from additional observations (e.g., from aircraft and/or rawindsondes)


Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.
SC
MS
AL
GA
Bermuda
30N
FL
25N
Bahamas
Cuba
8 PM Thu
8 AM Thu
8 PM Sun
8 PM Sat
20N
Mexico
8 PM Fri
Haiti
Dominican Republic
Puerto Rico
11 PM Tue
Jamaica
8 PM Wed
Belize
Guatemala
15N
Honduras
El Salvador
Nicaragua
90W
85W
80W
75W
70W
65W
60W
55W
Hurricane Irma
Tuesday September 05, 2017
11 PM AST Advisory 28
NWS National Hurricane Center
Current information:
Center location 17.4 N 61.1 W
Maximum sustained wind 185 mph
Movement WNW at 15 mph
Forecast positions:
Tropical Cyclone
Post/Potential TC
Sustained winds:
D < 39 mph
S 39-73 mph H 74-110 mph M > 110 mph
Potential track area:
Day 1-3
Day 4-5
Watches:
Hurricane
Trop Storm
Warnings:
Hurricane
Trop Storm

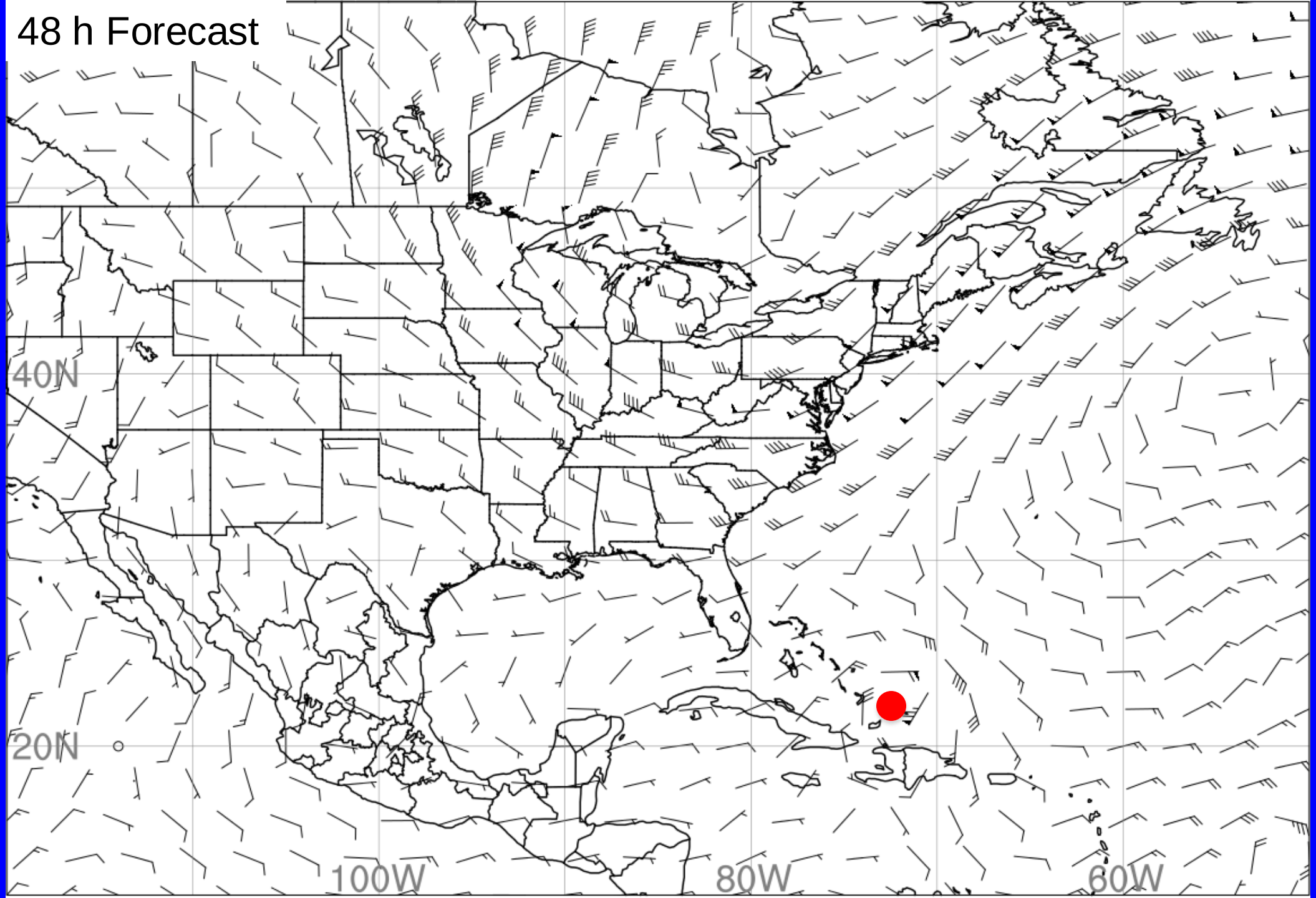

2017090600 ECMWF forecast of irma11l (al112017)
ECMWF 0000 UTC
6 September 2017
40°N
35°N
30°N
25°N
20°N
15°N
85°W
80°W
75°W
70°W
65°W
60°W

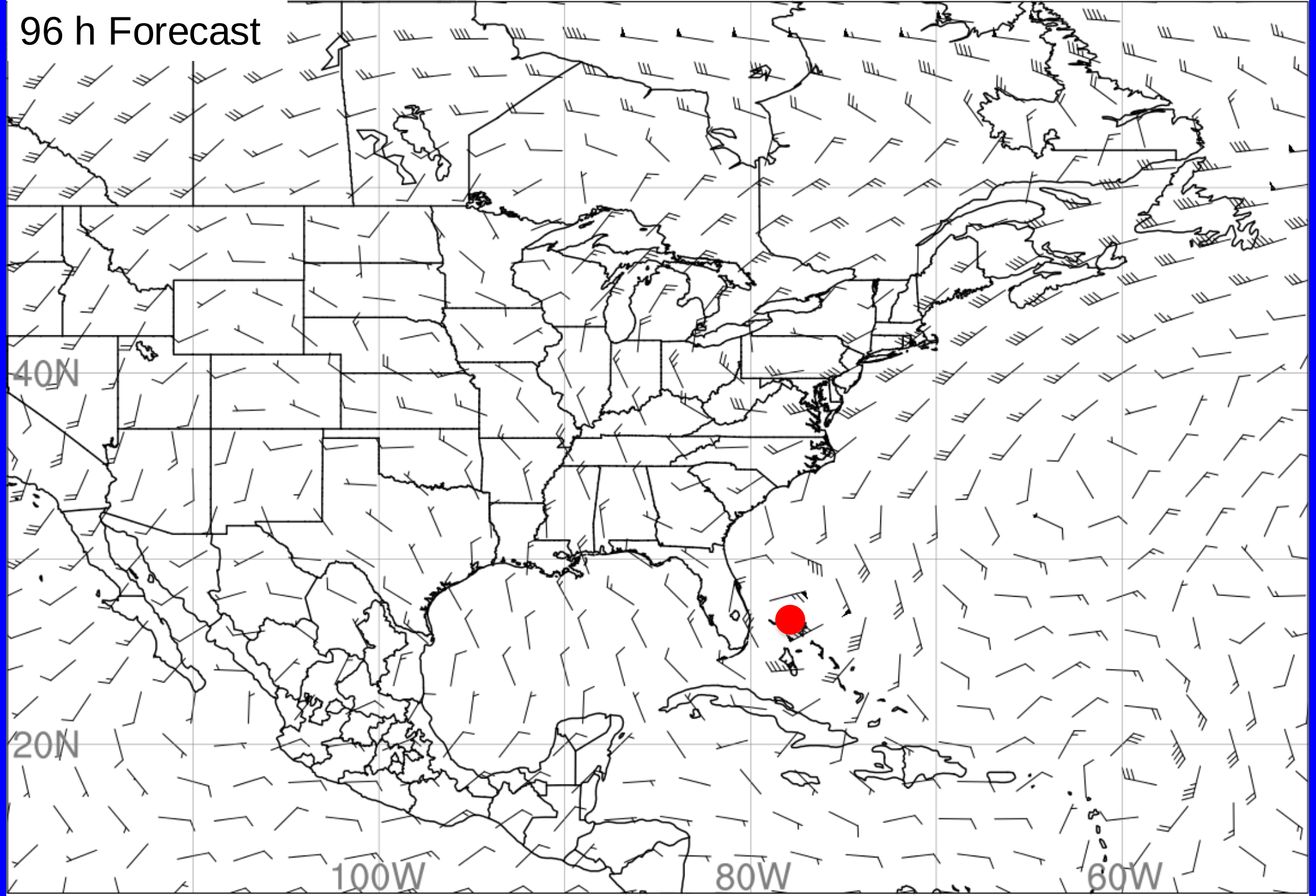


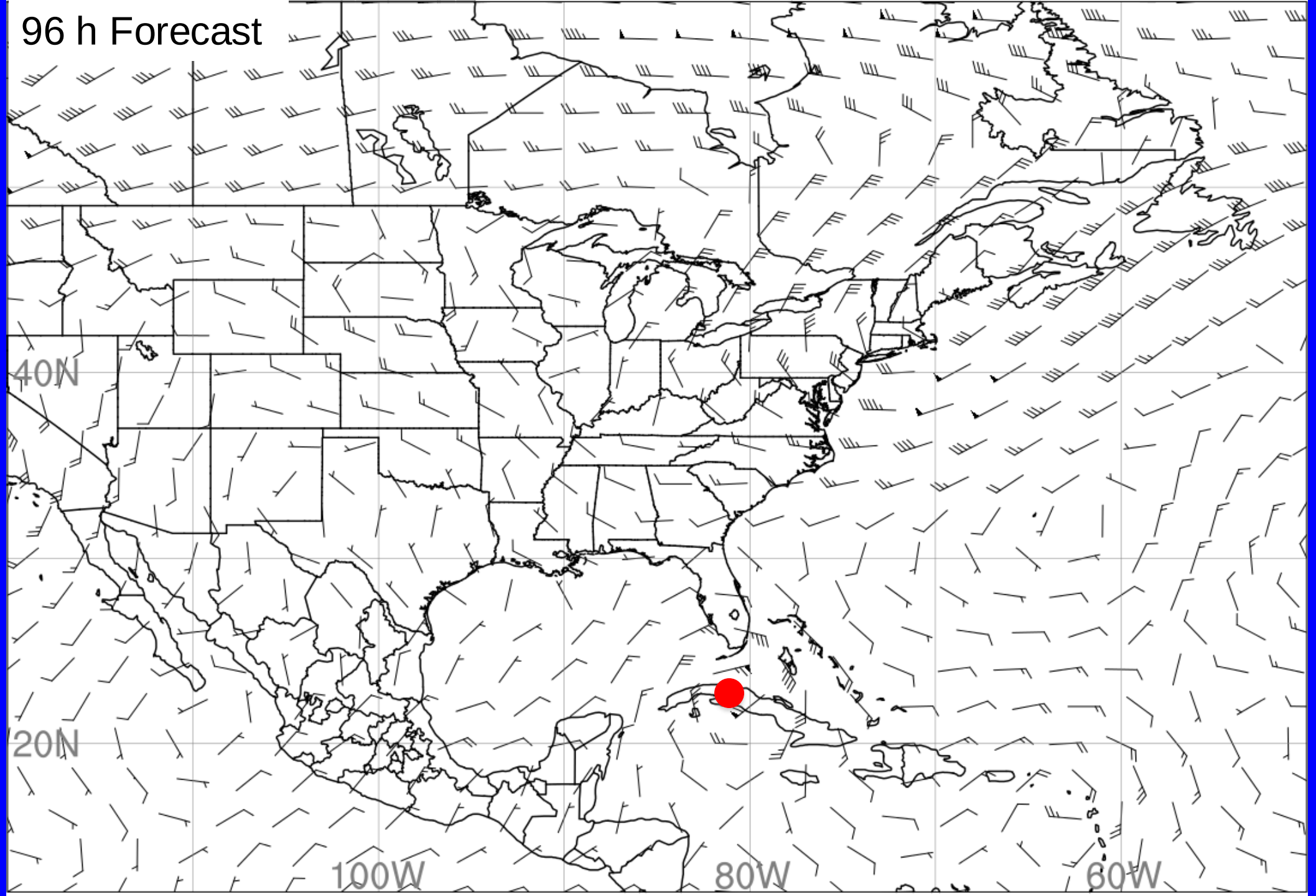
What processes are associated with ensemble members at the east side of this distribution vs. the west?

Overview

- Tropical Cyclone motion is highly influenced by a deep-tropospheric “steering flow” (typically defined as the 250-850 hPa layer-average wind)
- One way to understand the forecast differences is to analyze the evolution of the steering wind between these two forecast scenarios


48 h Forecast
40N
20N
100W
80W
60W


96 h Forecast
40N
20N
100W
80W
60W


96 h Forecast
40N
20N
100W
80W
60W

Overview

- Would be helpful to have a suite of methods that could quickly analyze ensemble forecast output to identify sensitive locations of forecast state
  - Sensitive means making a small change to a model at a specific location and field at earlier time yields large change in forecast
  - Regions of large sensitivity denote areas that could benefit from additional observations

NOAA

Q: How can you estimate the change in a forecast outcome to the model at an earlier lead time?

$$J = f(\mathbf{x})$$

Model state vector: Vector that contains wind, temperature, etc., at all grid points

Forecast metric: Forecast outcome that is a function of the model state

Can estimate how changes in model state impact forecast metric via Taylor expansion

$$\delta J = \left[\frac{\partial J}{\partial \mathbf{x}_t}\right]^{\mathrm{T}} \delta \mathbf{x}_t$$

Change in forecast state at the time of the metric

Sensitivity of forecast metric to model state at same time

Change in forecast metric

Q: How can you estimate the change in a forecast outcome to the model at an earlier lead time?

You can estimate the growth of forecast errors via:

$$\delta \mathbf{x}_t = \mathbf{R}_{t,t-\delta t}\,\delta \mathbf{x}_{t-\delta t}$$

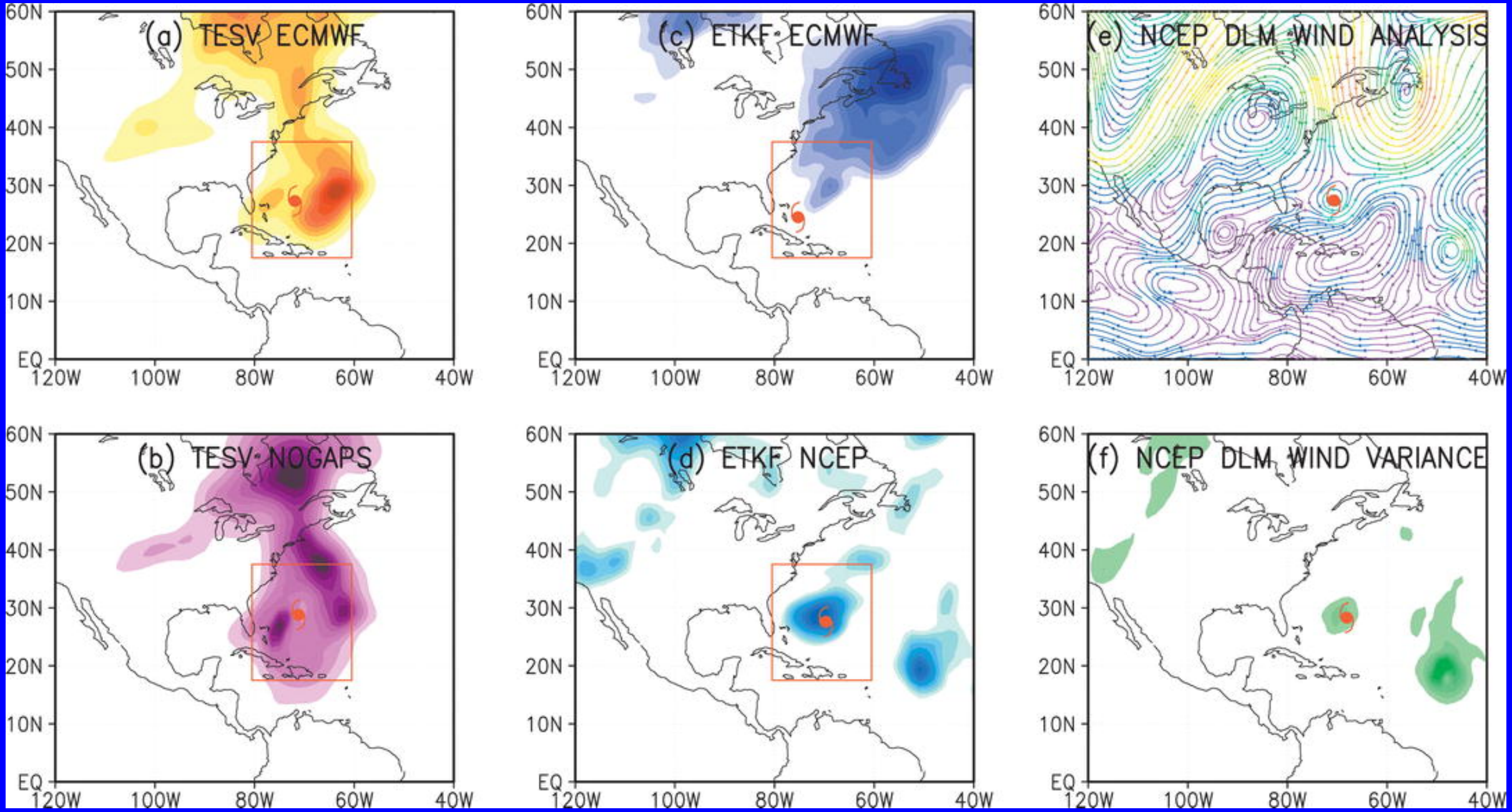
Change to the model at an earlier lead time

Linear Model to advance from earlier time to the time of the metric

Substitute into previous equation:

$$\delta J = \left[\mathbf{R}^{\mathrm{T}}_{t,t-\delta t}\frac{\partial J}{\partial \mathbf{x}_t}\right]\delta \mathbf{x}_{t-\delta t} = \left[\frac{\partial J}{\partial \mathbf{x}_{t-\delta t}}\right]^{\mathrm{T}}\delta \mathbf{x}_{t-\delta t}$$

Sensitivity of forecast metric to earlier time model state. Many different ways to calculate this



Majumdar et al. 2006, DOI: https://doi.org/10.1175/MWR3193.1

Ensemble Sensitivity

$$\frac{\partial J}{\partial x_{t-\delta t,j}}_{e} \equiv cov(\mathbf{J}, \delta\mathbf{X}_{t-\delta t,j})\mathbf{D}_j^{-1} = \frac{cov(\mathbf{J}, \mathbf{X}_j)}{var(\mathbf{X}_j)}$$

Ancell and Hakim 2007, Torn and Hakim 2008

- Ensemble-based method of computing the sensitivity to model state variables at earlier time
- Above equation is linear regression based on ensemble:
  - Dependent variable (J) is "forecast metric", or the ensemble estimate of a user-defined forecast outcome (e.g., TC position)
  - Independent variable (X) is "the field" or the ensemble estimate of state variable (i.e., steering wind, vorticity, PV) at a given location at some time before the forecast metric valid time

Advantages of Ensemble Sensitivity:

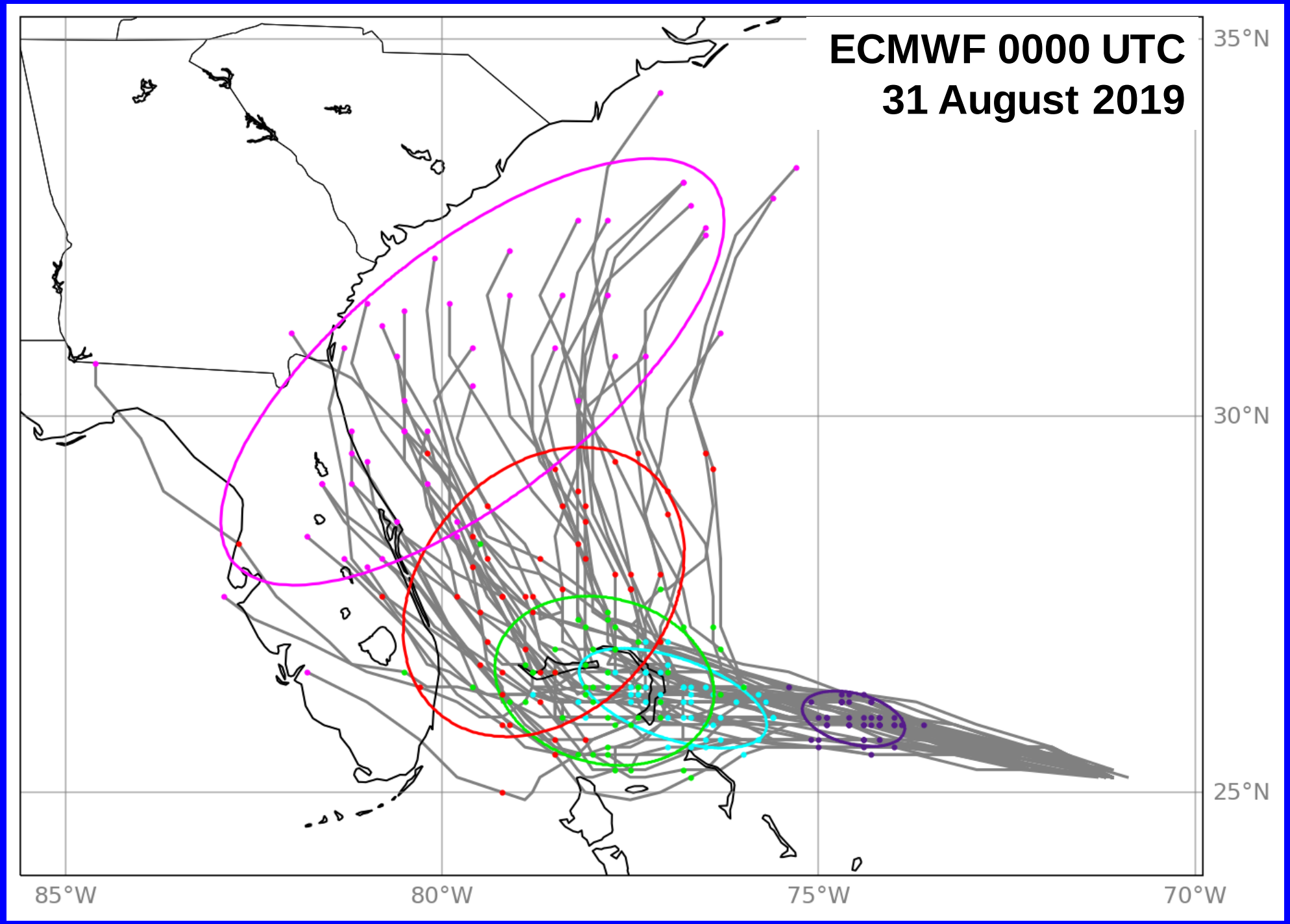
- Flexible set of metrics (i.e., metrics specific to TCs)
- Computationally inexpensive
- Can use ensemble forecasts produced for other purposes
- No linear error growth assumptions (i.e., uses non-linear forecast trajectories

Disadvantages of Ensemble Sensitivity:

- Makes use of linear statistics, Cannot resolve non-linear relationships between field and metric

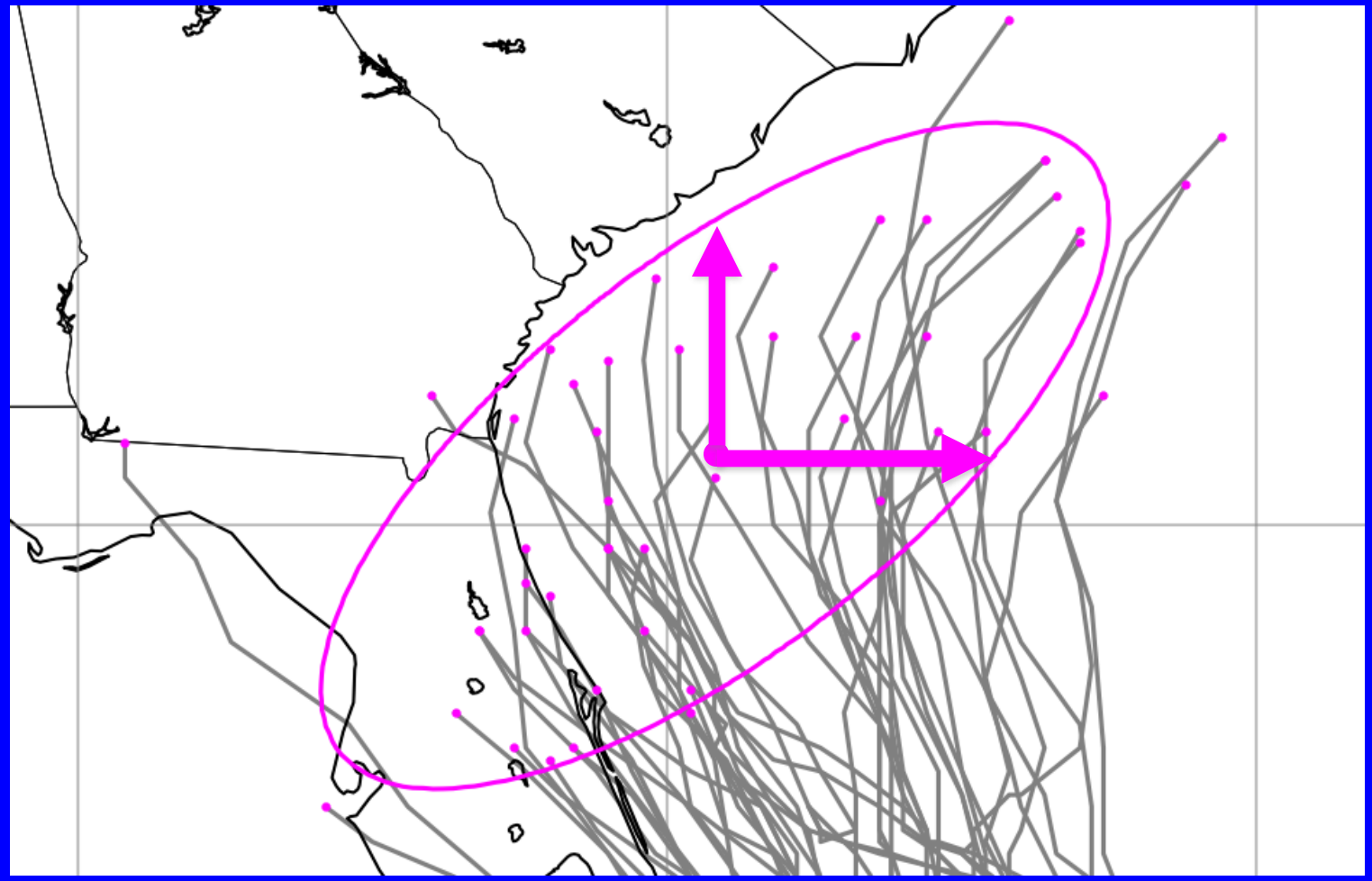
Methodology

- Remainder of this talk provides a demonstration of quasi-operational ensemble-based sensitivity products that are used in TC applications with the NOAA National Hurricane Center (NHC)
- Guidance has been regularly used for NOAA G-IV flight planning since 2018
- Forecast metric is measure of TC track forecast
- Forecast field is the steering flow at an earlier time
- Demonstrate methods using Dorian 0000 UTC 31 August forecast for flight on 1200 UTC 1 September


ECMWF 0000 UTC
31 August 2019
35°N
30°N
25°N
85°W
80°W
75°W
70°W

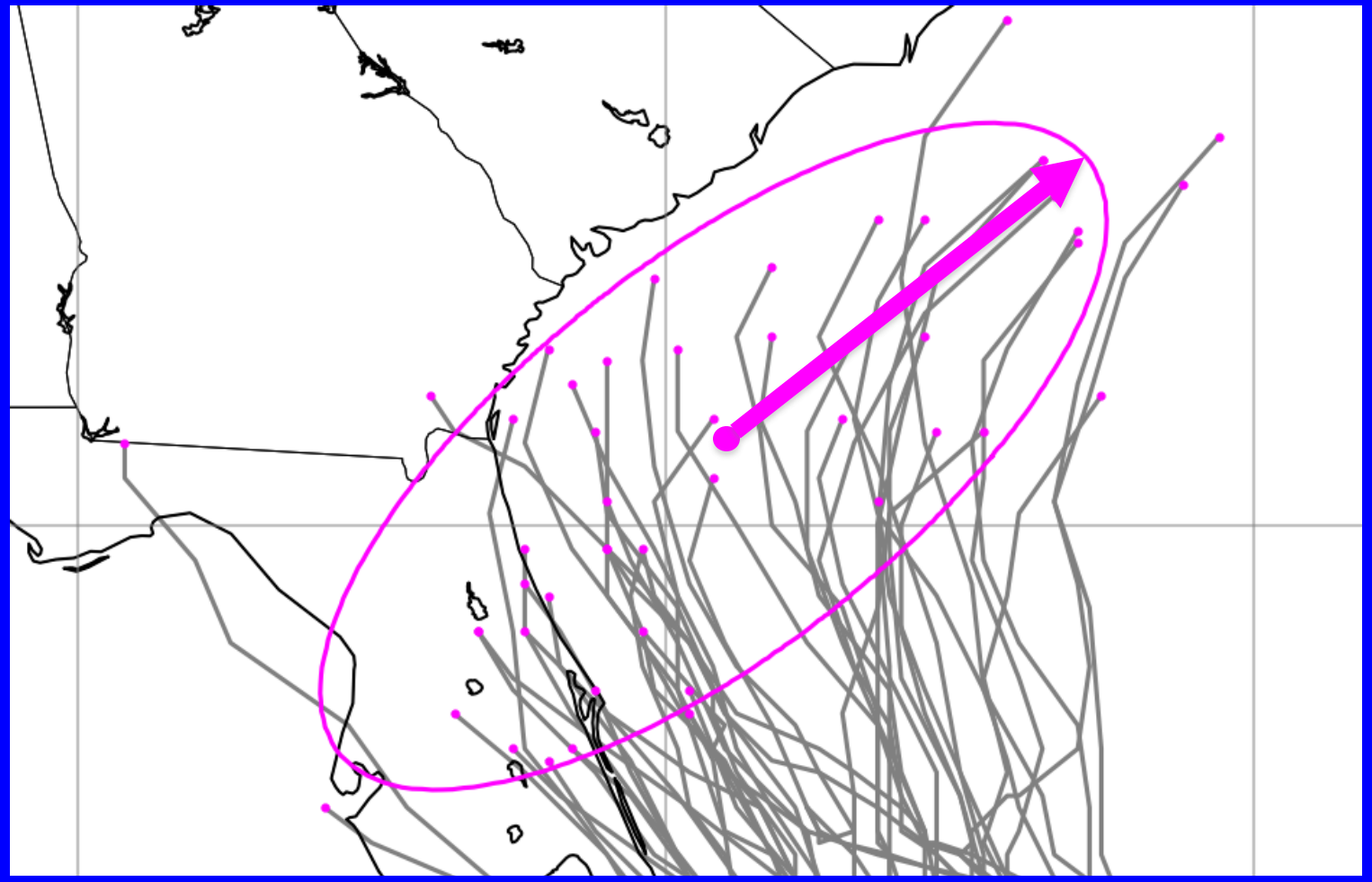
TC Track Forecast Metrics

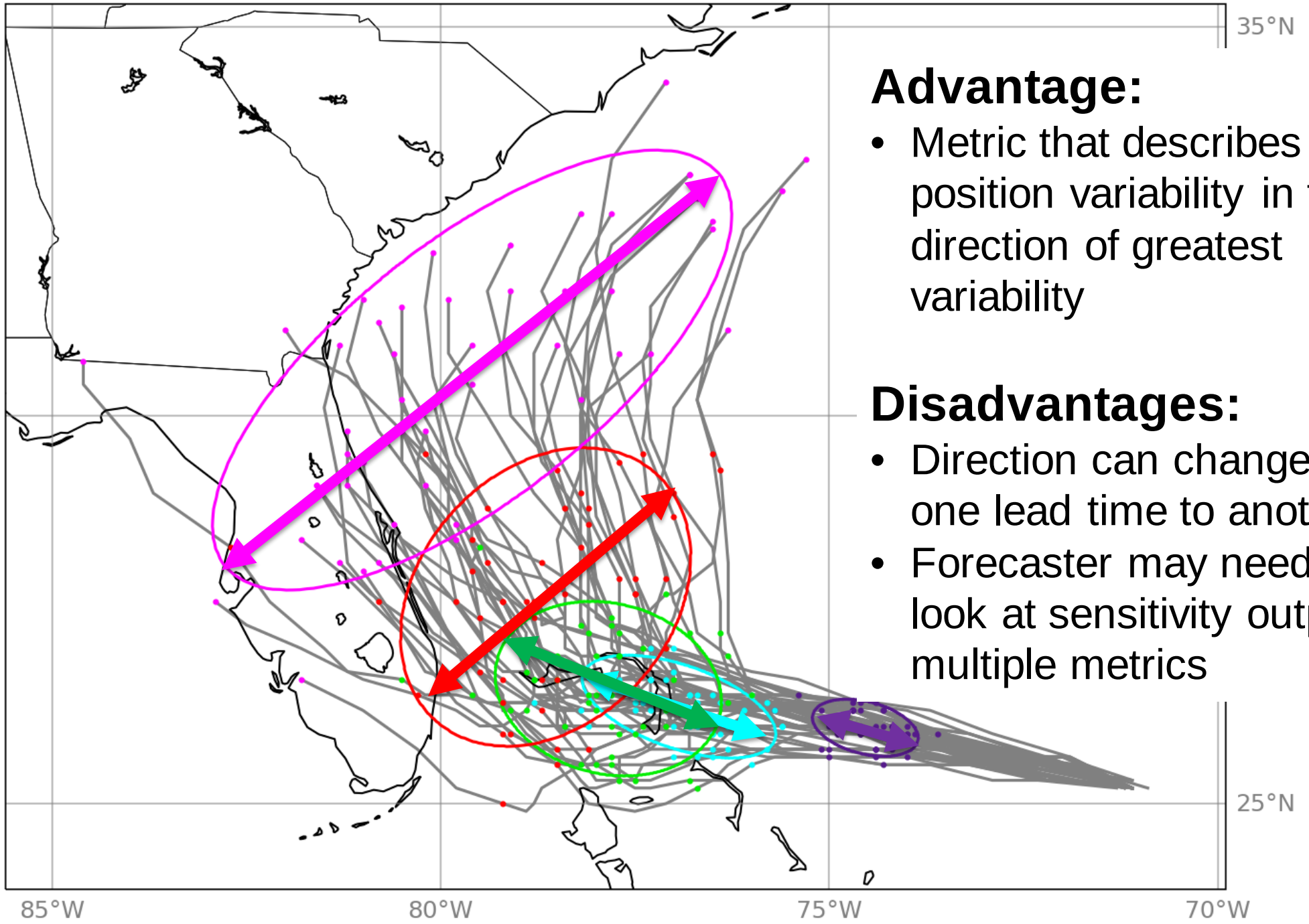
- Latitude and longitude of TC position is one possibility, but position variability often exists in both zonal/meridional directions



TC Track Forecast Metrics

- Alternative is position in direction of maximum variability (EOF of ensemble forecast positions)





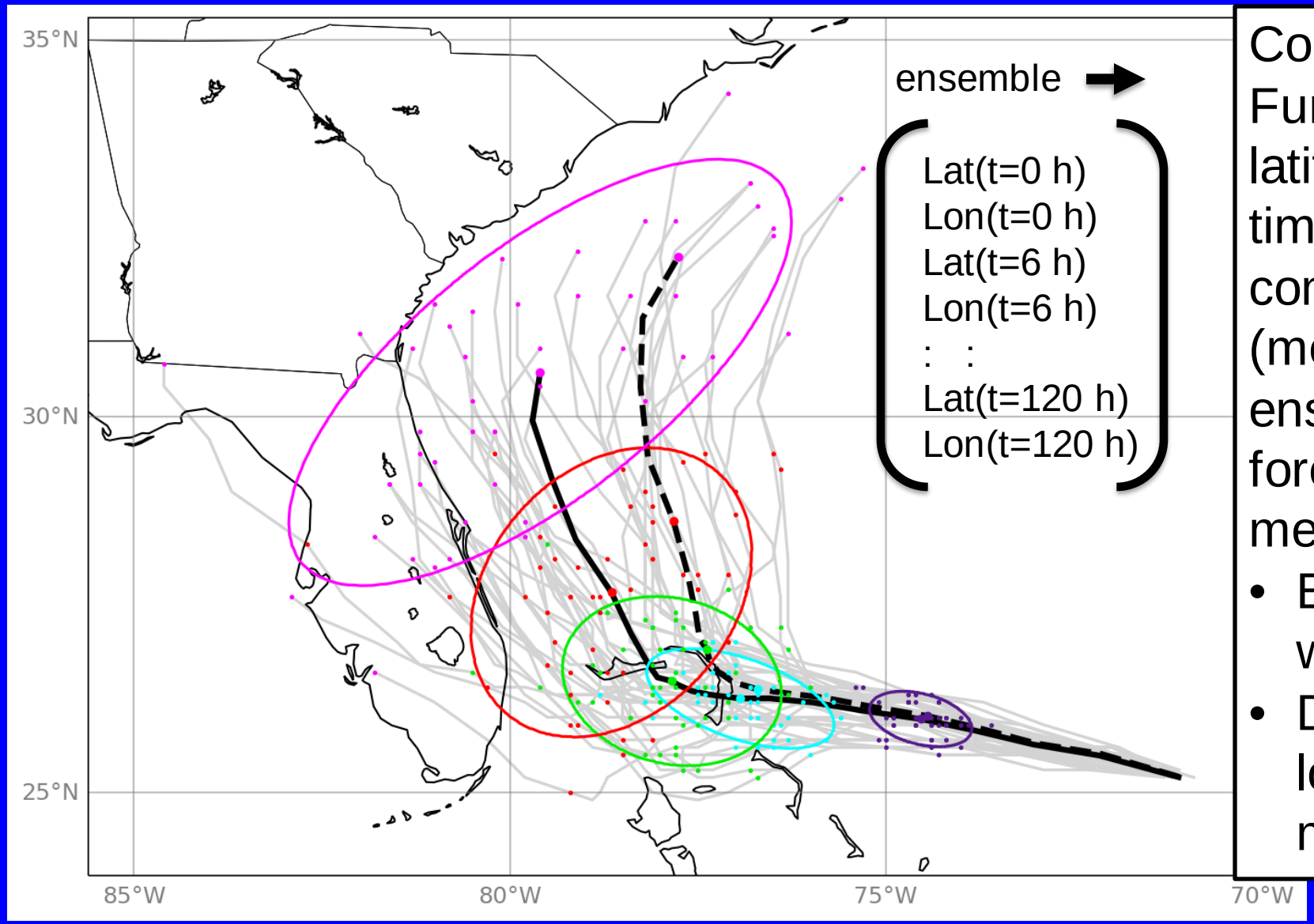
Advantage:

- Metric that describes position variability in the direction of greatest variability

Disadvantages:

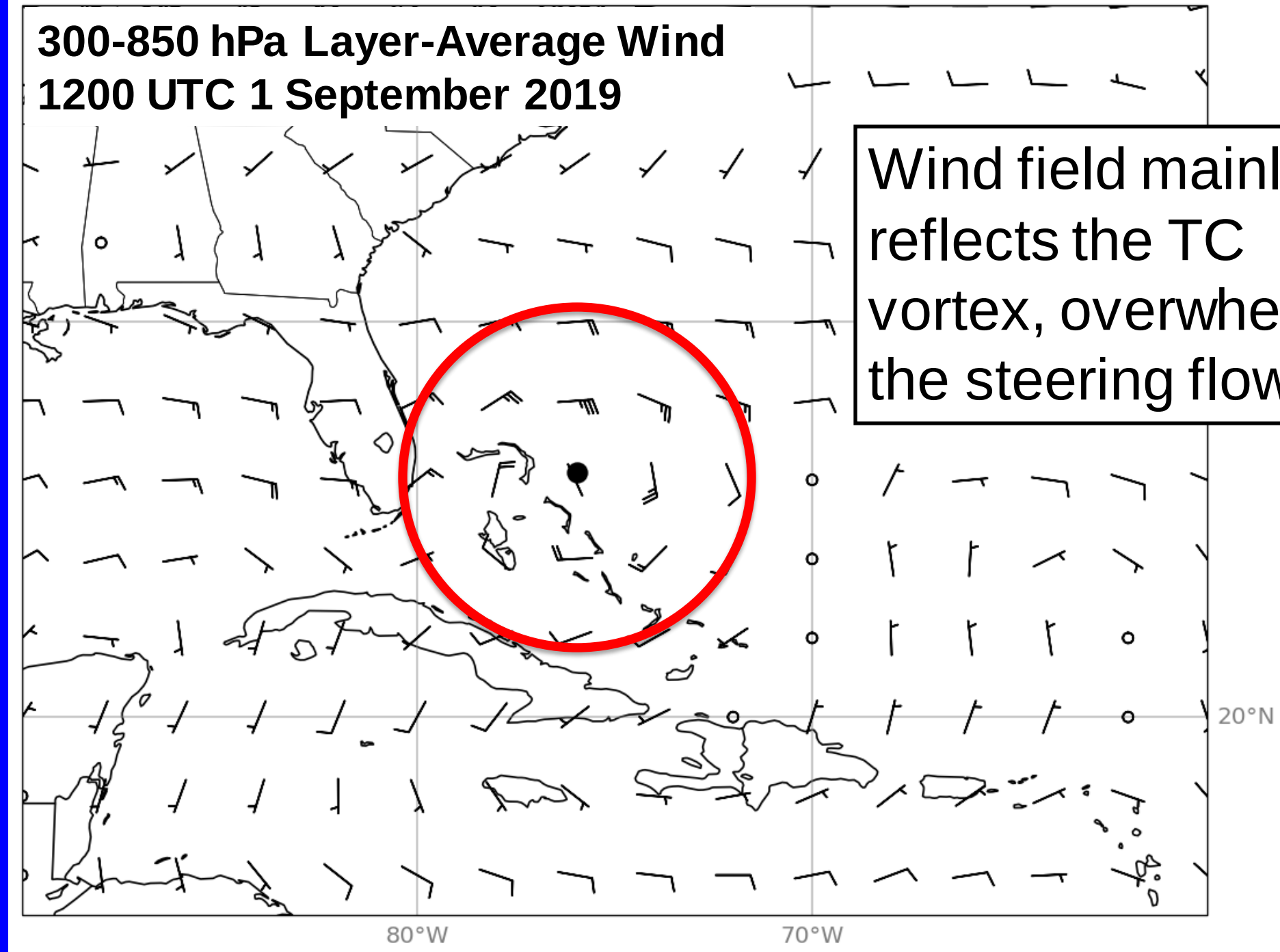
- Direction can change from one lead time to another
- Forecaster may need to look at sensitivity output for multiple metrics

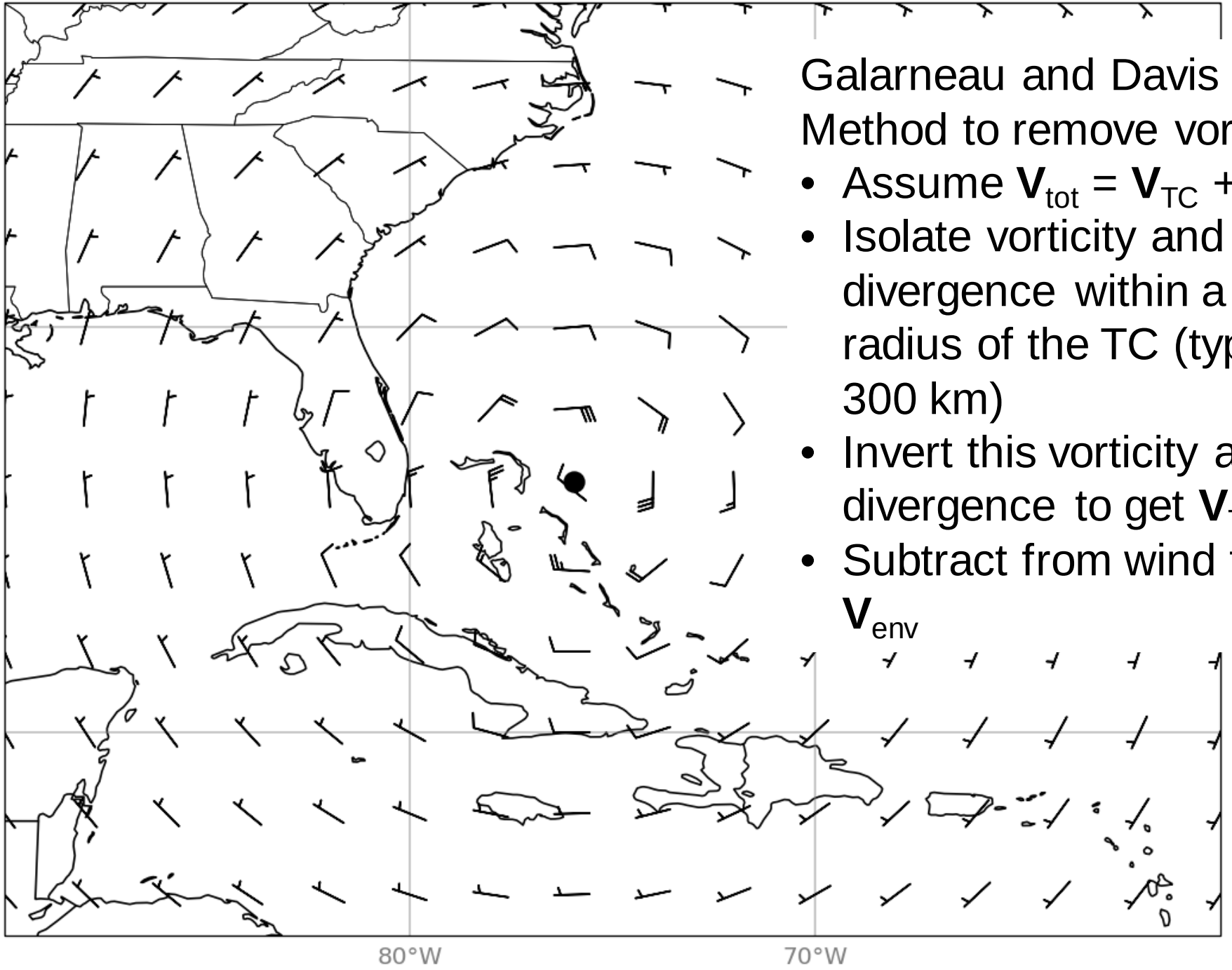
Track EOF Decomposition



Compute Empirical Orthogonal Function (EOF) of ensemble TC latitude and longitude at multiple times. Metric is principal component of the first EOF (measure of how close ensemble is to a representative forecast deviation from the mean).

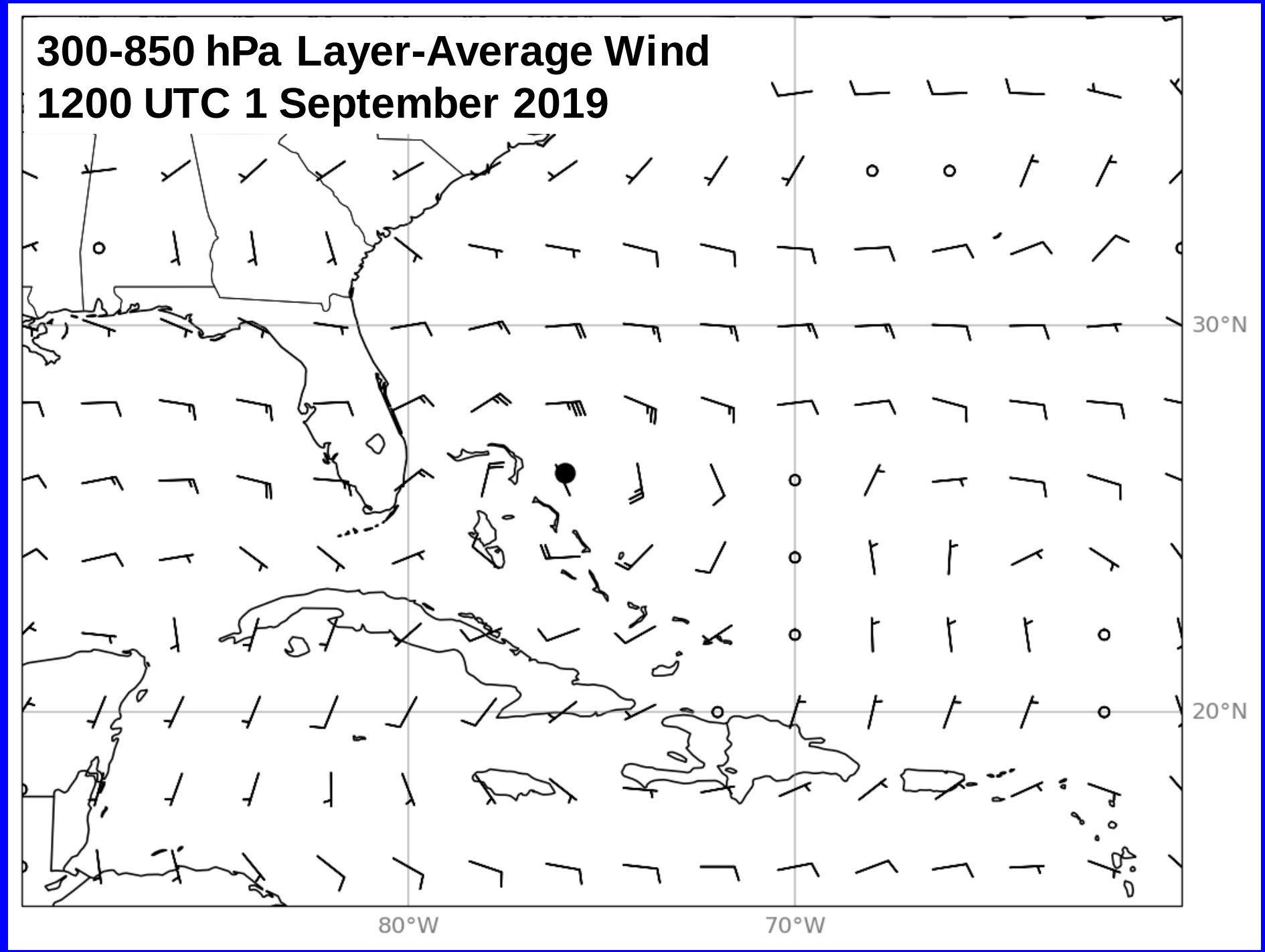
- Elegant method of dealing with track autocorrelation
- Does not require forecaster to look at sensitivity from multiple times

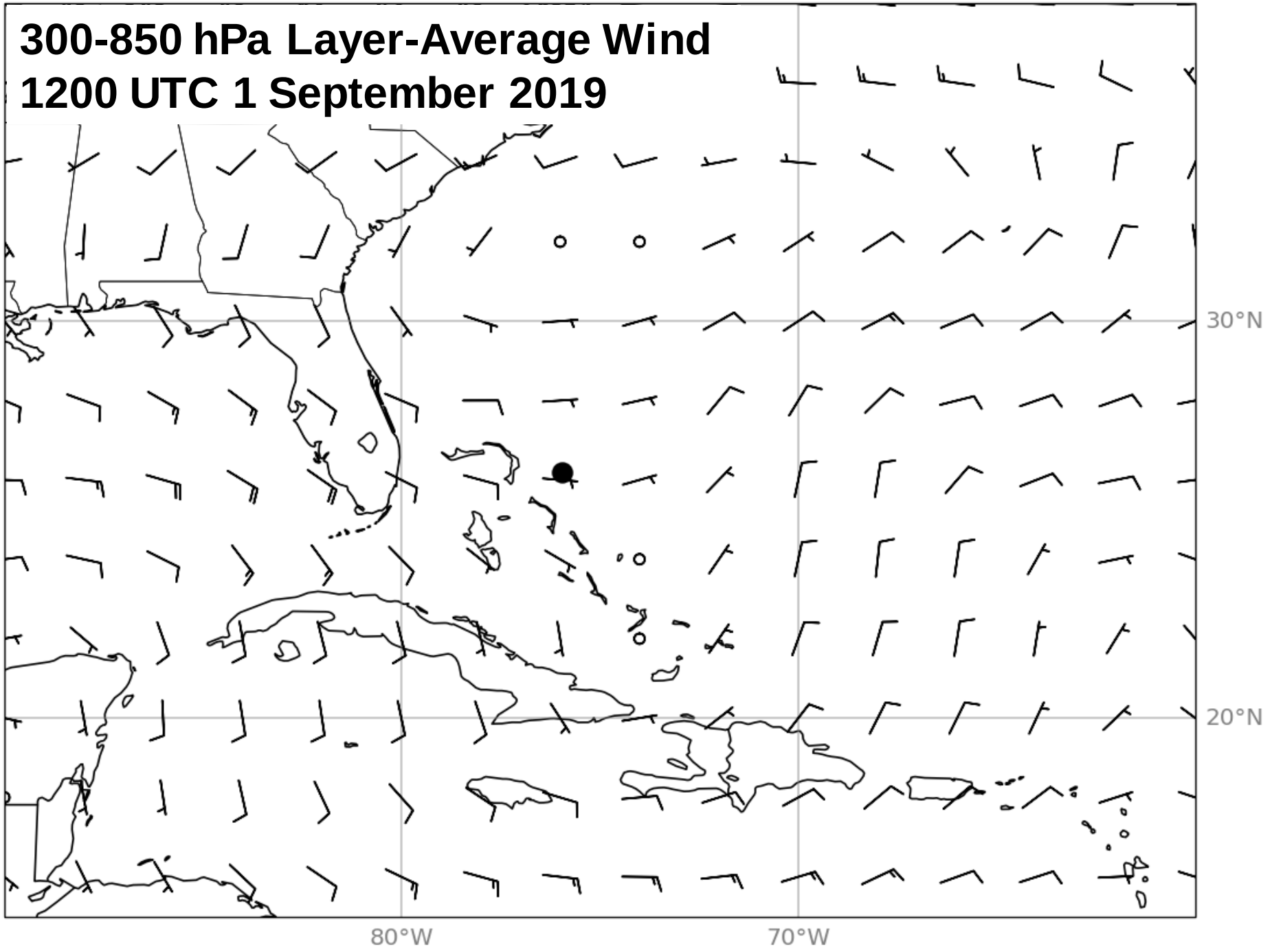

300-850 hPa Layer-Average Wind
1200 UTC 1 September 2019
Wind field mainly reflects the TC vortex, overwhelms the steering flow
20°N
80°W
70°W

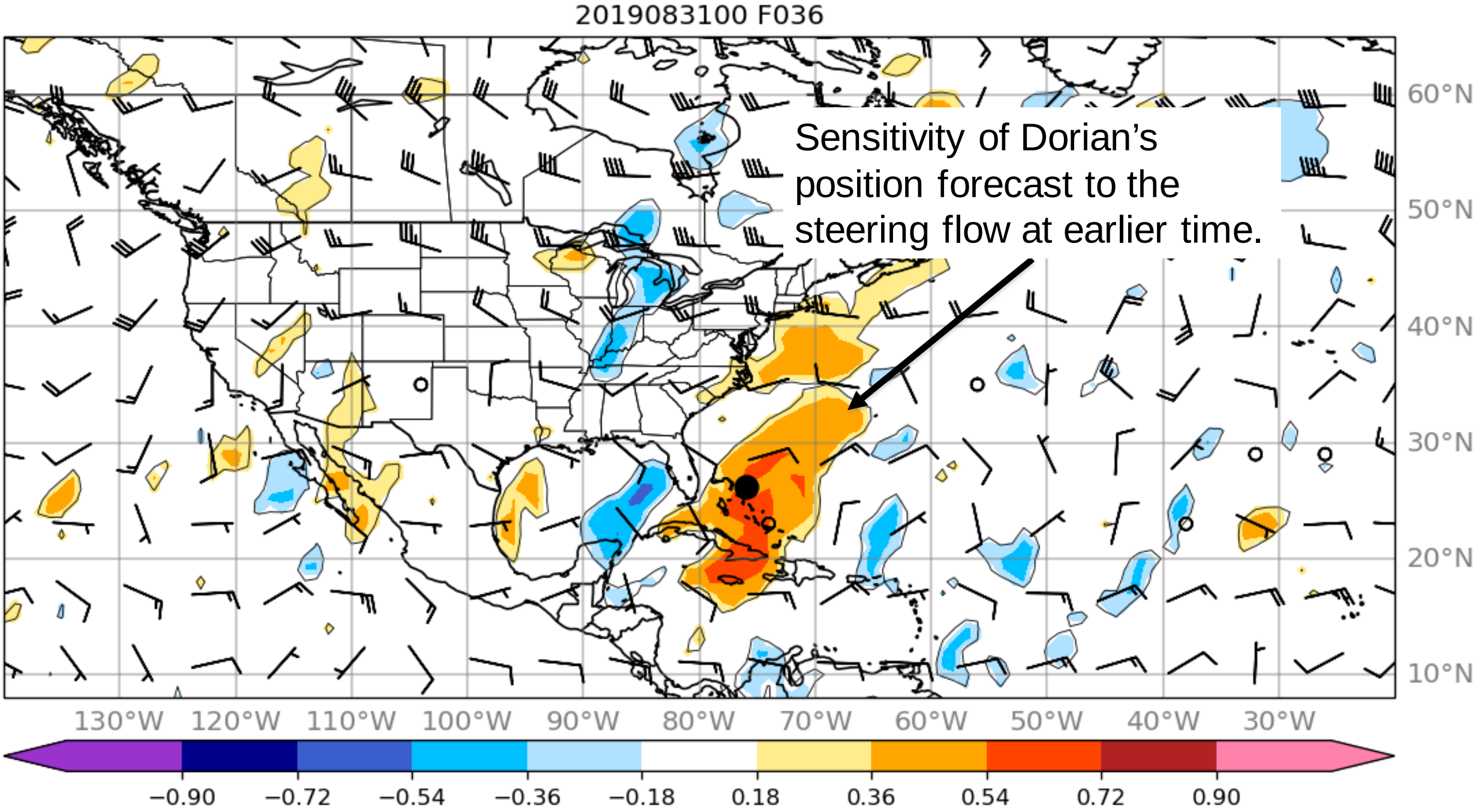


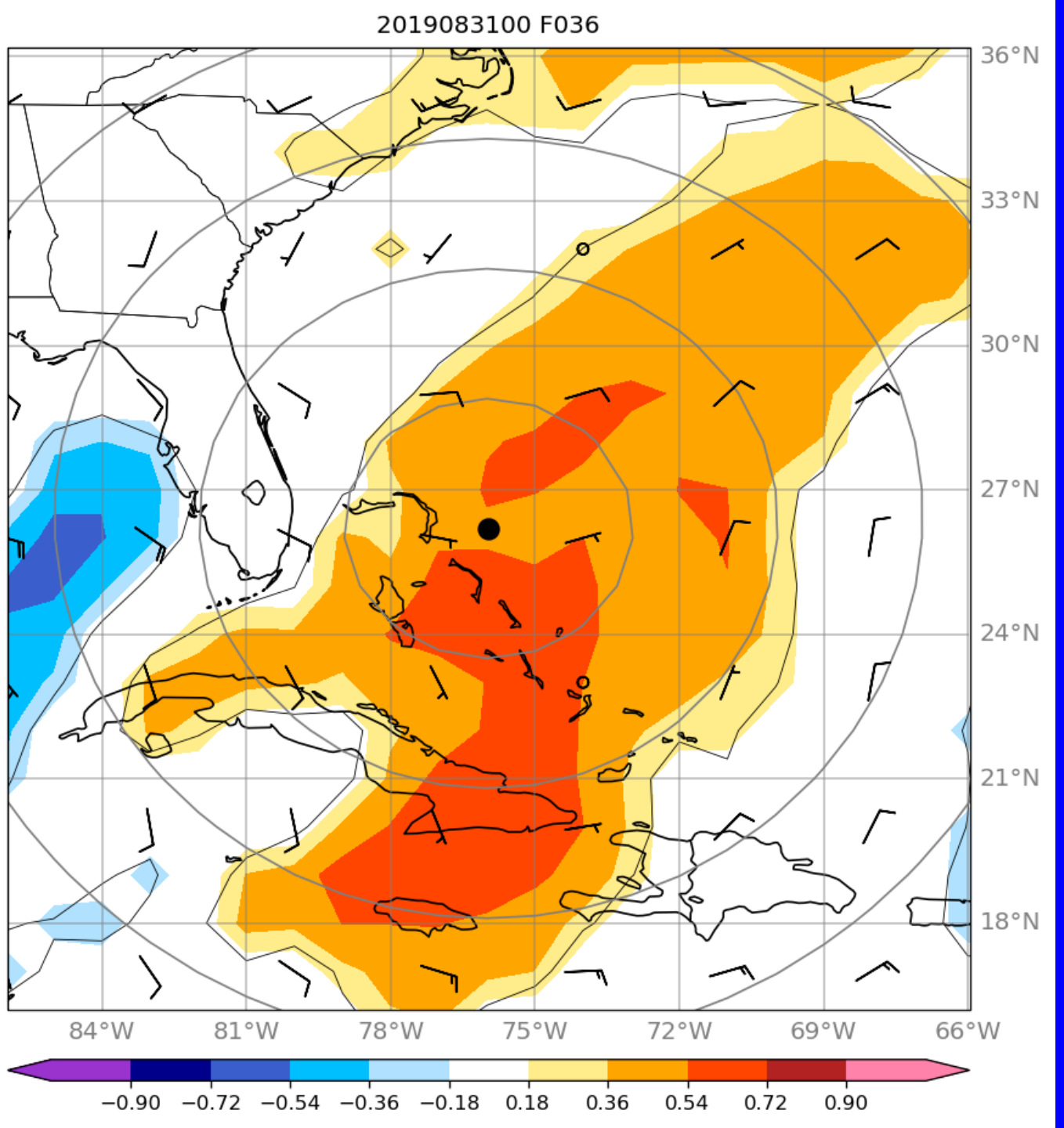
Galarneau and Davis (2013)
Method to remove vortex:

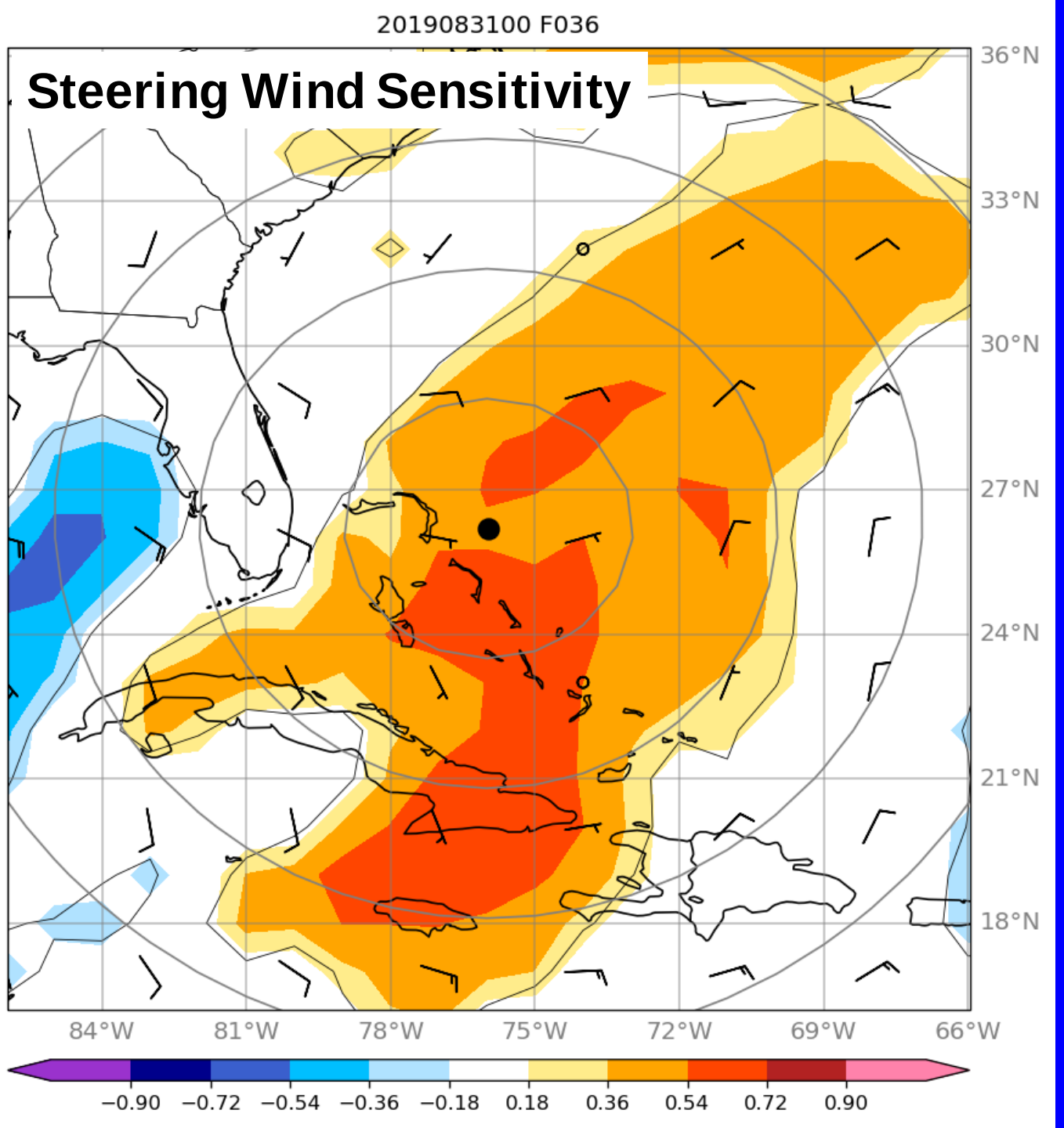
- Assume $\mathbf{V}_{tot} = \mathbf{V}_{TC} + \mathbf{V}_{env}$
- Isolate vorticity and divergence within a certain radius of the TC (typically 300 km)
- Invert this vorticity and divergence to get $\mathbf{V}_{TC}$
- Subtract from wind to get $\mathbf{V}_{env}$

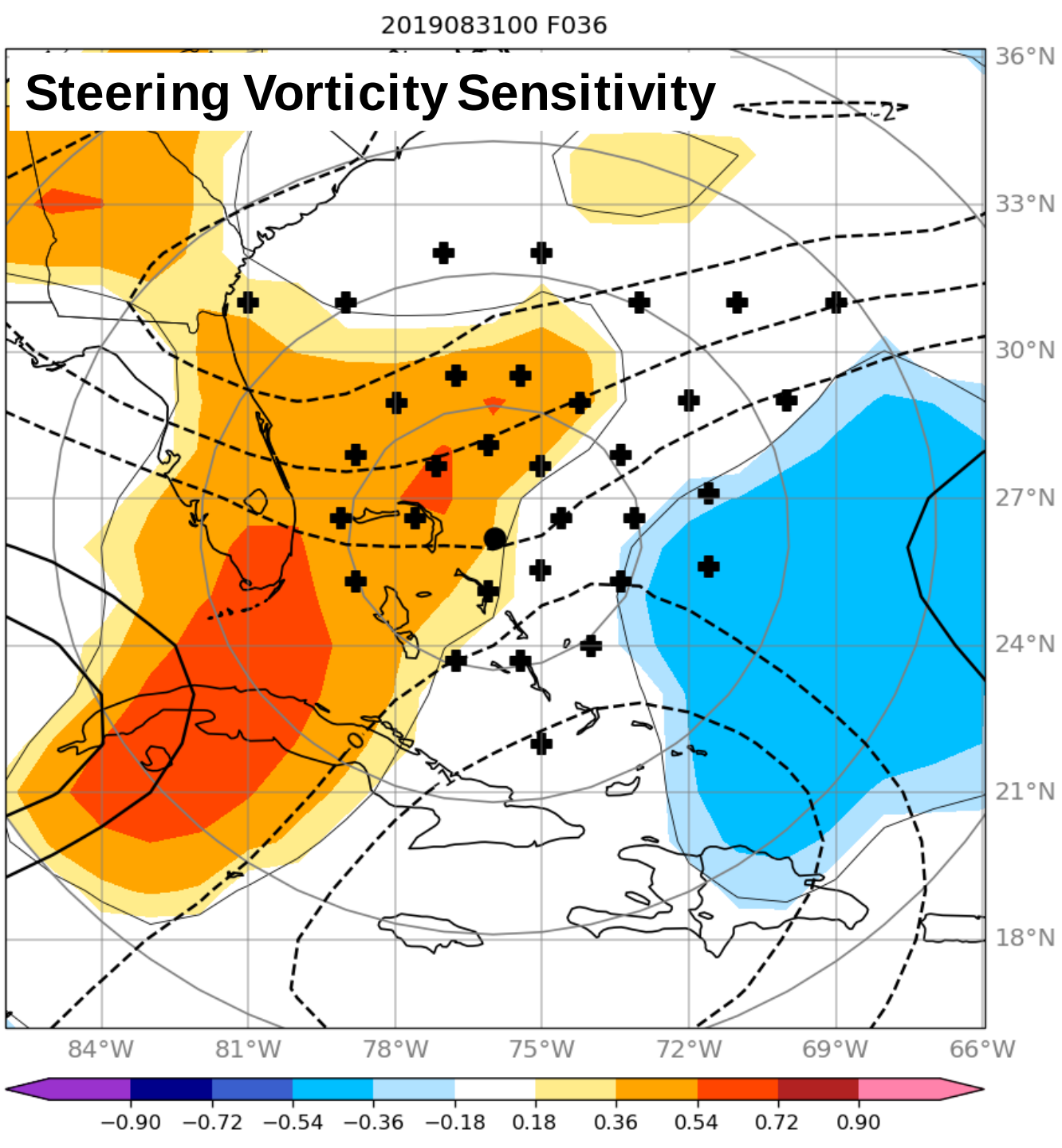

300-850 hPa Layer-Average Wind
1200 UTC 1 September 2019
30°N
20°N
80°W
70°W

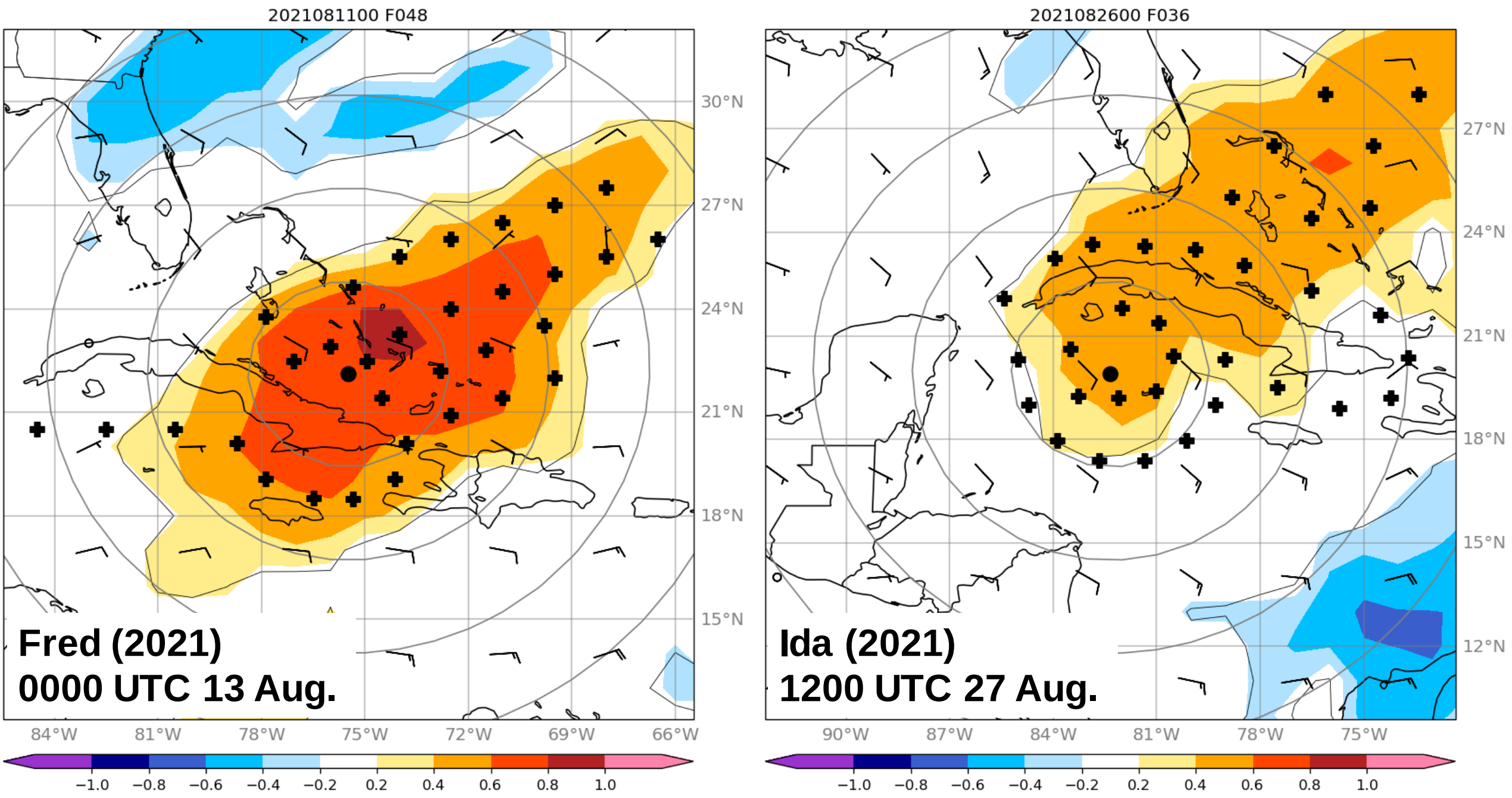

300-850 hPa Layer-Average Wind
1200 UTC 1 September 2019
30°N
20°N
80°W
70°W

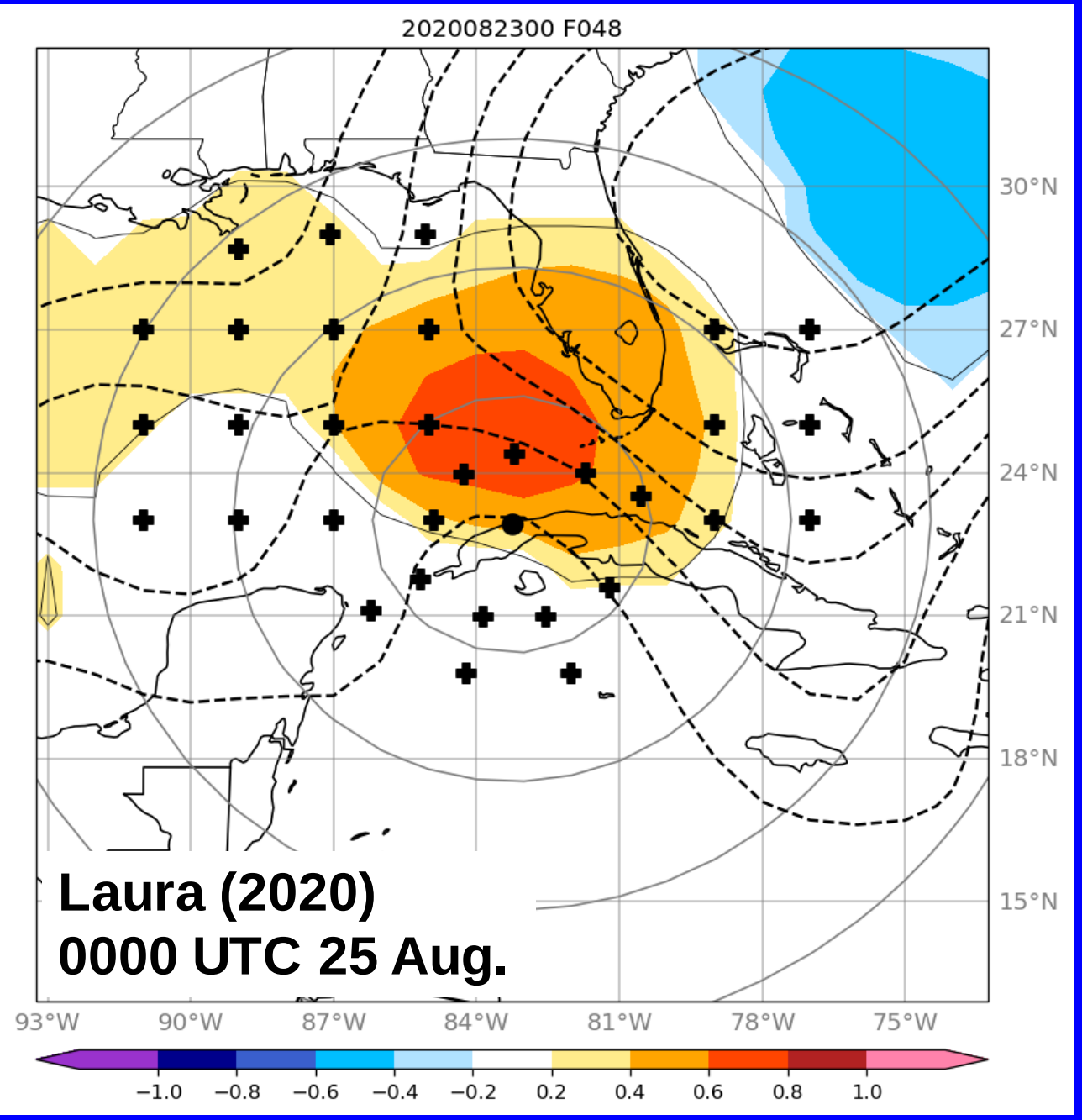

2019083100 F036
Sensitivity of Dorian's position forecast to the steering flow at earlier time.
60°N
50°N
40°N
30°N
20°N
10°N
130°W
120°W
110°W
100°W
90°W
80°W
70°W
60°W
50°W
40°W
30°W
−0.90
−0.72
−0.54
−0.36
−0.18
0.18
0.36
0.54
0.72
0.90

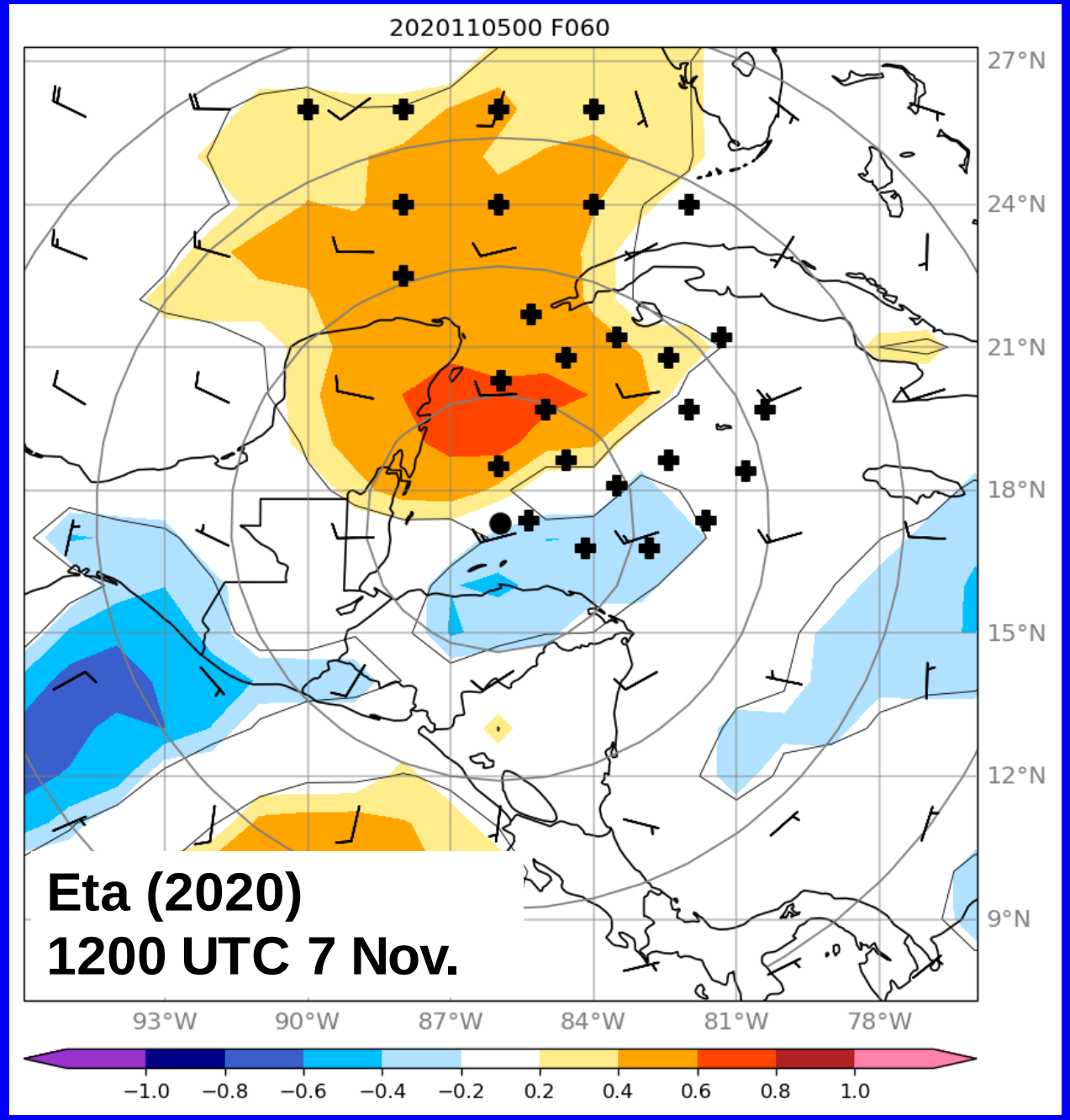

2019083100 F036
36°N
33°N
30°N
27°N
24°N
21°N
18°N
84°W
81°W
78°W
75°W
72°W
69°W
66°W
−0.90
−0.72
−0.54
−0.36
−0.18
0.18
0.36
0.54
0.72
0.90

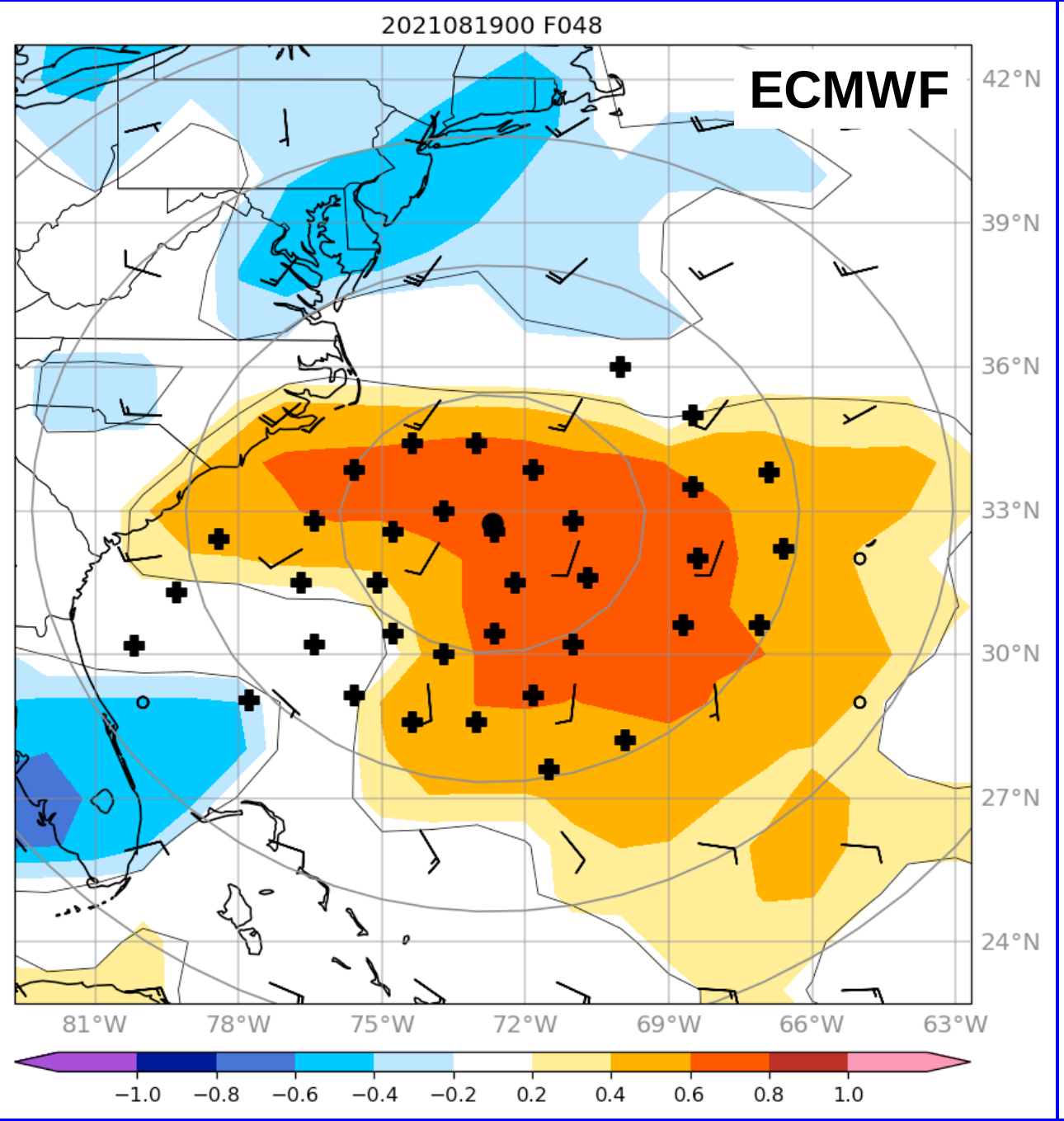

2019083100 F036
Steering Wind Sensitivity
36°N
33°N
30°N
27°N
24°N
21°N
18°N
84°W
81°W
78°W
75°W
72°W
69°W
66°W
−0.90
−0.72
−0.54
−0.36
−0.18
0.18
0.36
0.54
0.72
0.90

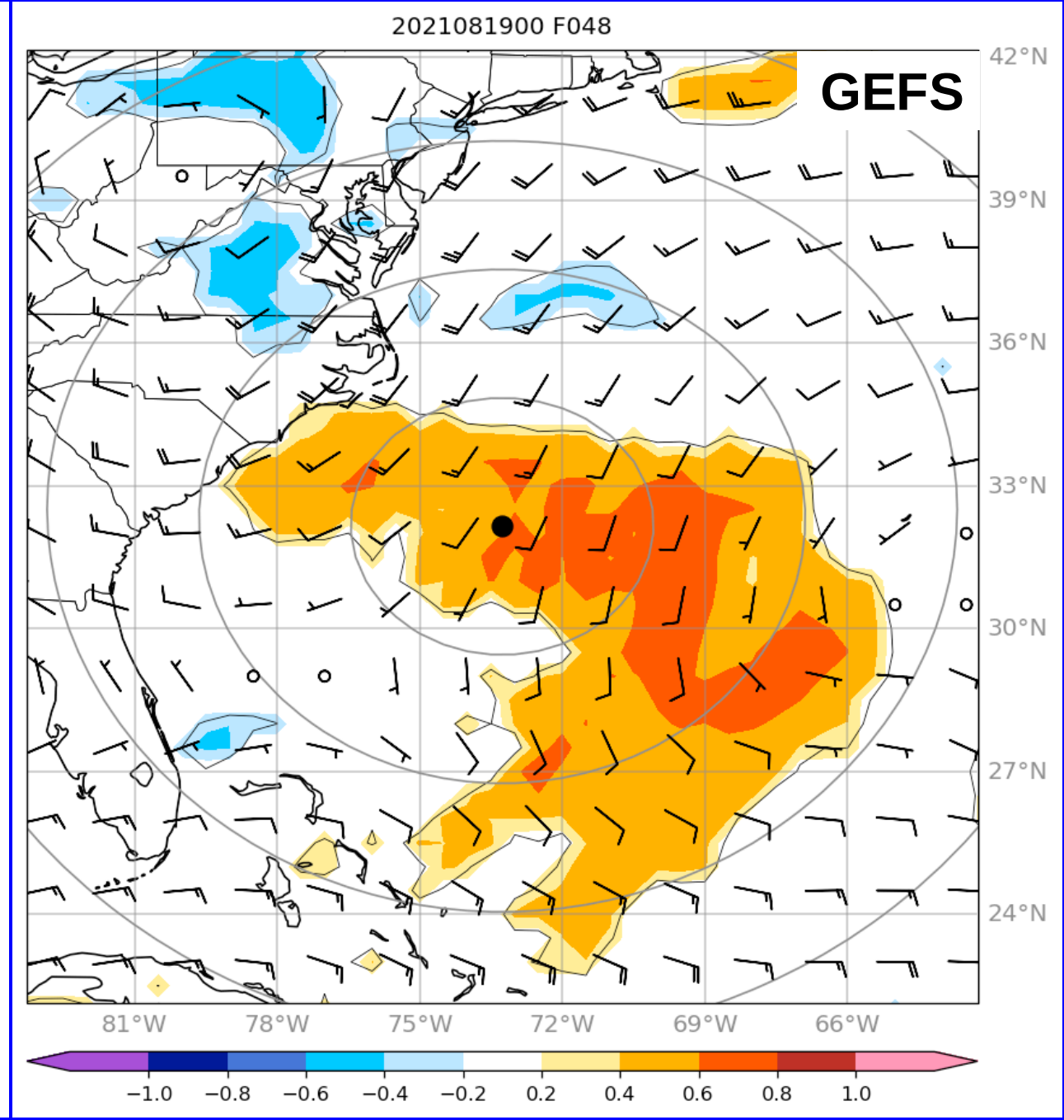

2019083100 F036
Steering Vorticity Sensitivity
2
36°N
33°N
30°N
27°N
24°N
21°N
18°N
84°W
81°W
78°W
75°W
72°W
69°W
66°W
−0.90
−0.72
−0.54
−0.36
−0.18
0.18
0.36
0.54
0.72
0.90


2021081100 F048
30°N
27°N
24°N
21°N
18°N
15°N
84°W
81°W
78°W
75°W
72°W
69°W
66°W
−1.0
−0.8
−0.6
−0.4
−0.2
0.2
0.4
0.6
0.8
1.0
Fred (2021)
0000 UTC 13 Aug.
2021082600 F036
27°N
24°N
21°N
18°N
15°N
12°N
90°W
87°W
84°W
81°W
78°W
75°W
−1.0
−0.8
−0.6
−0.4
−0.2
0.2
0.4
0.6
0.8
1.0
Ida (2021)
1200 UTC 27 Aug.


2020082300 F048
30°N
27°N
24°N
21°N
18°N
15°N
93°W
90°W
87°W
84°W
81°W
78°W
75°W
−1.0
−0.8
−0.6
−0.4
−0.2
0.2
0.4
0.6
0.8
1.0
Laura (2020)
0000 UTC 25 Aug.


2020110500 F060
27°N
24°N
21°N
18°N
15°N
12°N
9°N
93°W
90°W
87°W
84°W
81°W
78°W
−1.0
−0.8
−0.6
−0.4
−0.2
0.2
0.4
0.6
0.8
1.0
Eta (2020)
1200 UTC 7 Nov.





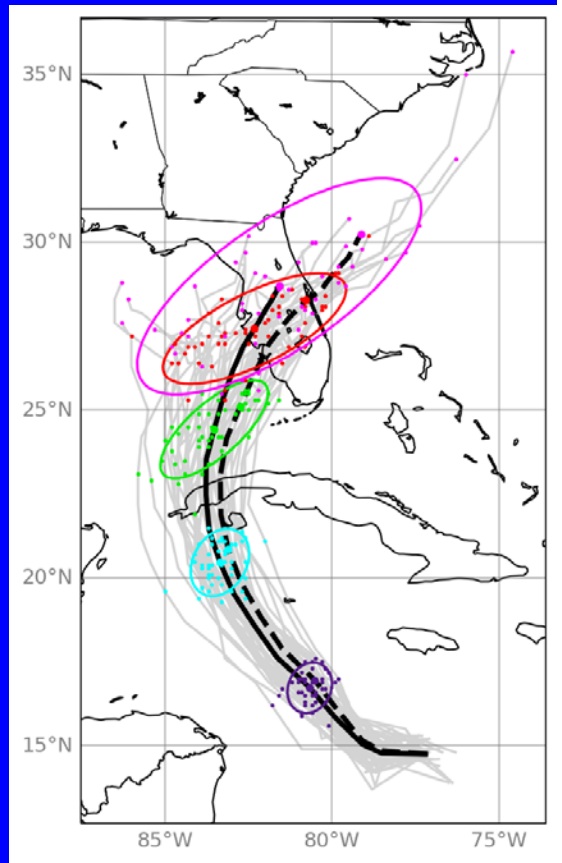
TS Henri initialized 0000 UTC 19 August 2021

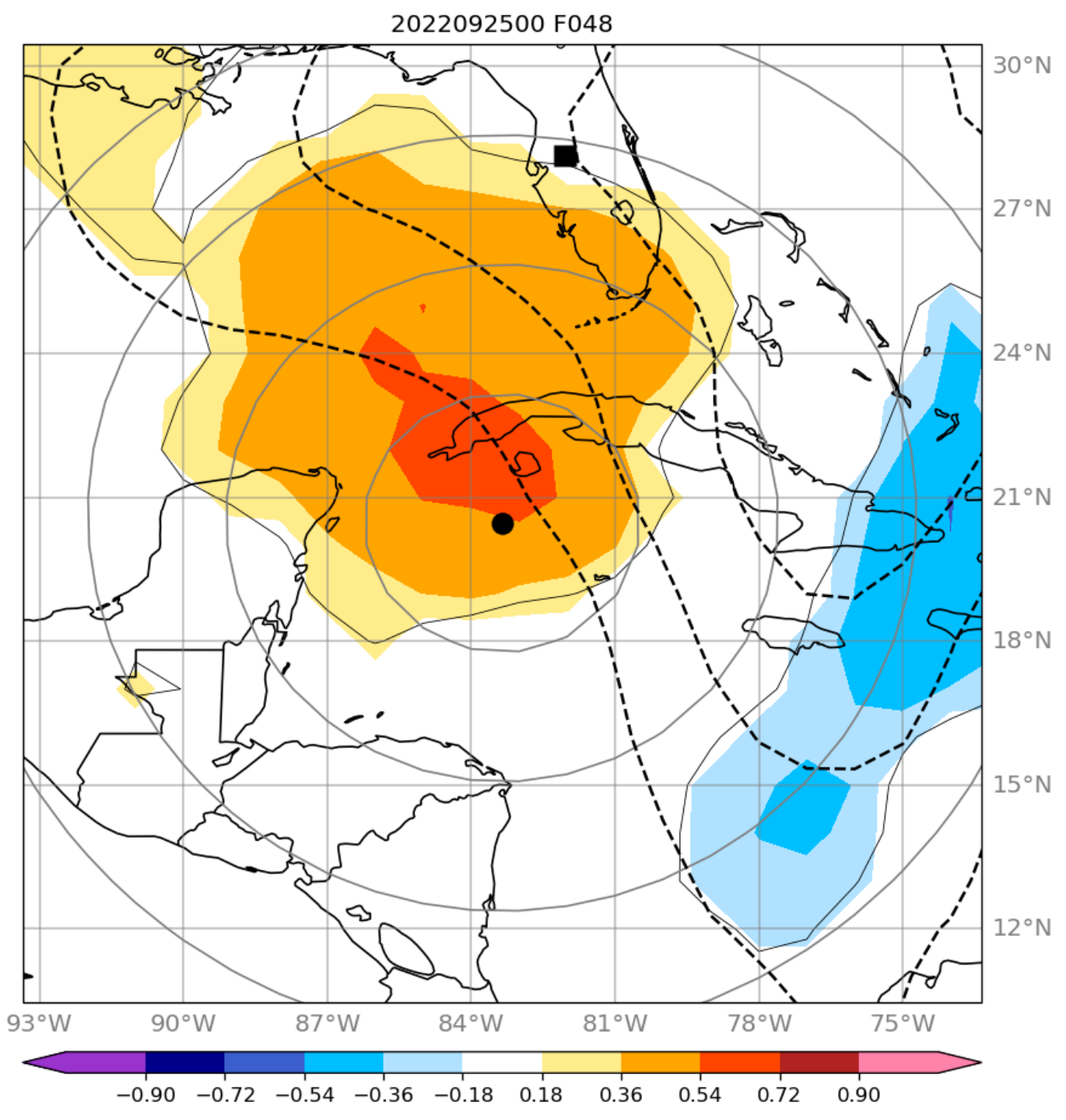
Exercise

- Now is your chance to draw flight tracks based on sensitivity guidance for hypothetical G-IV flight
- Ground Rules:
  - Aircraft has a range of ~5900 km
  - Takeoff-landing at Lakeland, FL (square)
  - Must do at least one circumnavigation of the storm at ~300 km radius (can do a second at 600 km radius)
  - Roughly 30 dropwindsondes per mission

Hurricane Ian at 0000 UTC 27 September

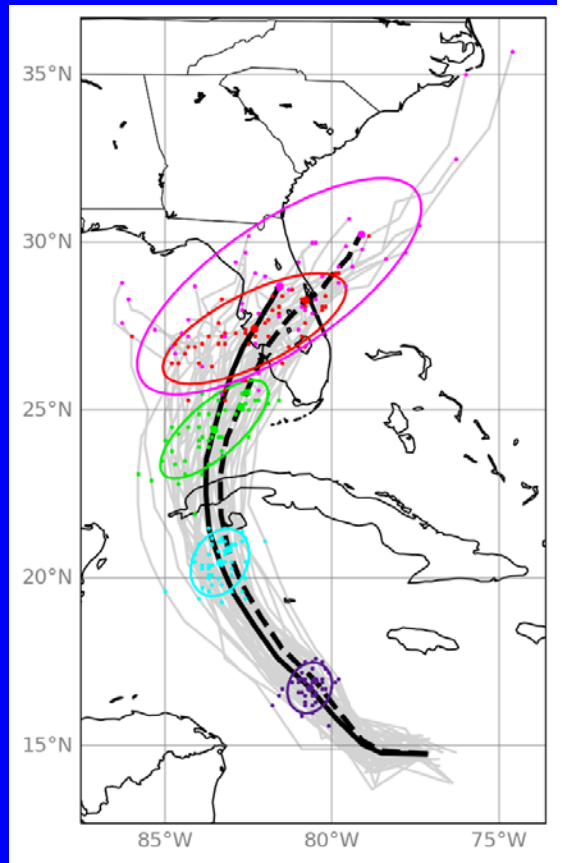
- Sensitivity to steering flow vorticity
- 300 km range rings

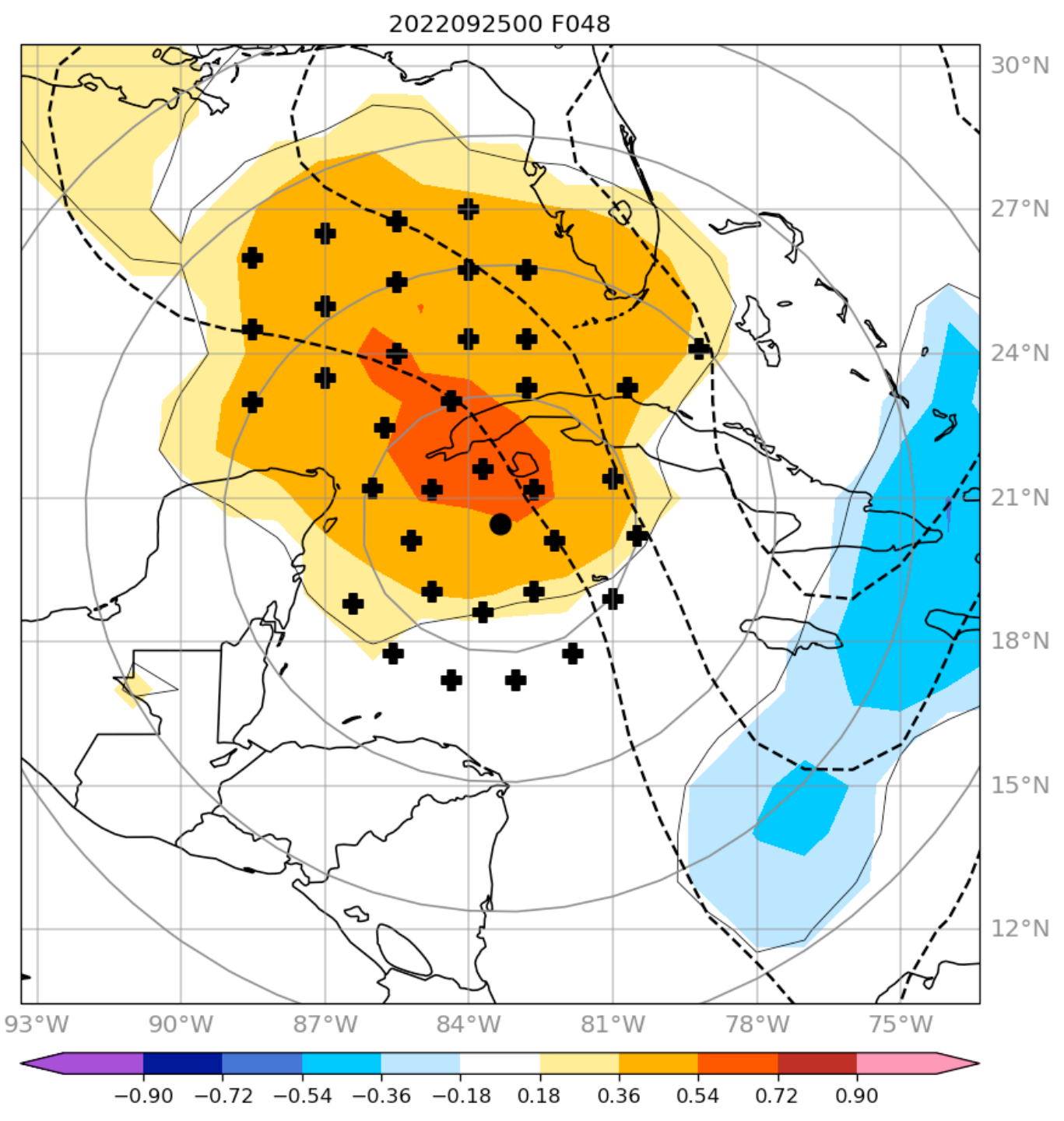




Hurricane Ian at 0000 UTC 27 September

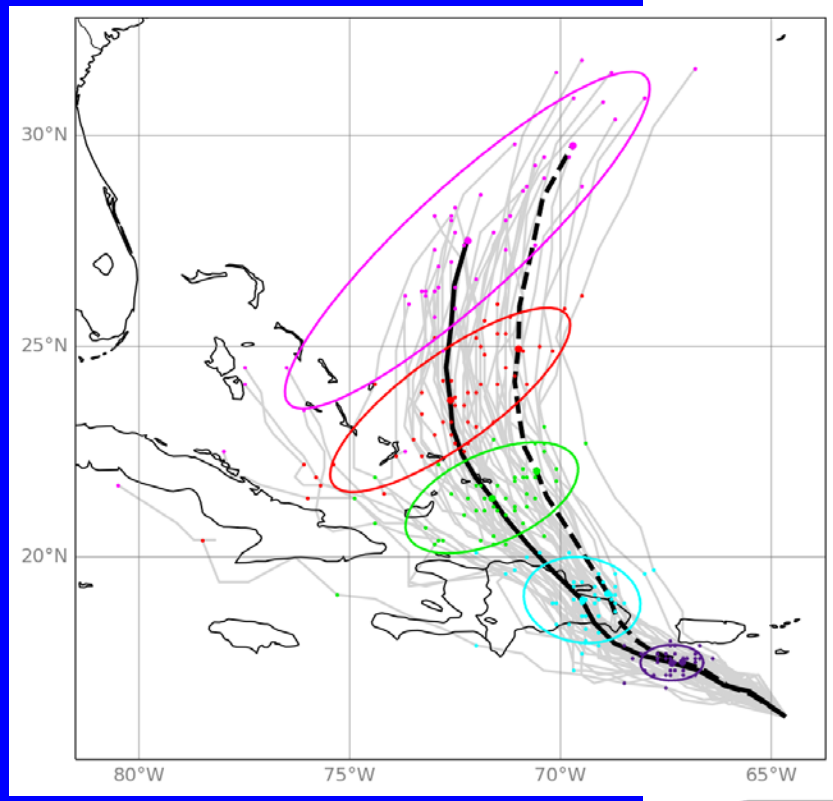
- Sensitivity to steering flow vorticity
- 300 km range rings

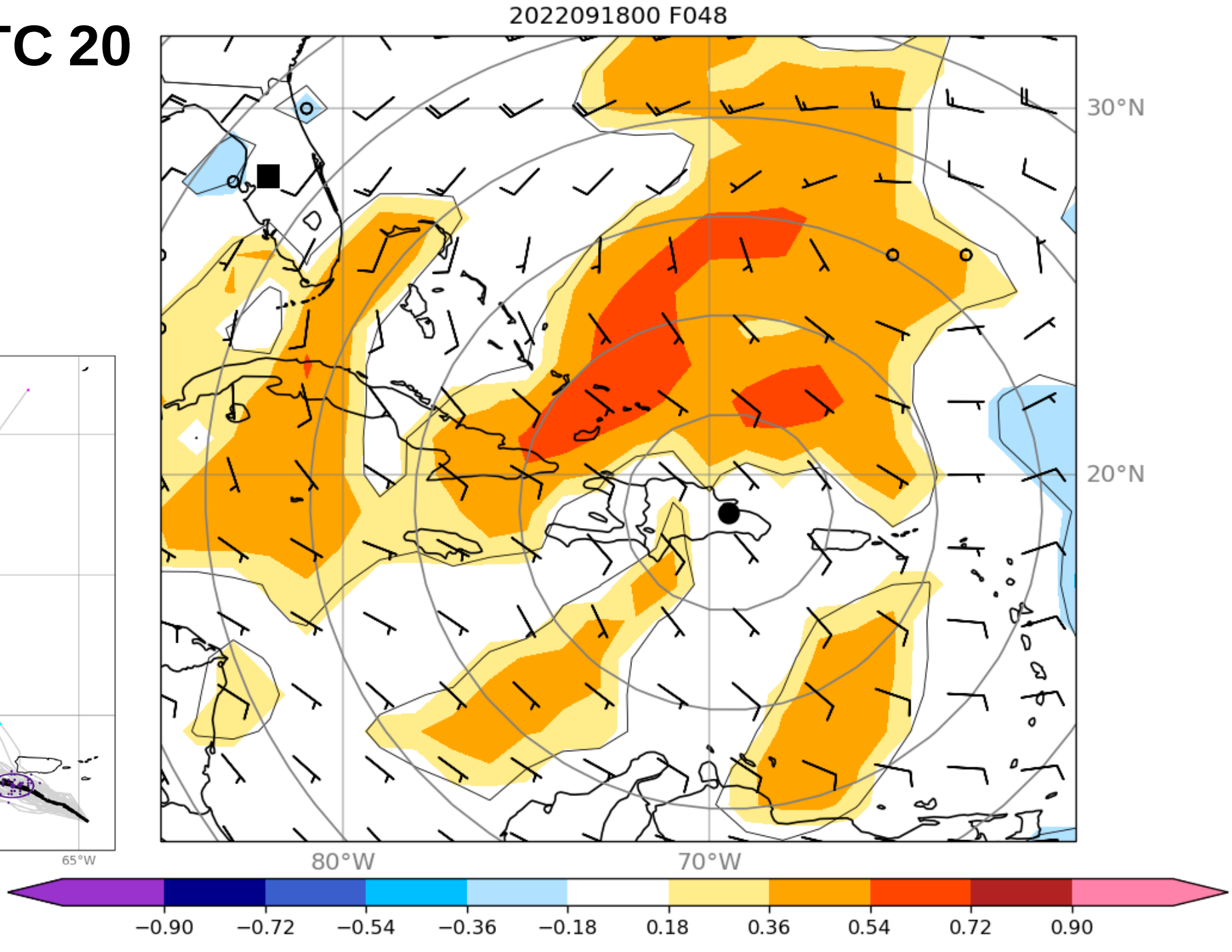




Fiona at 0000 UTC 20 September

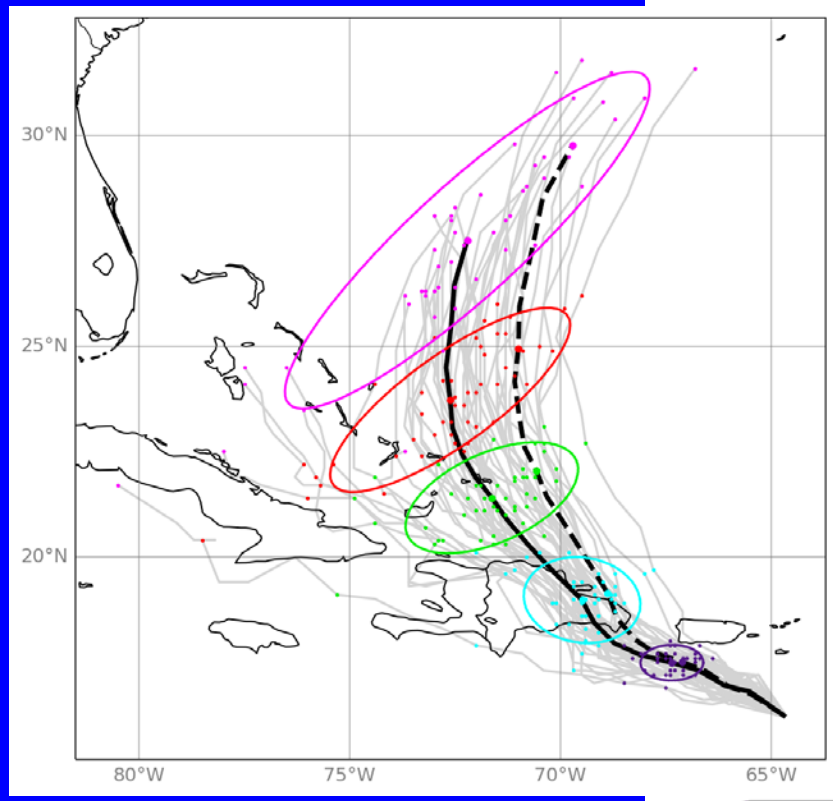
- Sensitivity to steering wind

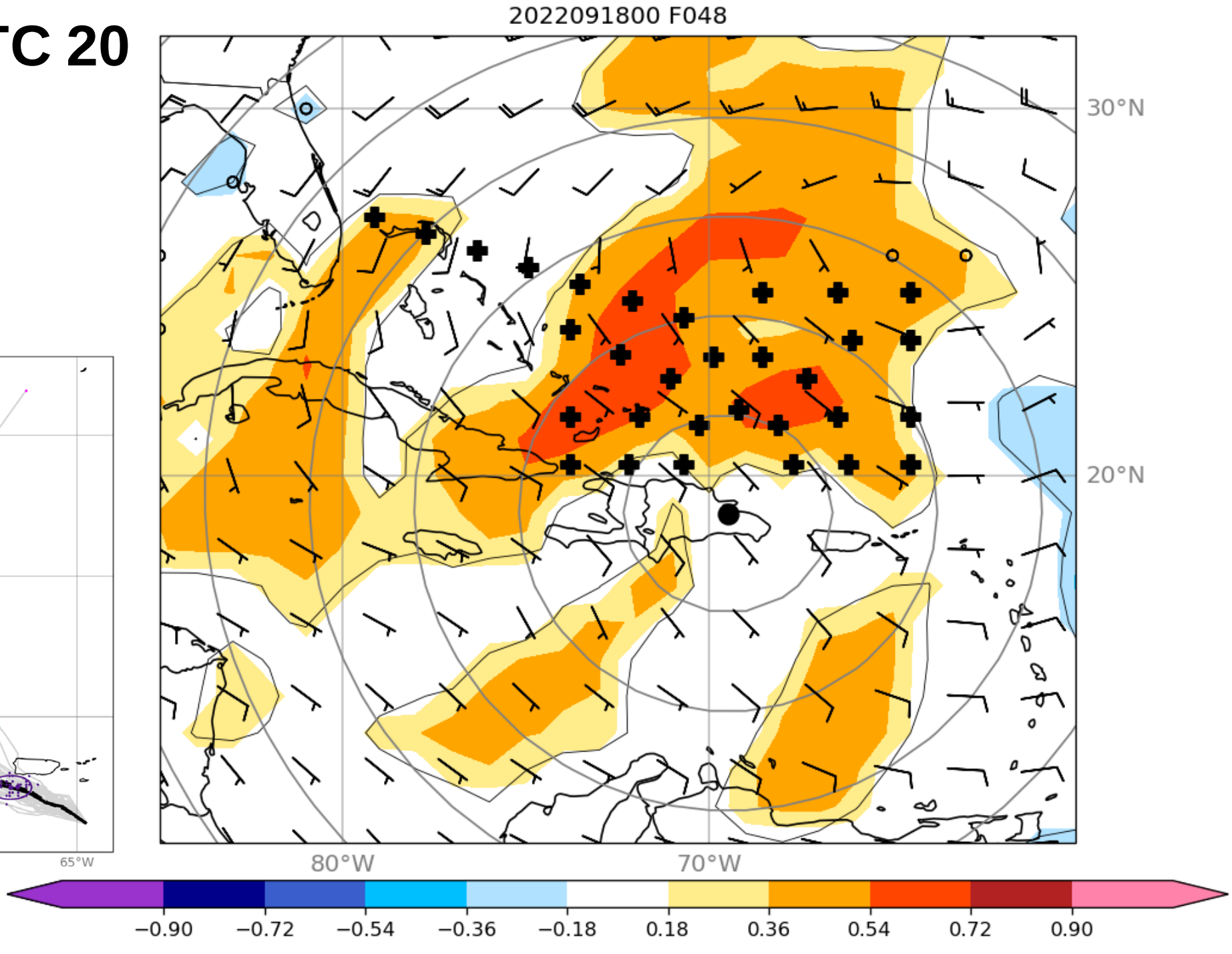




Fiona at 0000 UTC 20 September

- Sensitivity to steering wind



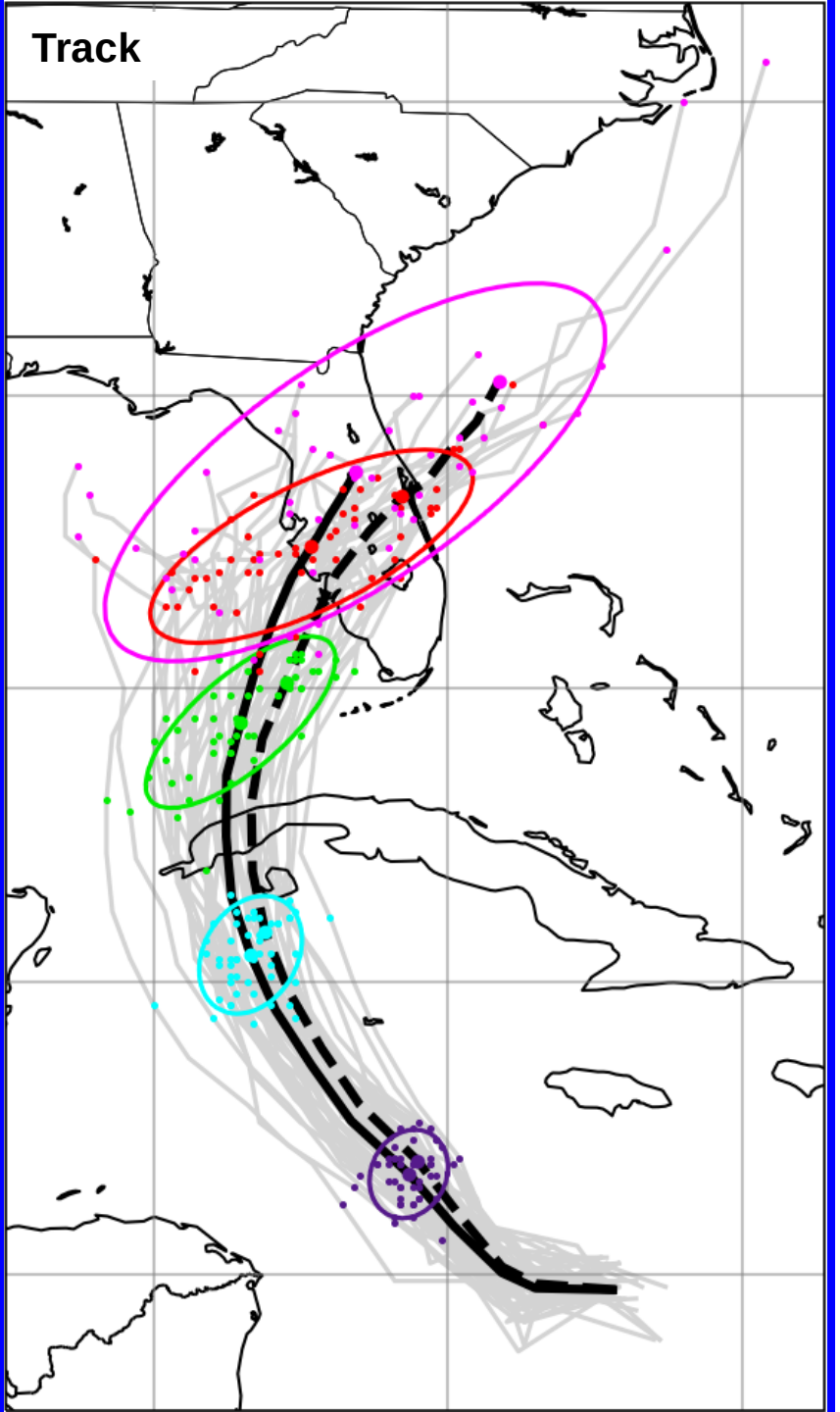


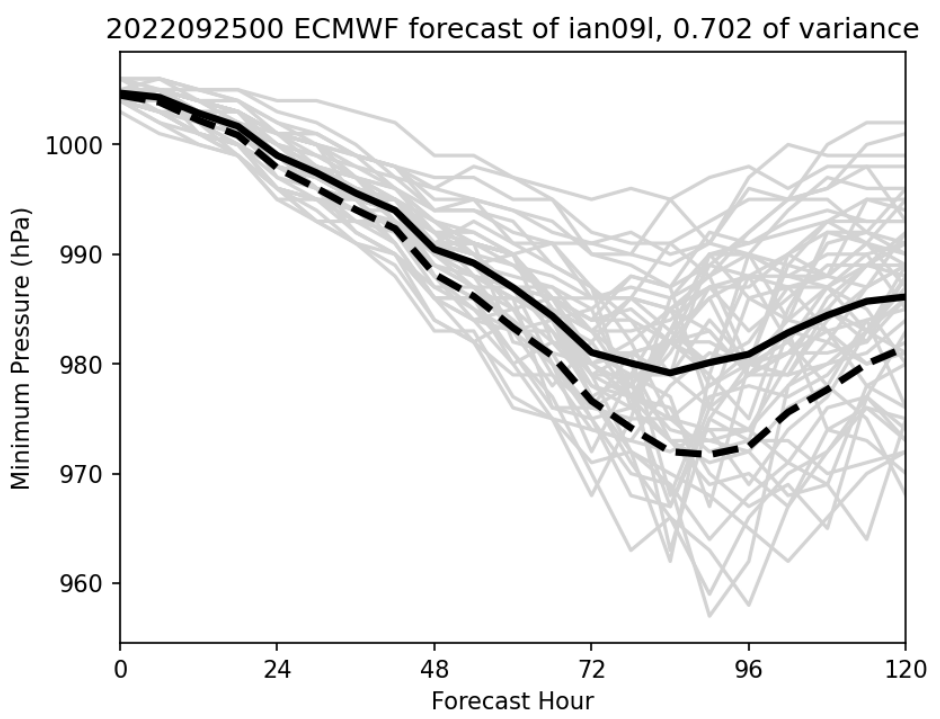
Highlights

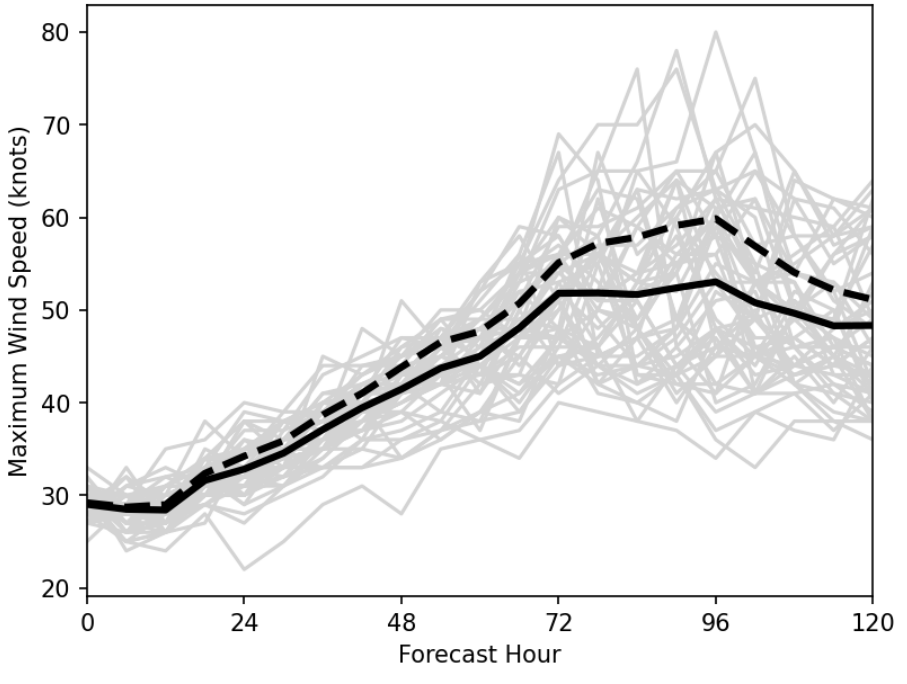
- Provided input to NHC on 71 potential flights from 19 storms during 2019-2022
- Methodology run on all storms starting in 2020
- Capability to calculate using both ECMWF and GEFS ensemble output
- Portable python-based software package
- Software provides grids that can be input into NHC software that is used to develop flight tracks
- Currently being evaluated for transition to operations

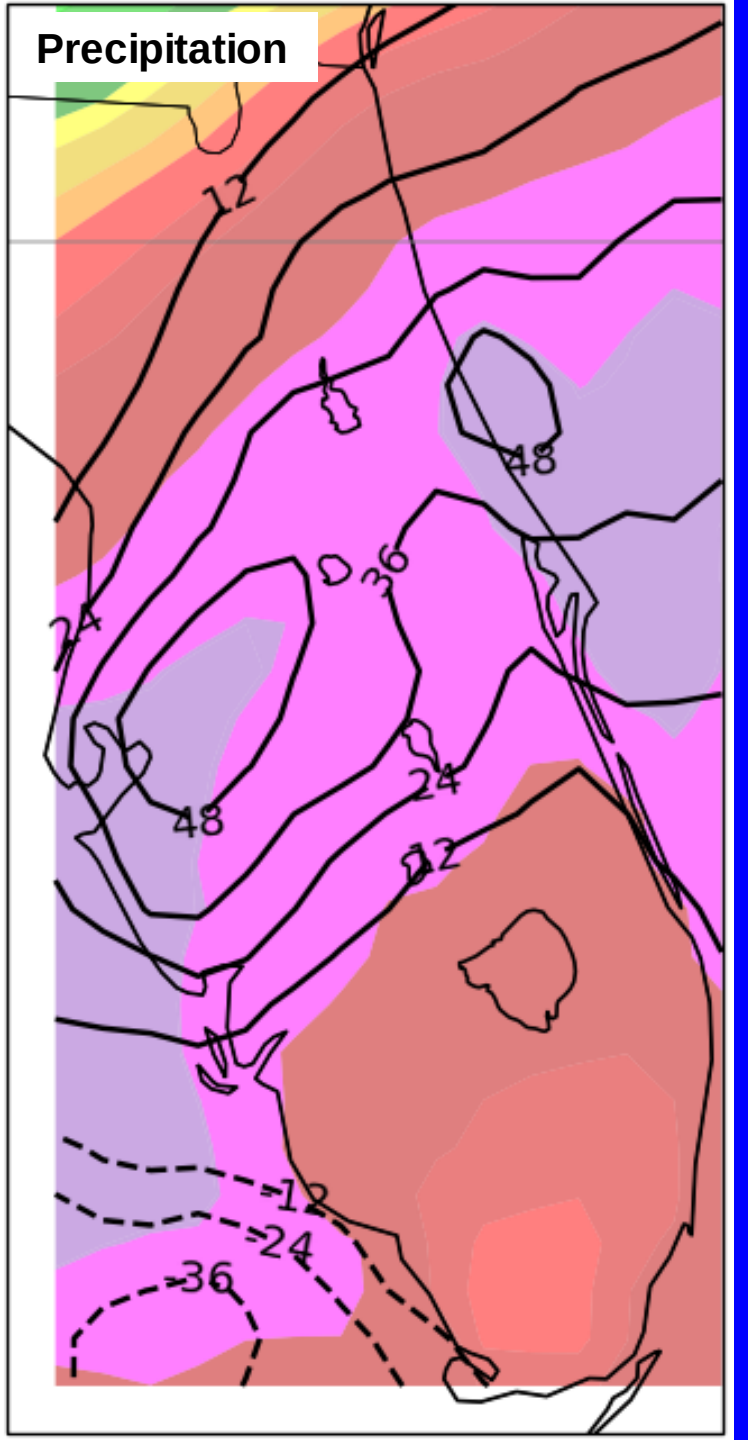
Future Directions

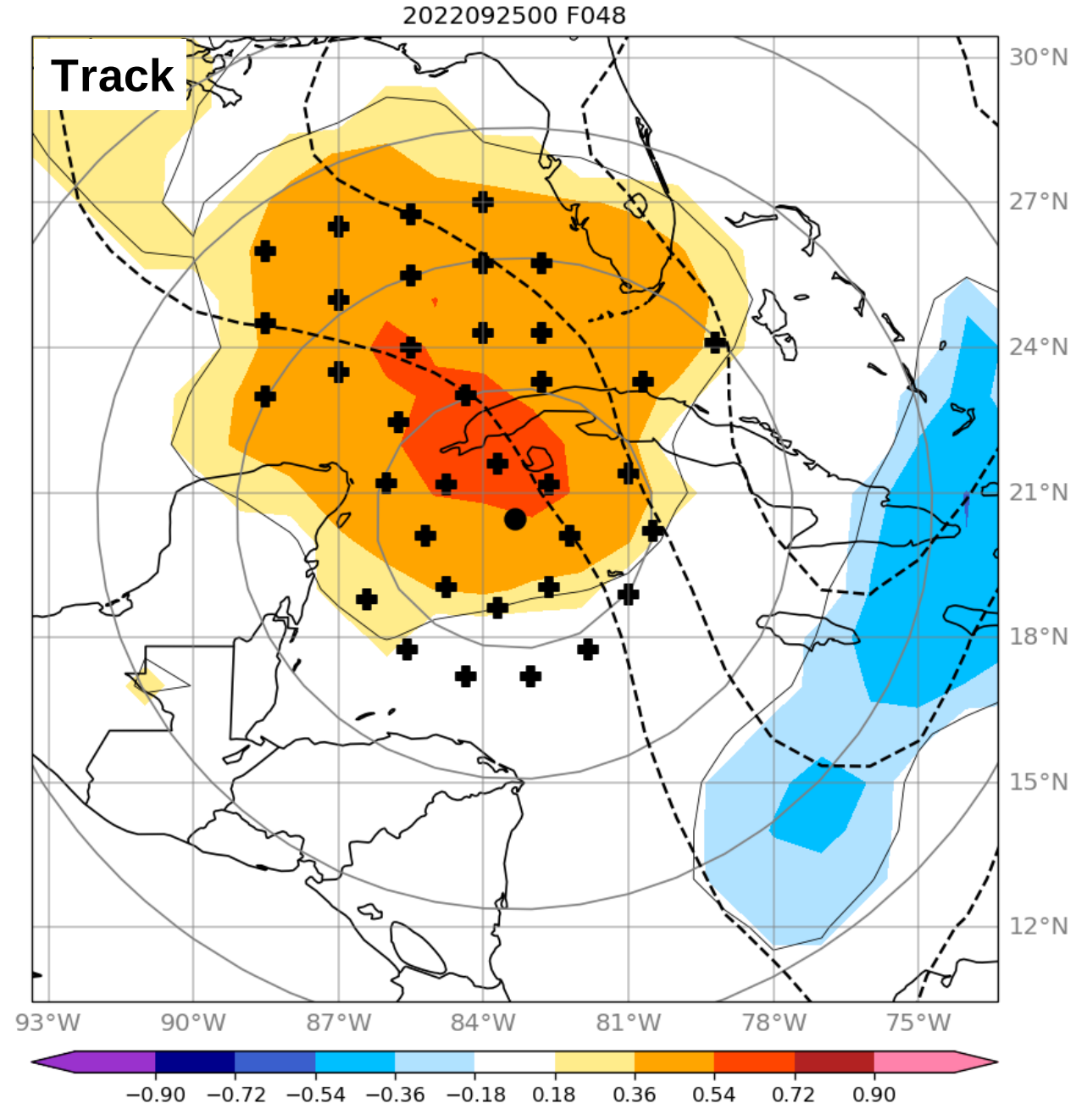
- Applications of ensemble sensitivity have focused on trying to improve TC track forecasts
- Can extend to other properties of the TC that can be impactful to society, such as intensity, wind, and precipitation
- Remainder of time shows application of this method to new forecast outcomes using Ian forecast from exercise

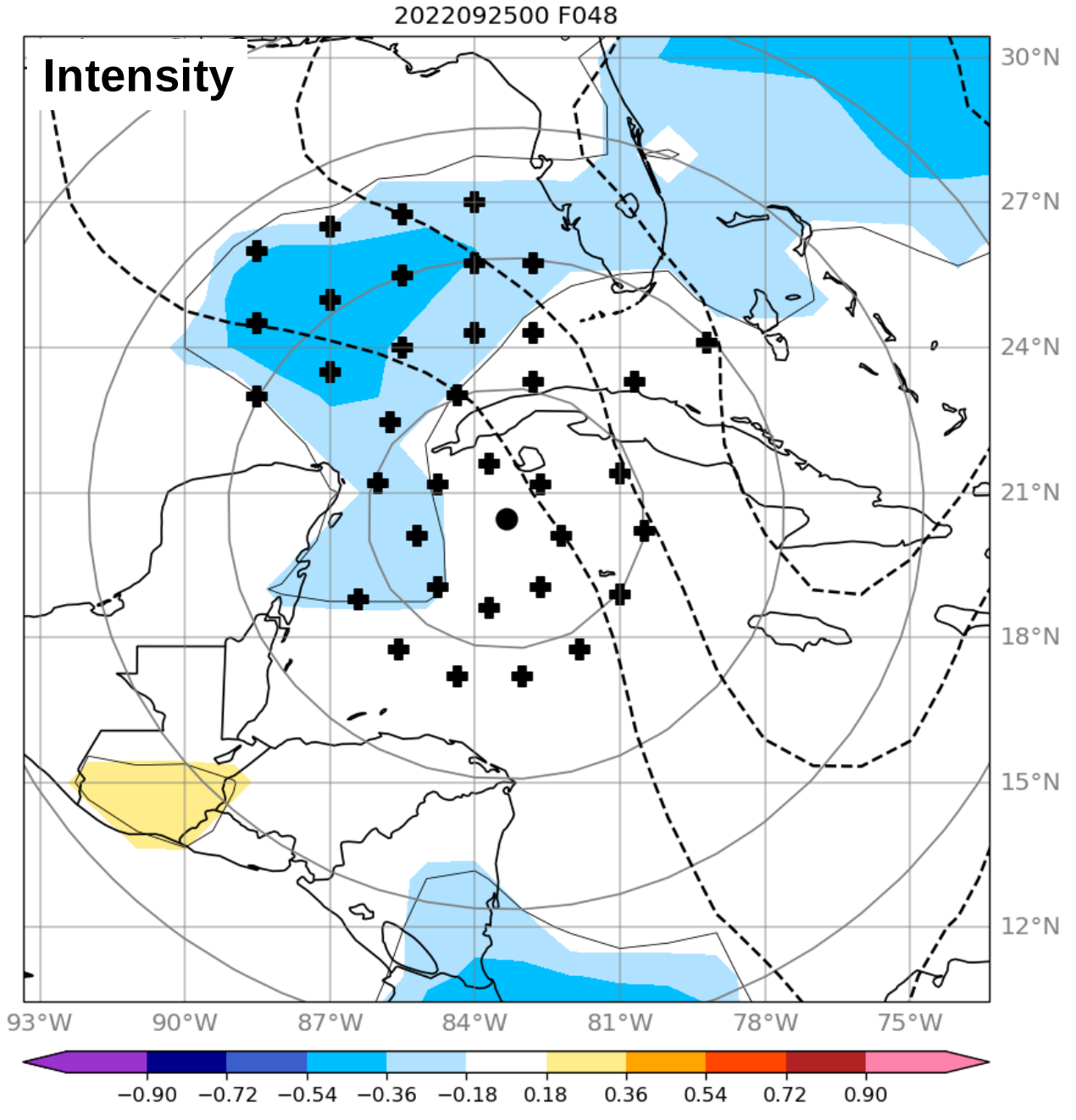

Track

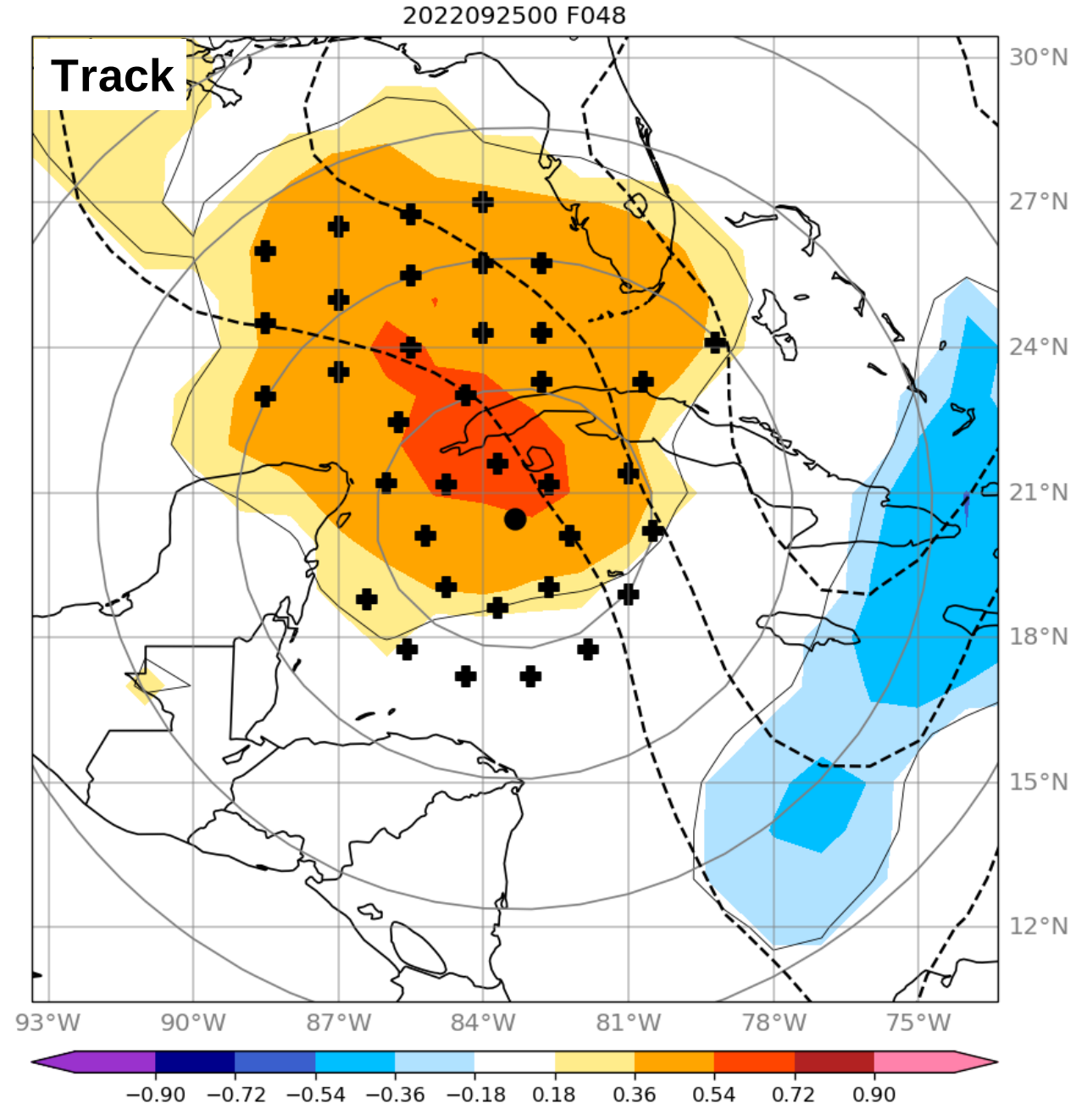

2022092500 ECMWF forecast of ian09l, 0.702 of variance
Minimum Pressure (hPa)
1000
990
980
970
960
0
24
48
72
96
120
Forecast Hour

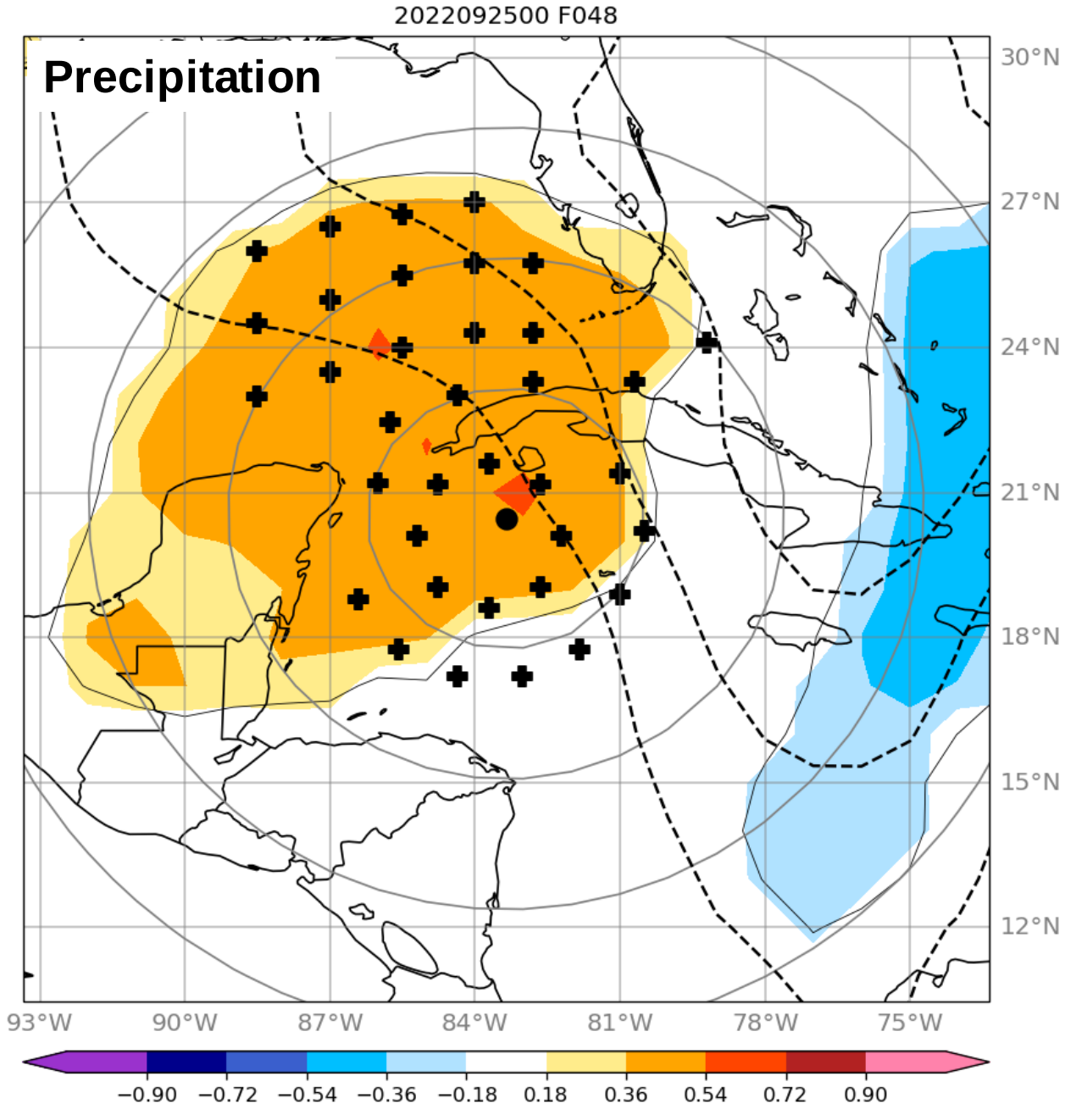

Maximum Wind Speed (knots)
80
70
60
50
40
30
20
0
24
48
72
96
120
Forecast Hour


Precipitation
12
48
36
24
48
24
12
12
24
36


2022092500 F048
Track
30°N
27°N
24°N
21°N
18°N
15°N
12°N
93°W
90°W
87°W
84°W
81°W
78°W
75°W
−0.90 −0.72 −0.54 −0.36 −0.18 0.18 0.36 0.54 0.72 0.90


2022092500 F048
Intensity
30°N
27°N
24°N
21°N
18°N
15°N
12°N
93°W
90°W
87°W
84°W
81°W
78°W
75°W
−0.90 −0.72 −0.54 −0.36 −0.18 0.18 0.36 0.54 0.72 0.90


2022092500 F048
Track
30°N
27°N
24°N
21°N
18°N
15°N
12°N
93°W
90°W
87°W
84°W
81°W
78°W
75°W
−0.90 −0.72 −0.54 −0.36 −0.18 0.18 0.36 0.54 0.72 0.90


2022092500 F048
Precipitation
30°N
27°N
24°N
21°N
18°N
15°N
12°N
93°W
90°W
87°W
84°W
81°W
78°W
75°W
−0.90 −0.72 −0.54 −0.36 −0.18 0.18 0.36 0.54 0.72 0.90

Summary

- Ensemble sensitivity provides a flexible method for computing forecast sensitivity and supplemental observation locations
- Computationally inexpensive assuming that forecasts already exist
- Vast majority of position forecasts sensitive to near-storm steering wind variability and/or weaknesses in subtropical ridge
  - Few cases of far-upstream sensitivity with troughs, etc.
- Future work will extend to other metrics (intensity, hazards)

Questions or Comments: Ryan Torn, rtorn@albany.edu