Application of Ensemble-based Sensitivity to ECMWF Ensemble Forecasts in Field Campaigns

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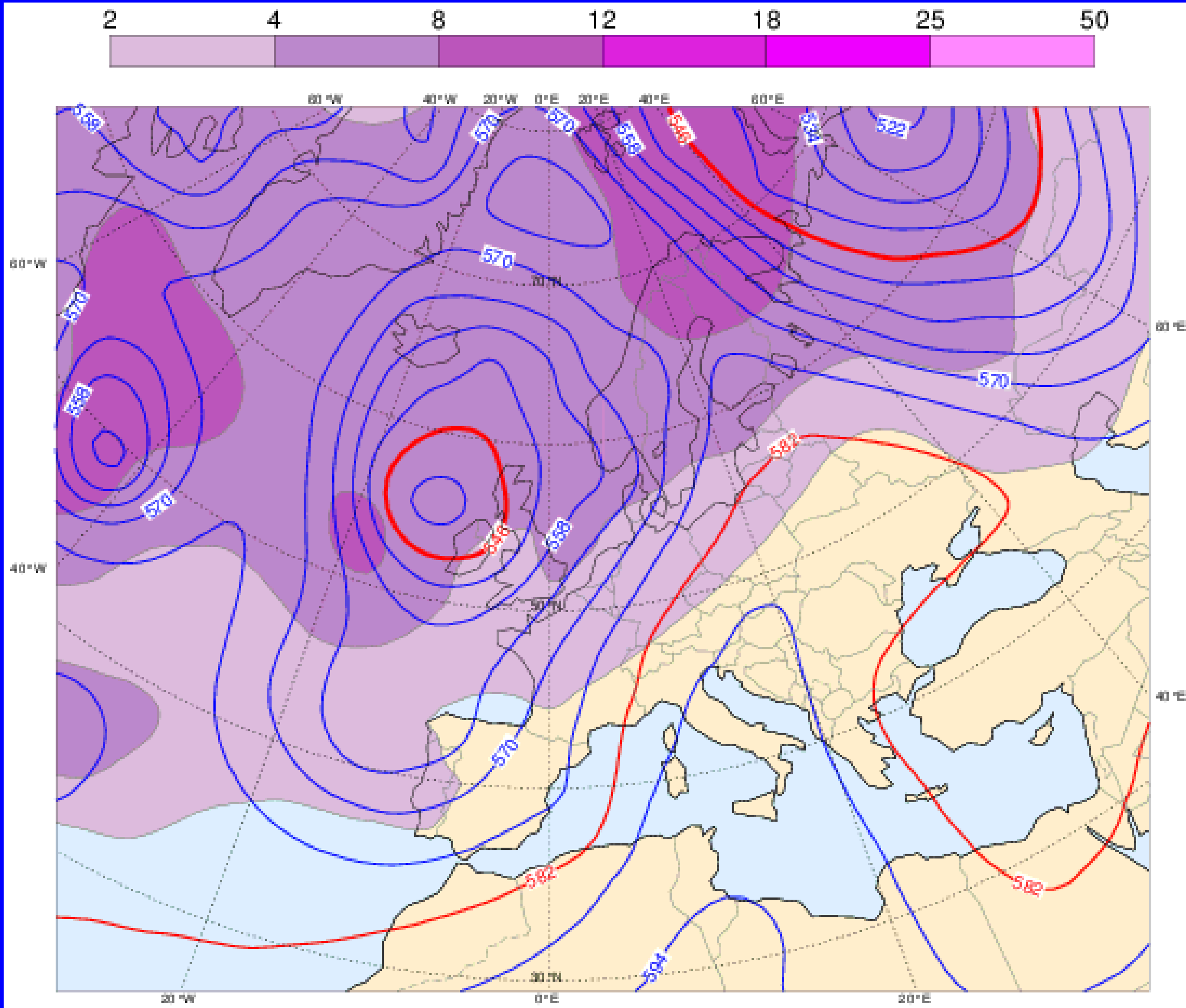
Support From: NSF 1239787, 1461753, 1545917
NOAA NA12NWS4680003, NA14OAR4830172, NA16NWS4680025

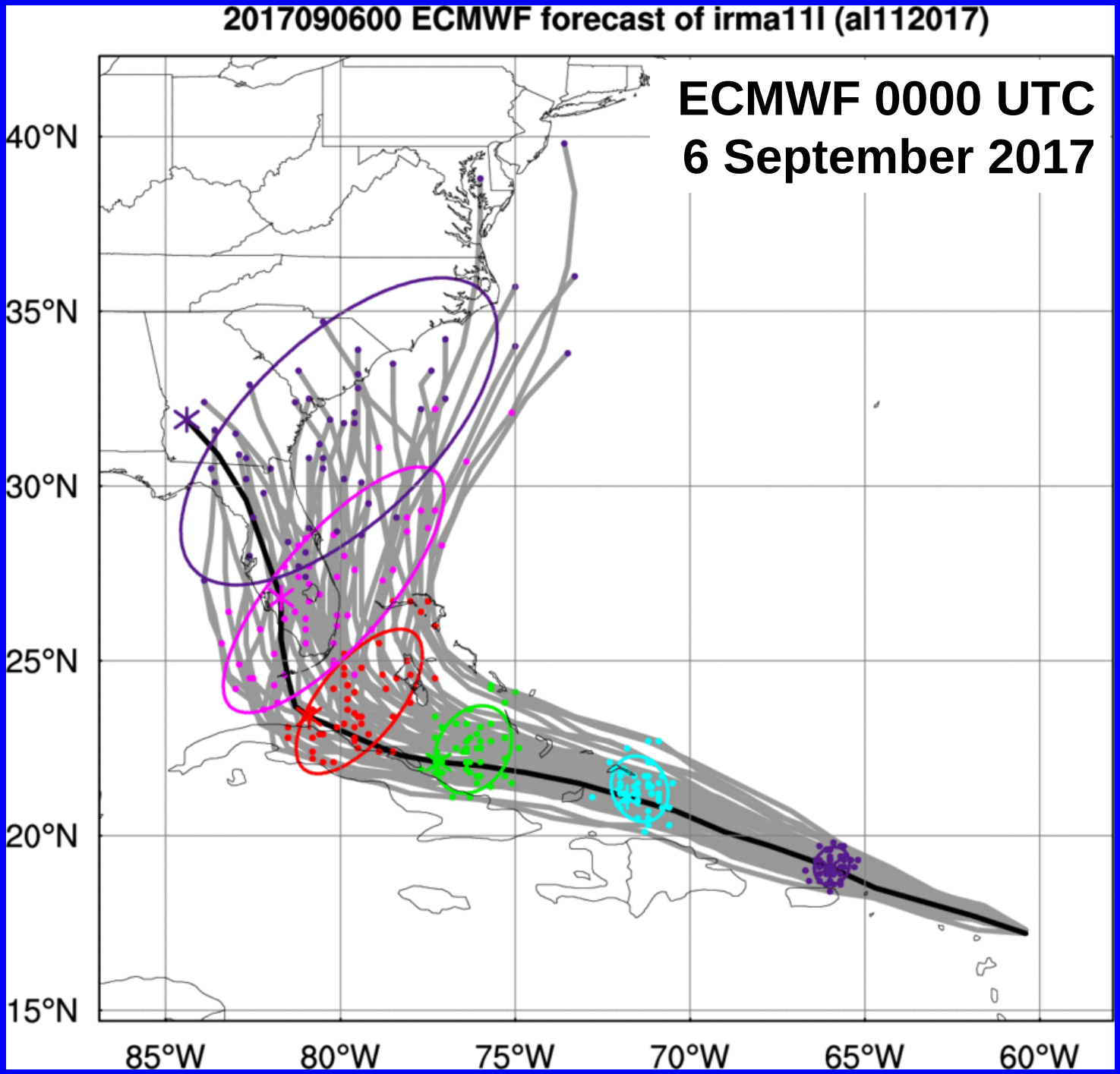
Ensemble Forecasting

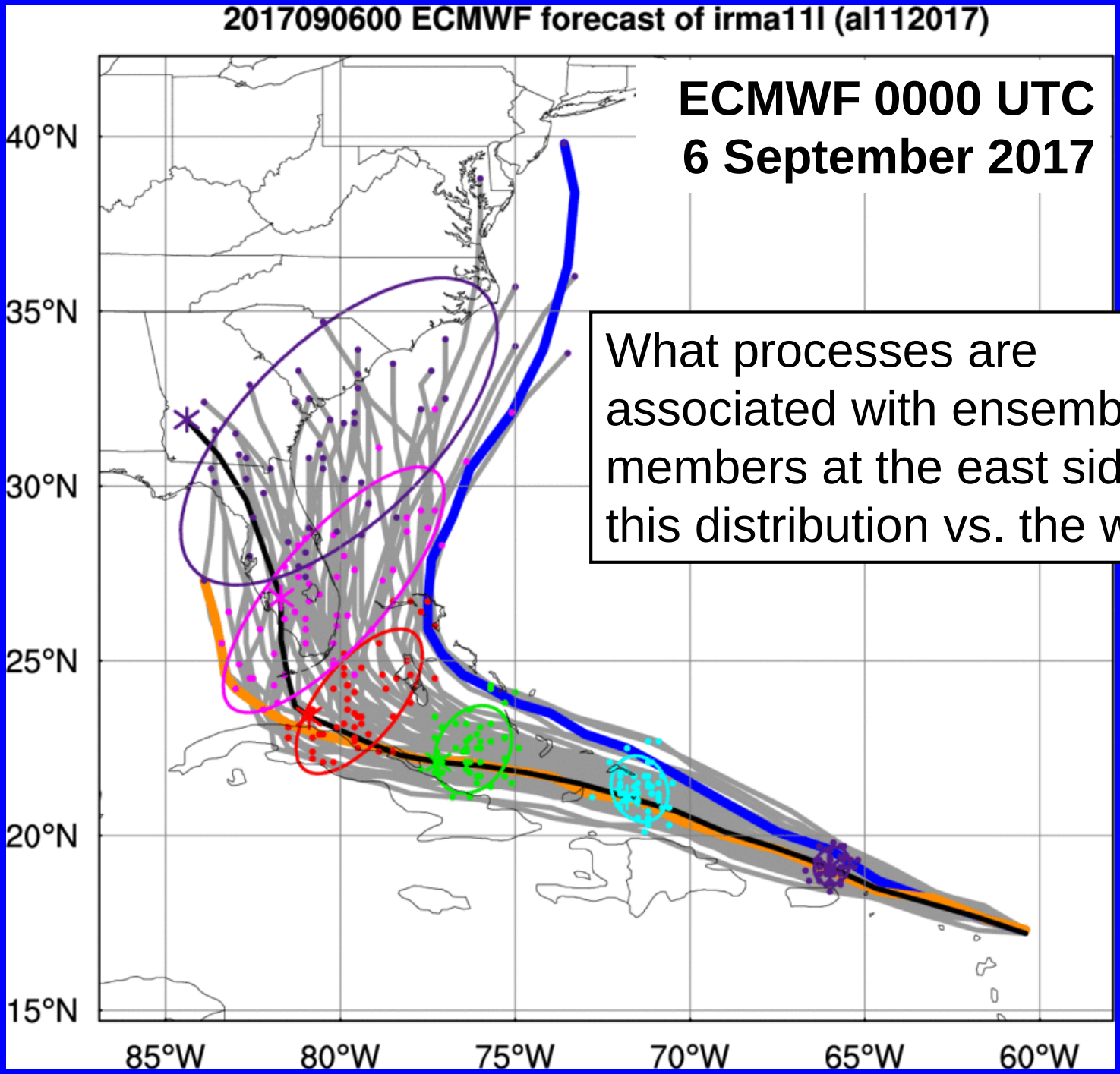
- The use of ensemble forecasts has grown significantly in the last 20 years as a means to deal with the chaotic nature of the atmosphere
  - Often used to compute forecast probability distributions
- These datasets have become very large, often exceeding O(Tb day^{-1})
- As a consequence, most applications use the first two moments of the forecast PDF (i.e., mean, standard deviation)


2
4
8
12
18
25
50
60°W
40°W
20°W
0°E
20°E
40°E
60°E
70°N
50°N
30°N
570
558
546
534
522
582
594

Overview

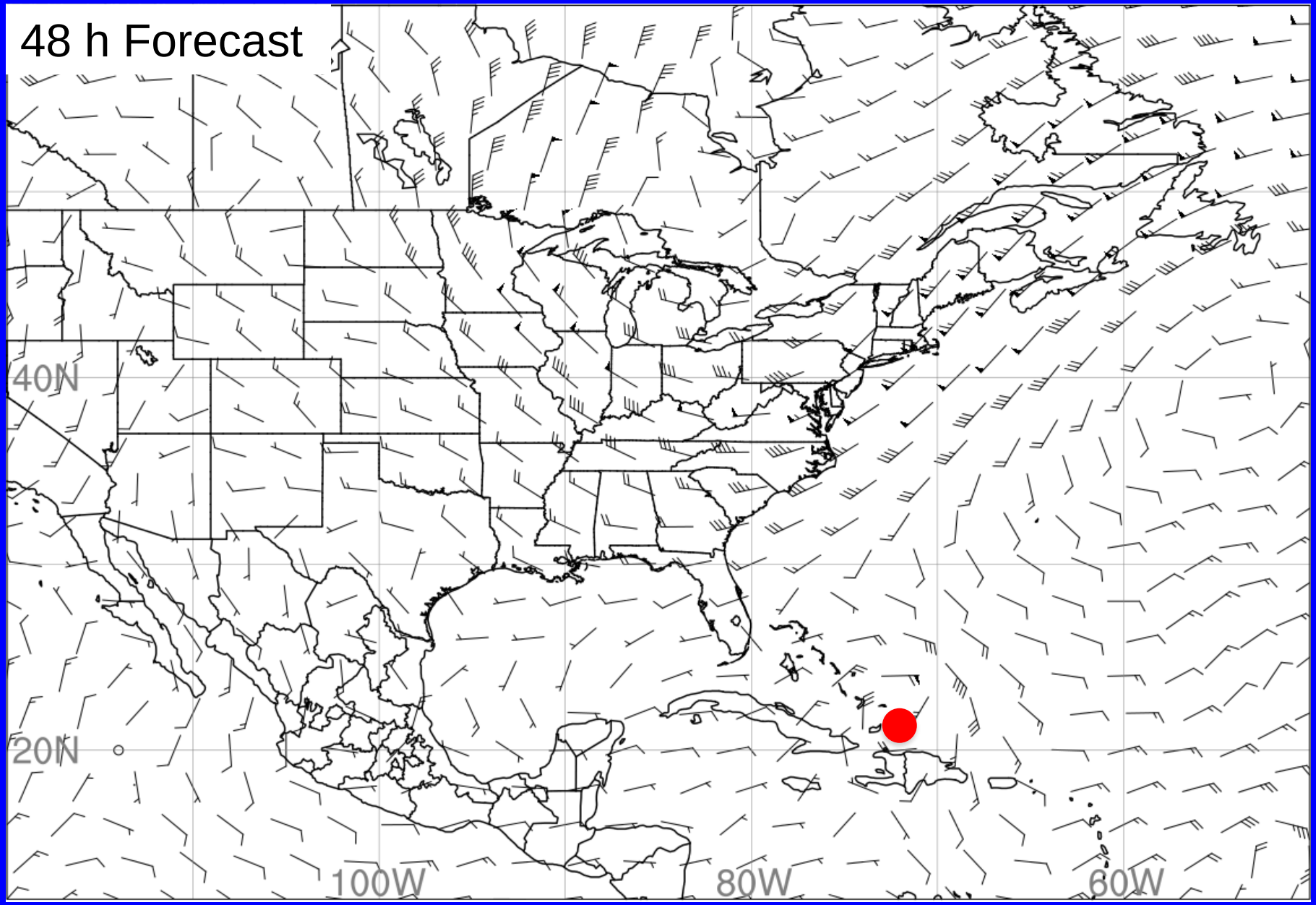
- While this approach might be satisfactory for many users, there are situations where it is of interest to understand why some particular forecast outcomes are obtained
- This information could be used to inform how to improve model either through more observations or targeted process studies
- Example: Hurricane Irma (2017)

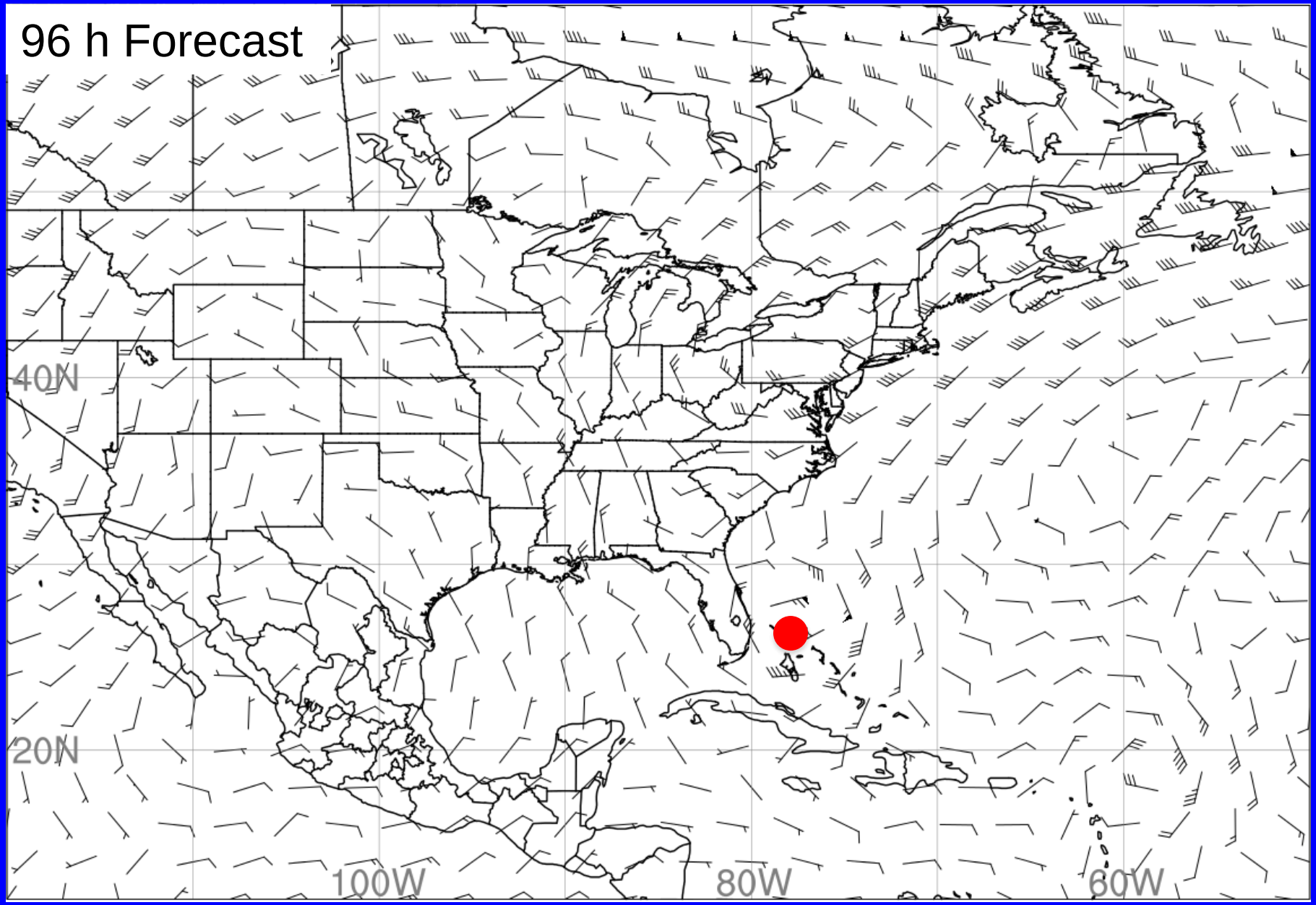

2017090600 ECMWF forecast of irma11l (al112017)
ECMWF 0000 UTC
6 September 2017
40°N
35°N
30°N
25°N
20°N
15°N
85°W
80°W
75°W
70°W
65°W
60°W

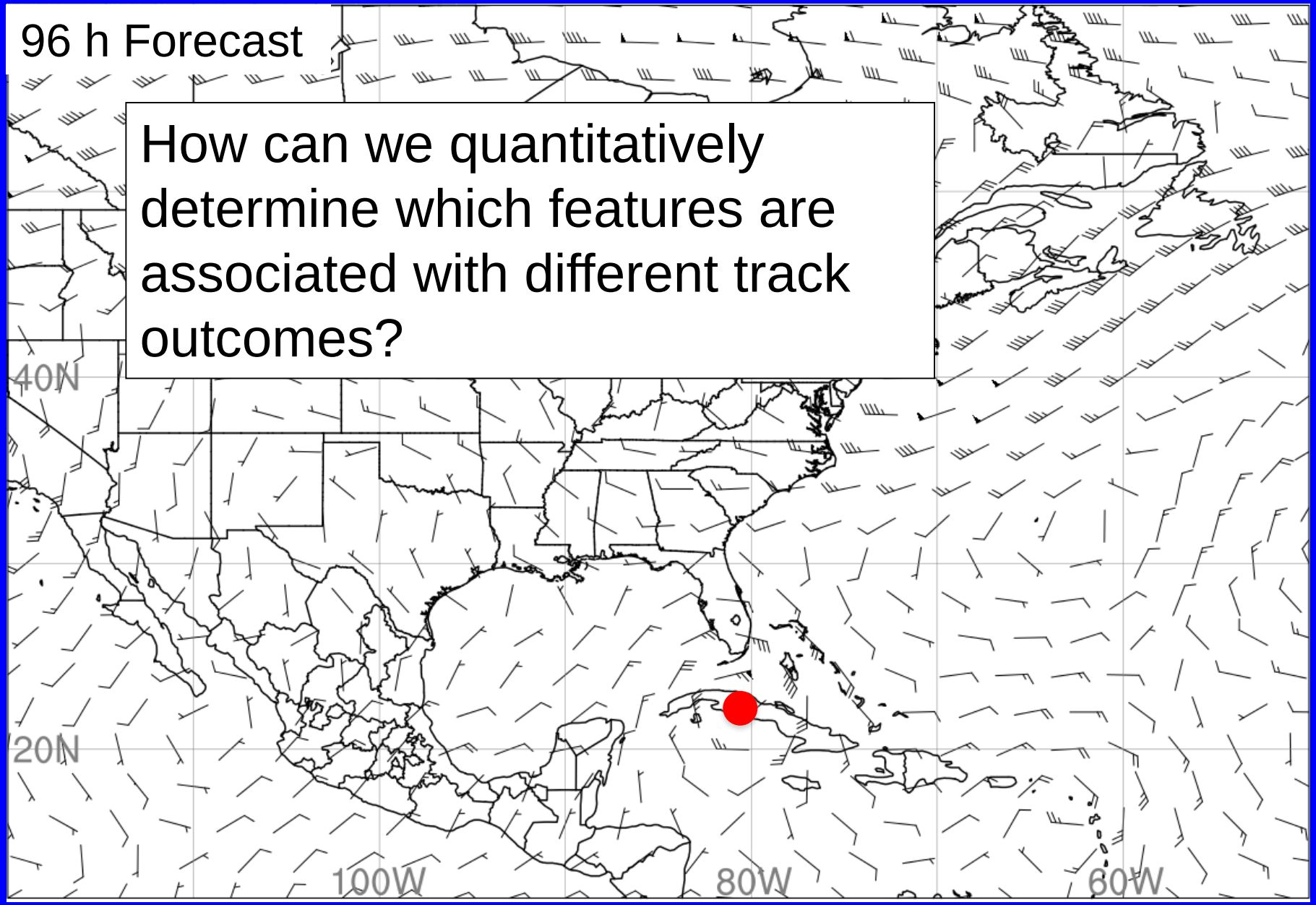

2017090600 ECMWF forecast of irma11l (al112017)
ECMWF 0000 UTC
6 September 2017
What processes are associated with ensemble members at the east side of this distribution vs. the west?
40°N
35°N
30°N
25°N
20°N
15°N
85°W
80°W
75°W
70°W
65°W
60°W

Overview

- Tropical Cyclone motion highly influenced by a deep-tropospheric “steering flow” (typically defined as the 250-850 hPa layer-average wind)
- Could 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
How can we quantitatively determine which features are associated with different track outcomes?
40N
20N
100W
80W
60W

Overview

- It is possible that a forecaster or model developer could evaluate individual ensemble members, but it can be difficult and time consuming to synthesize where and why different forecast evolutions occur.
- Fundamentally, ensemble forecasting is a statistical method; therefore, it lends itself to statistical hypothesis testing

Overview

- Would be helpful to have a suite of methods that could quickly analyze the ensemble information to identify sensitive areas of forecast state
  - i.e., regions of large sensitivity denote areas that could benefit from additional observations
  - In turn, feeds back onto the model forecasts
- Similar to adjoint or singular vector methods; however, these approaches can be problematic with non-linear error growth

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

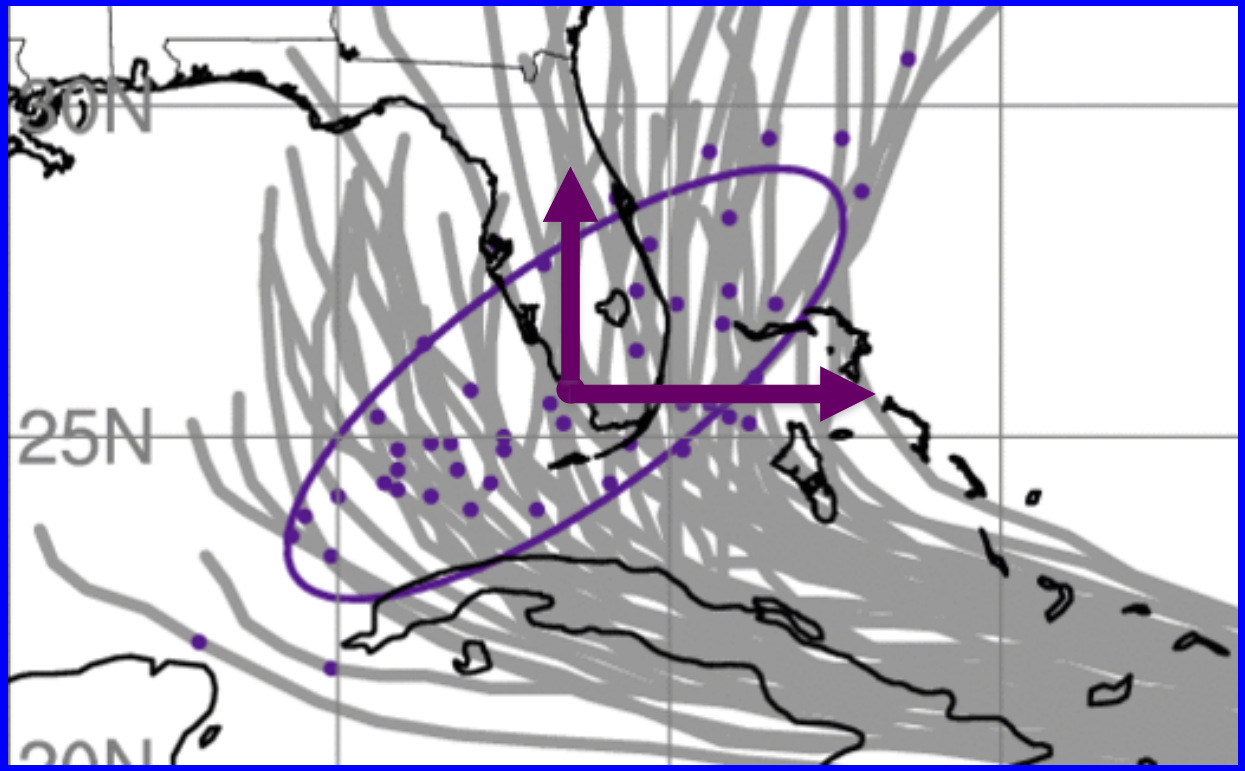
- Ensemble-based method of computing the sensitivity to model state variables at earlier time
- Above equation is linear regression based on ensemble:
  - Dependent variable is ensemble estimate of a forecast metric that is a function of the model output (i.e., TC track, precipitation, wind, etc.)
  - Independent variable is ensemble estimate of state variable (i.e., steering wind, vorticity, PV) at a given location and earlier time

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)
  - Began in NOAA SHOUT campaign (2015-2016)
- Products are based on 0000 UTC ECMWF ensemble forecasts
- Focus mainly on Irma 0000 UTC 6 September forecast, but with examples from other cases from last two years

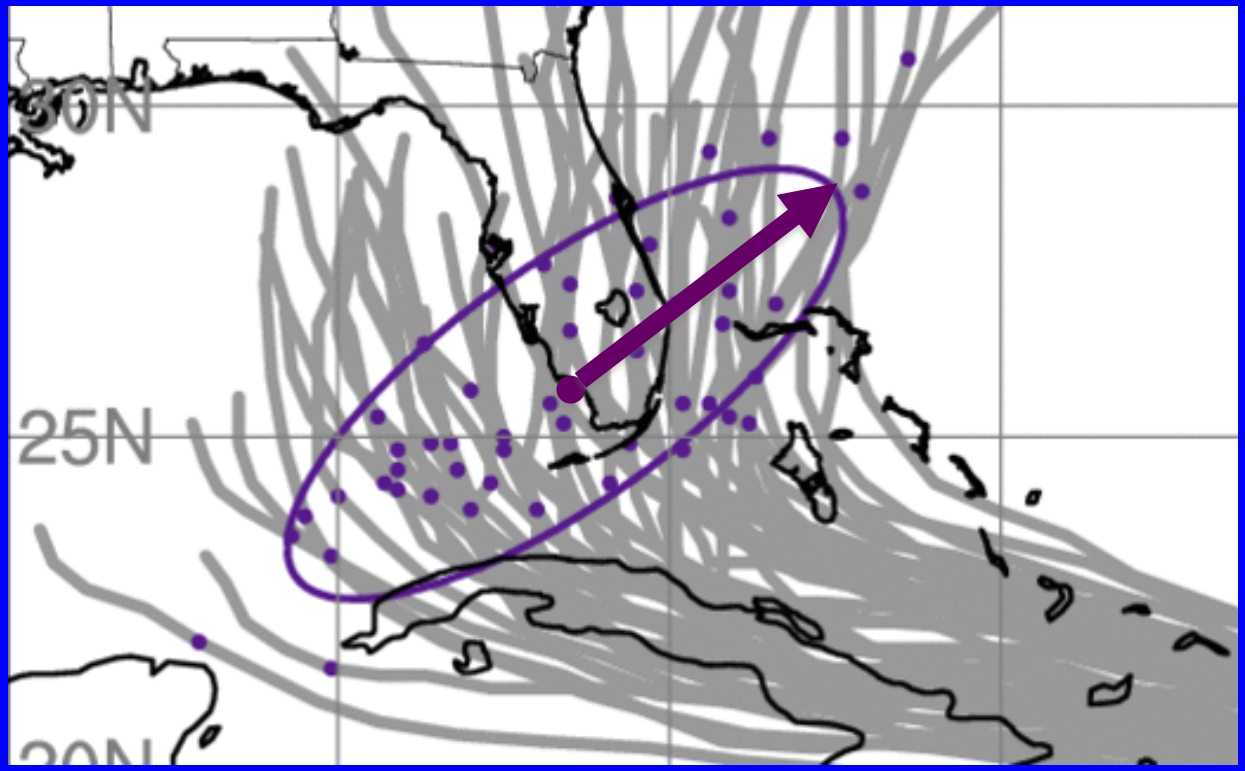
Methodology

- Multiple choices for forecast metric (J)
- Latitude and longitude of TC position is one possibility, but position variability often exists in both zonal/meridional directions



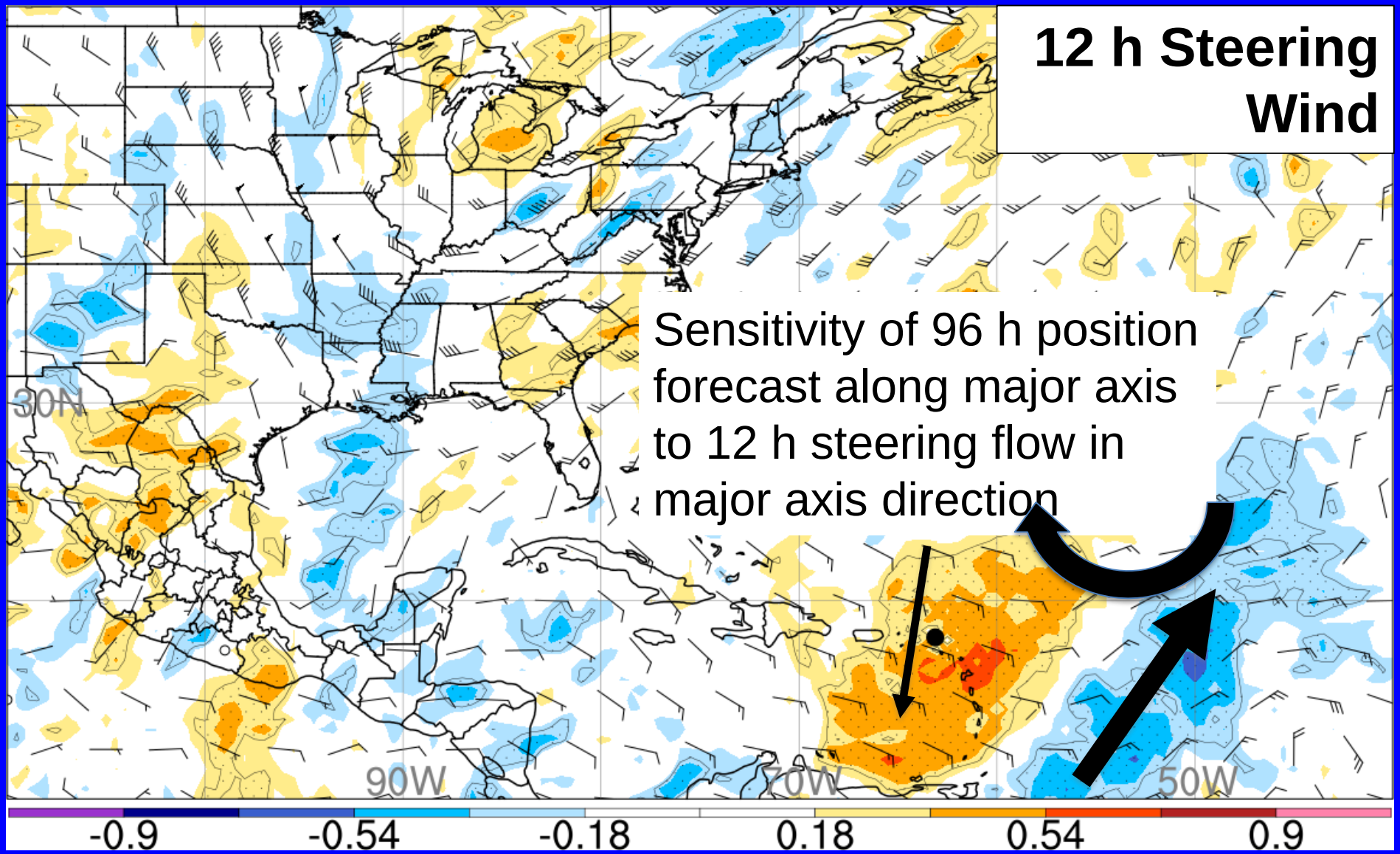
Methodology

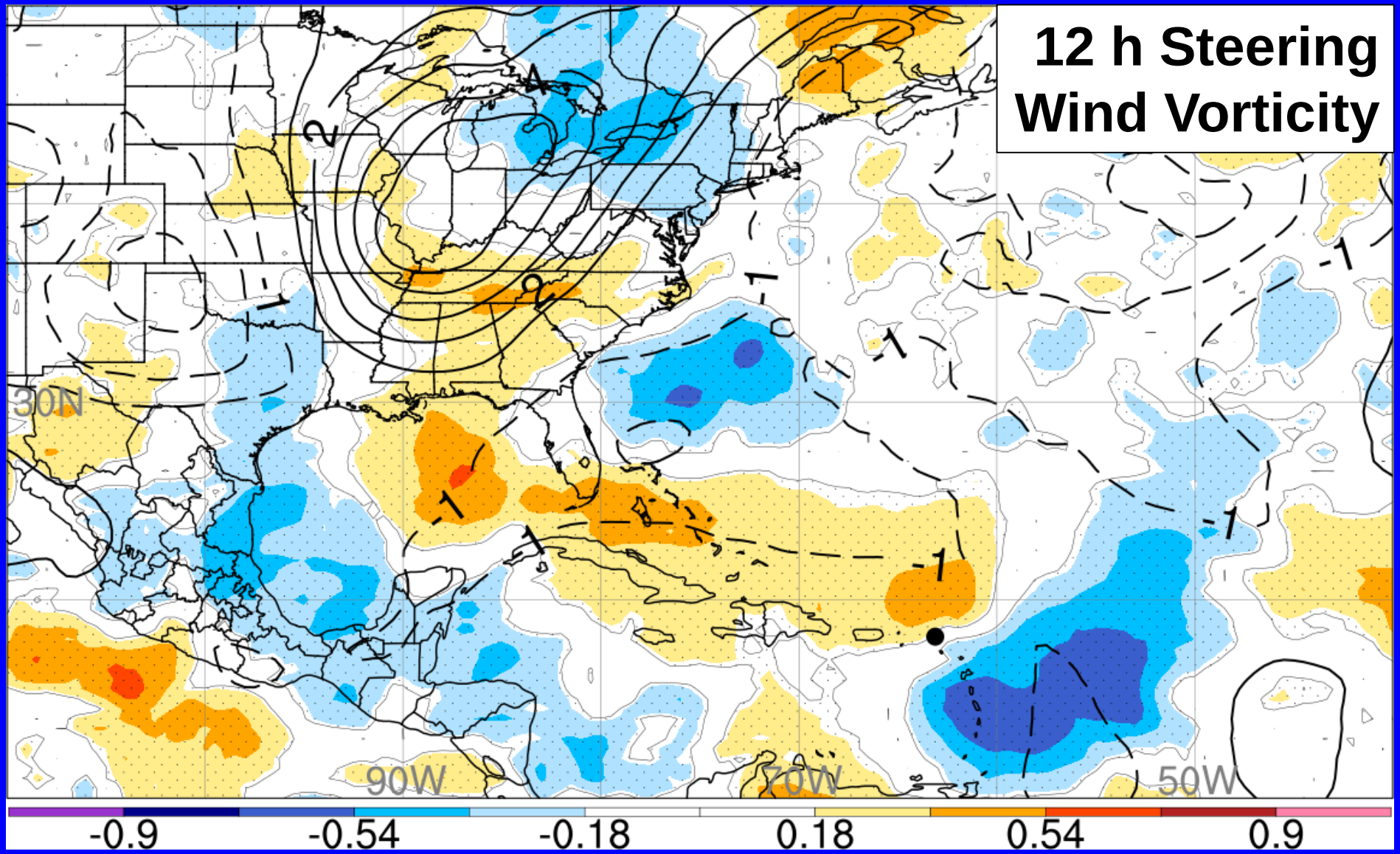
- Multiple choices for forecast metric (J)
- Alternative is position in direction of maximum variability (EOF of ensemble forecast positions)

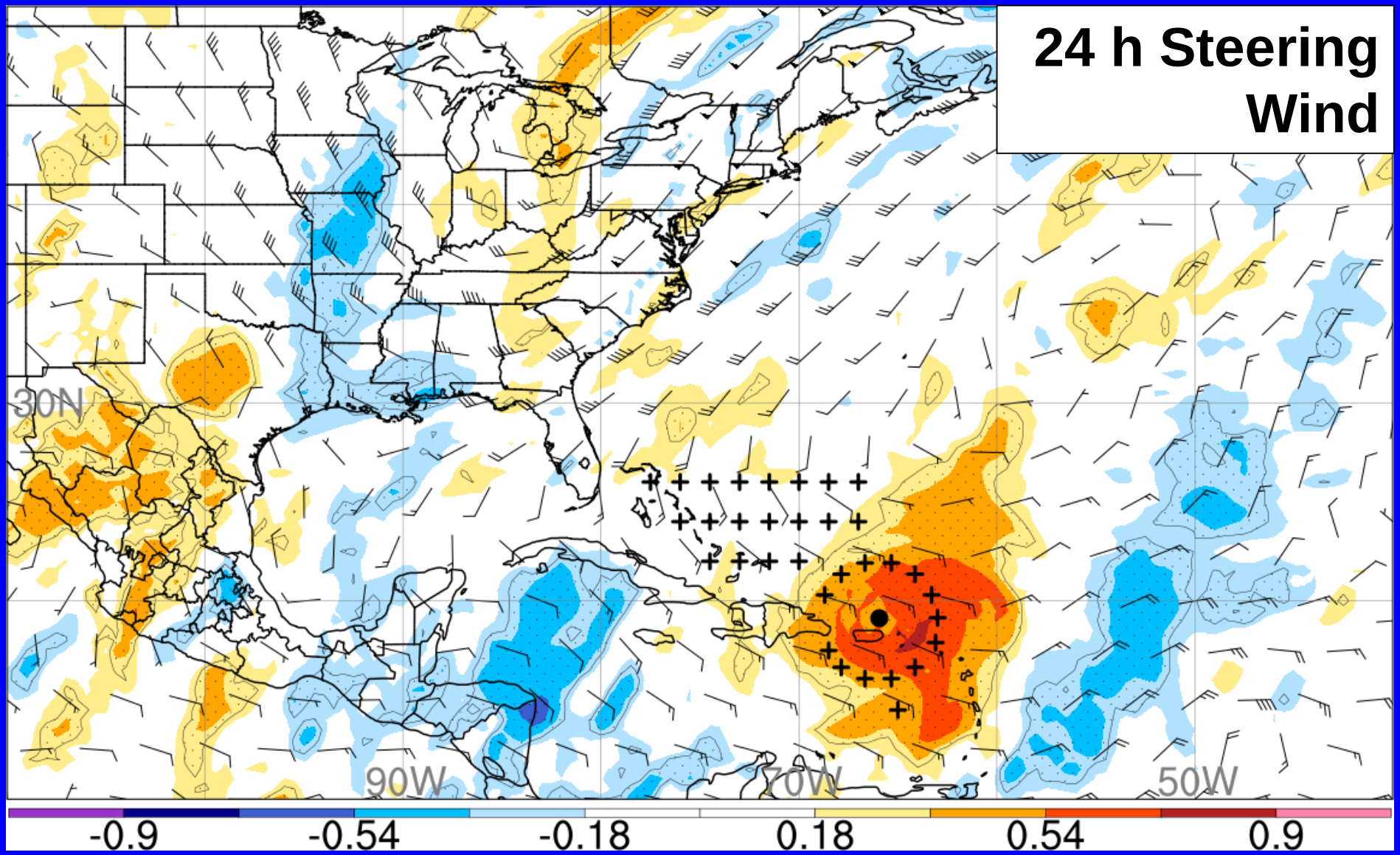


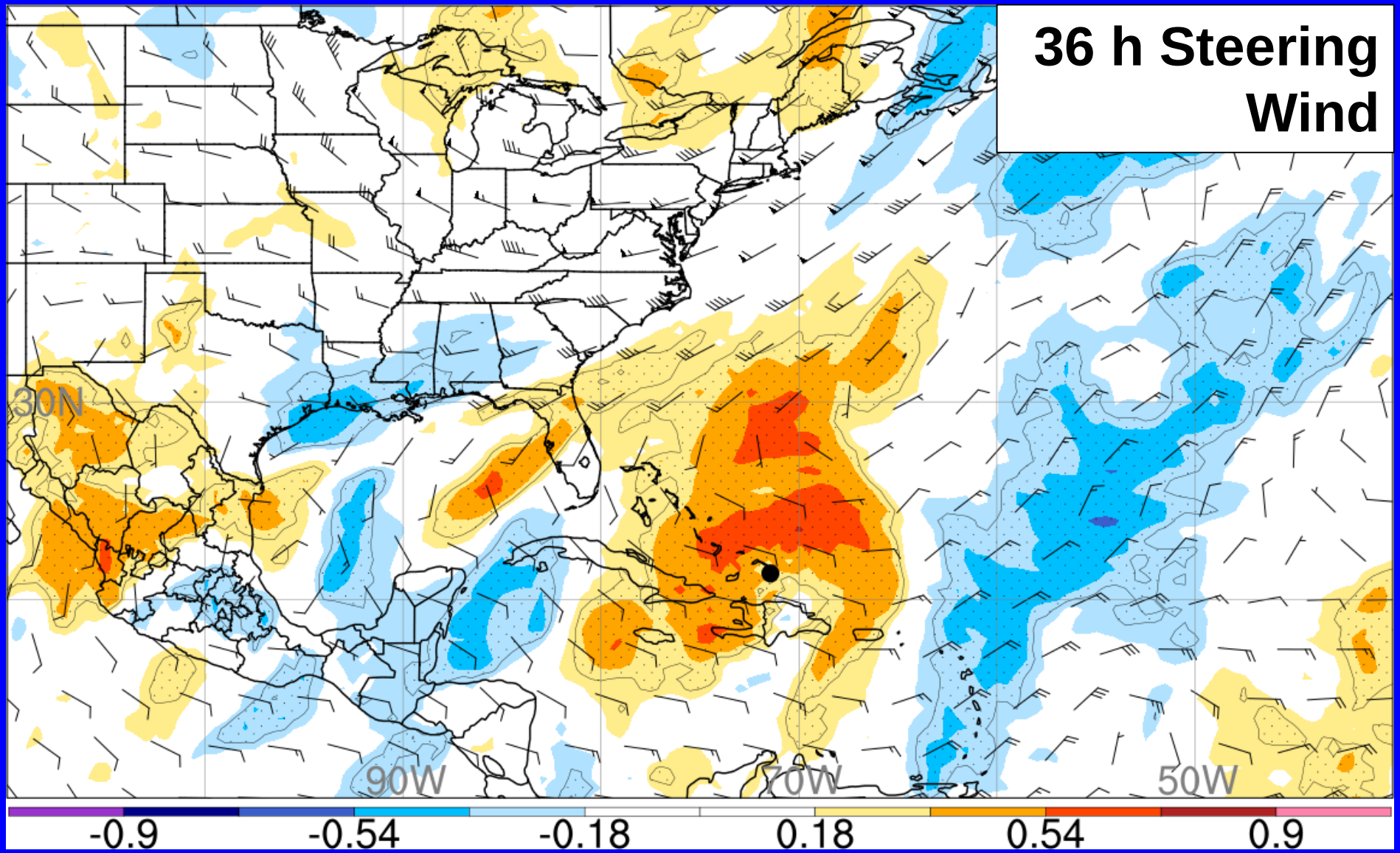
Hypotheses

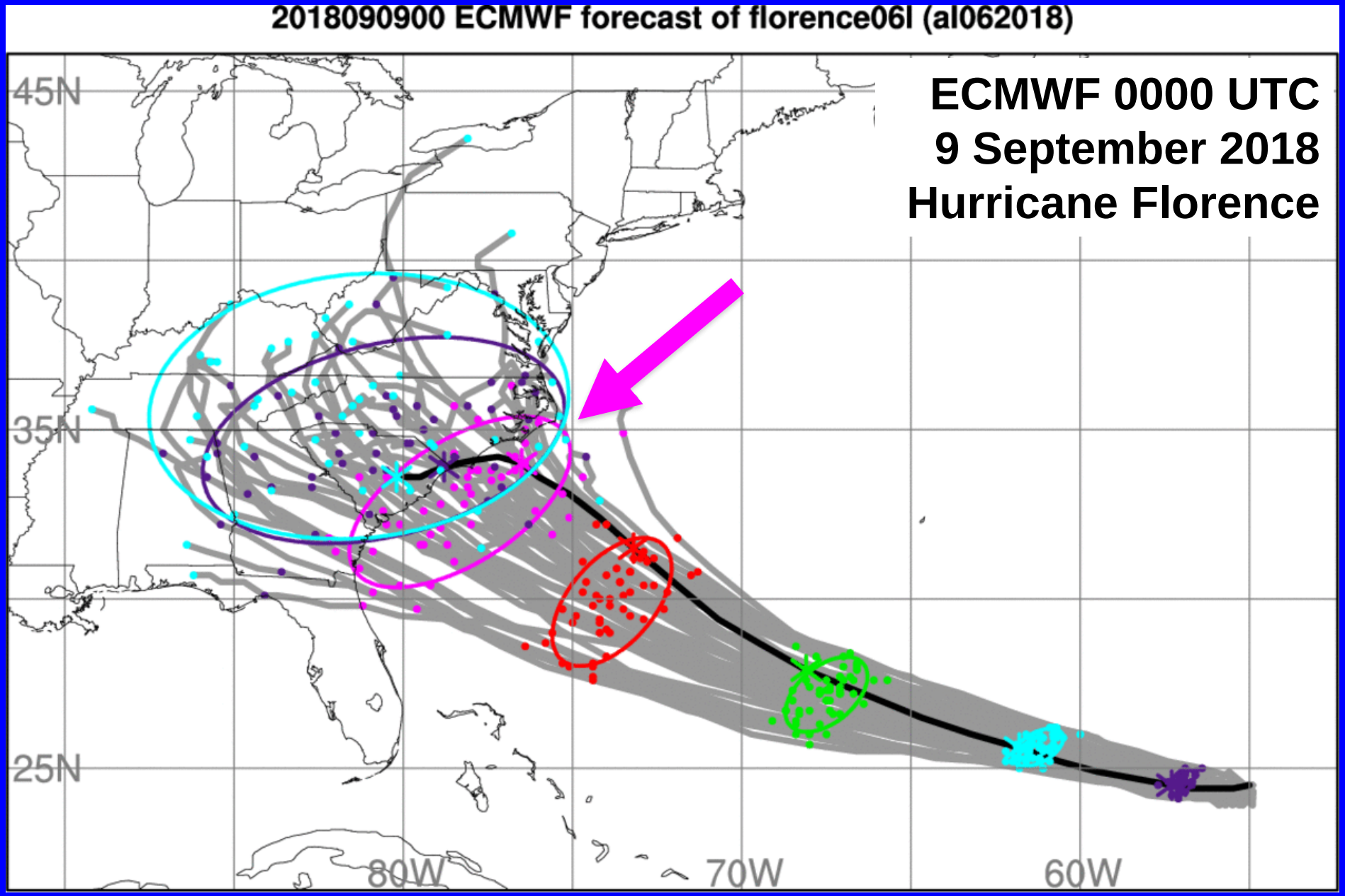
- Irma's position is most sensitive to synoptic features close to Irma early in the forecast
  - Take additional observations near Irma at initial time
- Irma's position is most sensitive to remote midlatitude features that influence Irma near landfall
  - Take additional upstream observations over CONUS


12 h Steering Wind
Sensitivity of 96 h position forecast along major axis to 12 h steering flow in major axis direction
30N
90W
70W
50W
-0.9
-0.54
-0.18
0.18
0.54
0.9

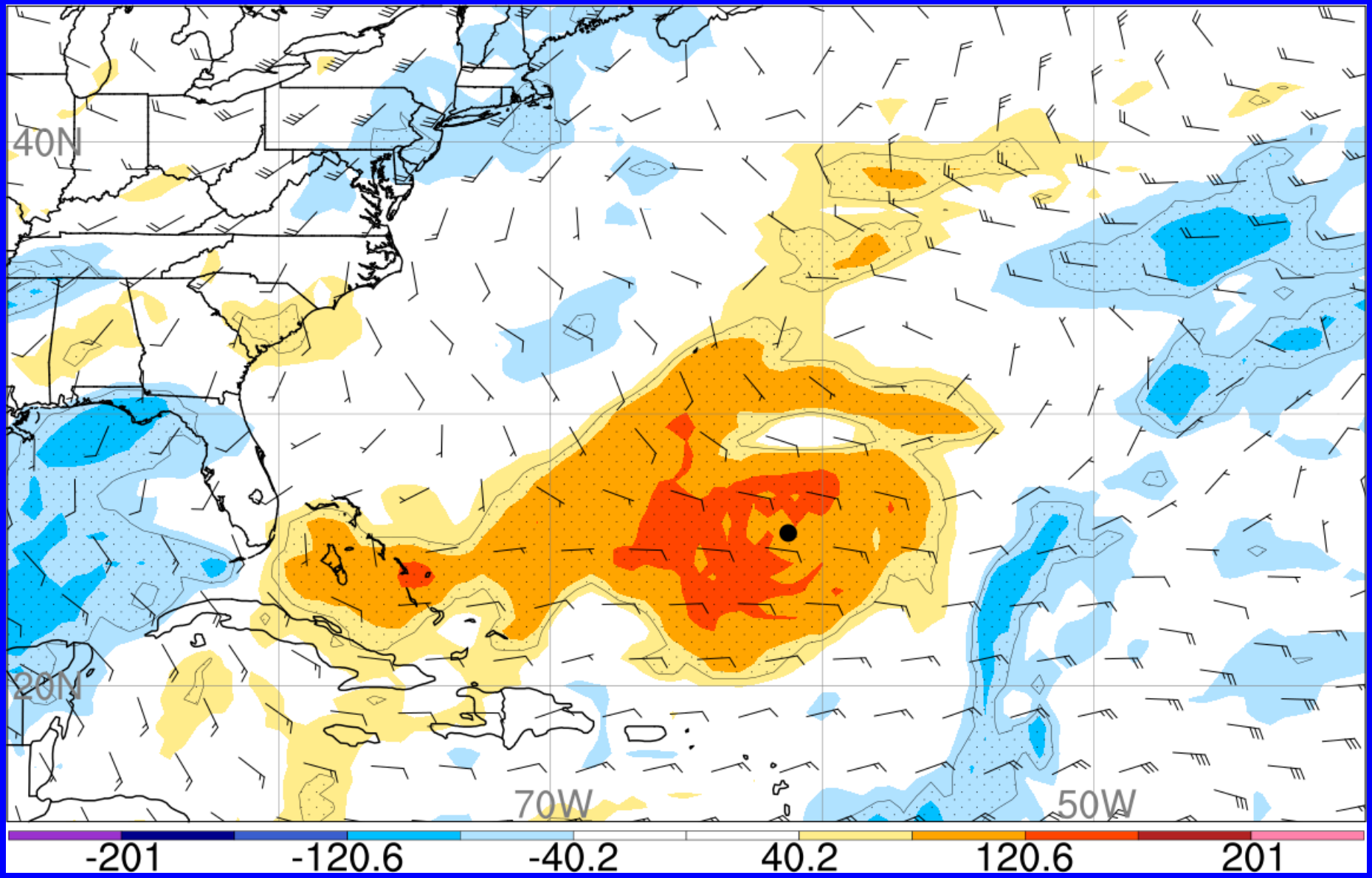

12 h Steering
Wind Vorticity
30N
90W
70W
50W
-0.9
-0.54
-0.18
0.18
0.54
0.9


24 h Steering Wind
30N
90W
70W
50W
-0.9
-0.54
-0.18
0.18
0.54
0.9

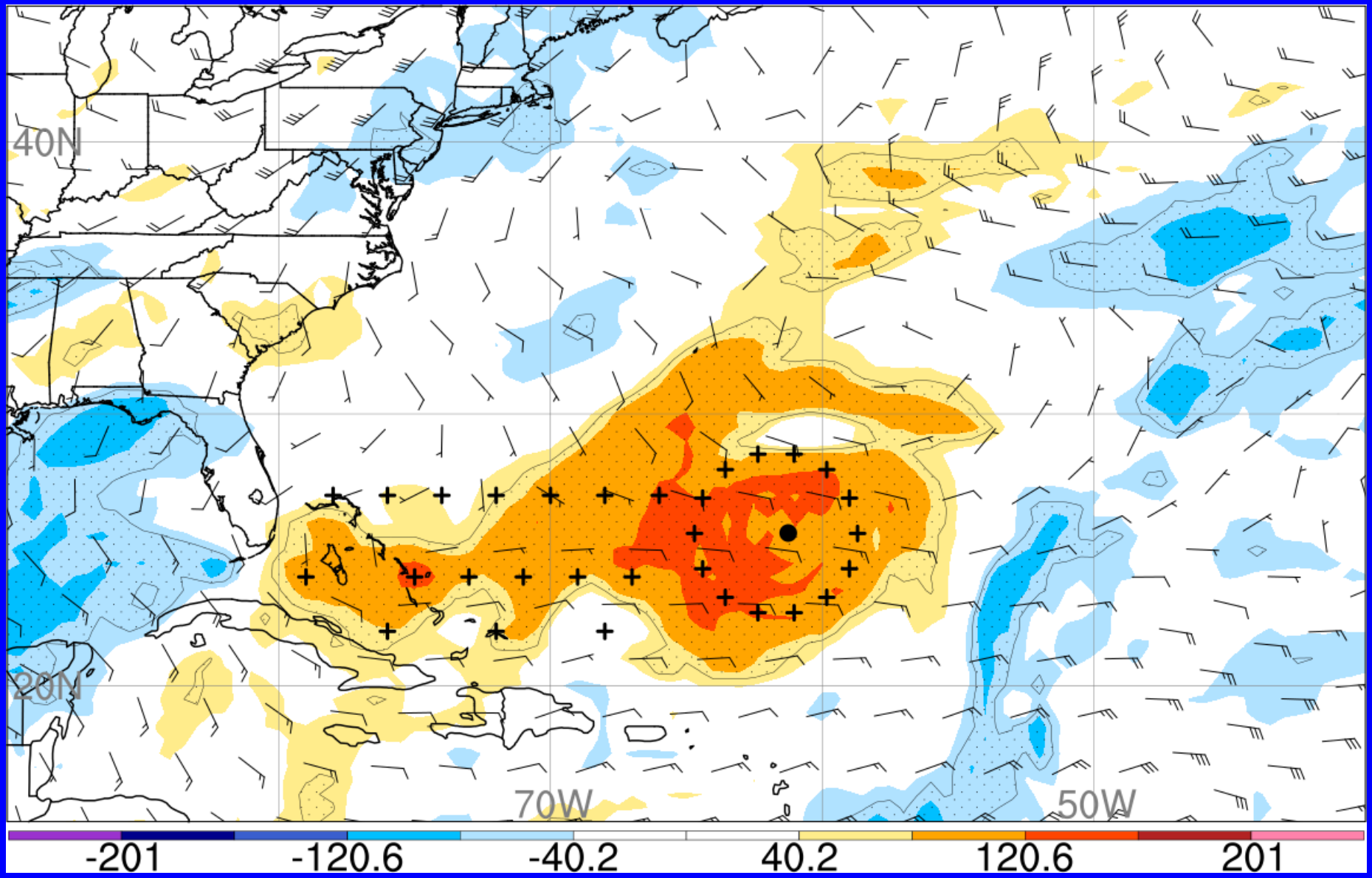

36 h Steering Wind
30N
90W
70W
50W
-0.9
-0.54
-0.18
0.18
0.54
0.9

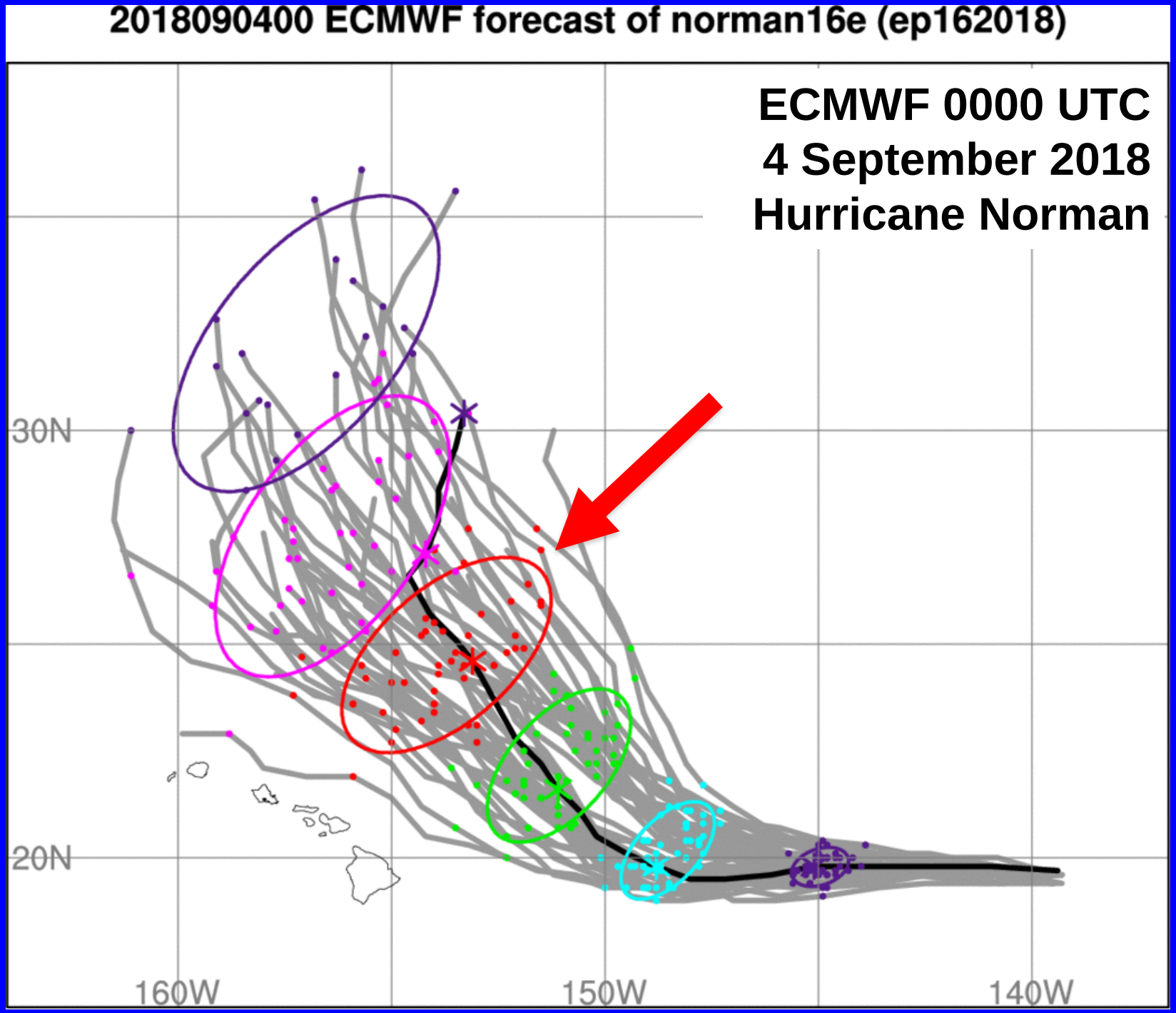

2018090900 ECMWF forecast of florence06l (al062018)
ECMWF 0000 UTC
9 September 2018
Hurricane Florence
45N
35N
25N
80W
70W
60W

00 UTC 11 Sept. Florence

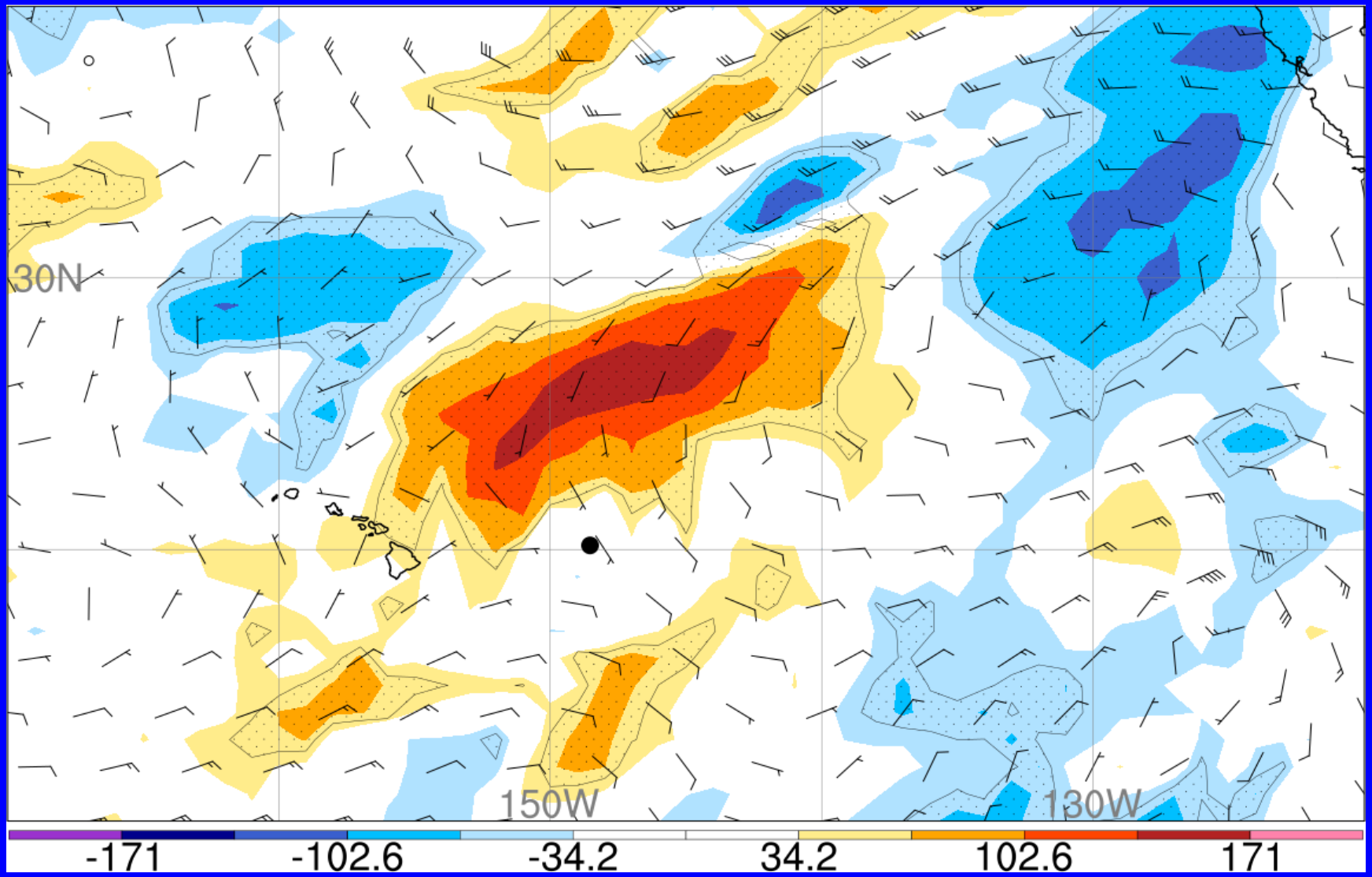


00 UTC 11 Sept. Florence

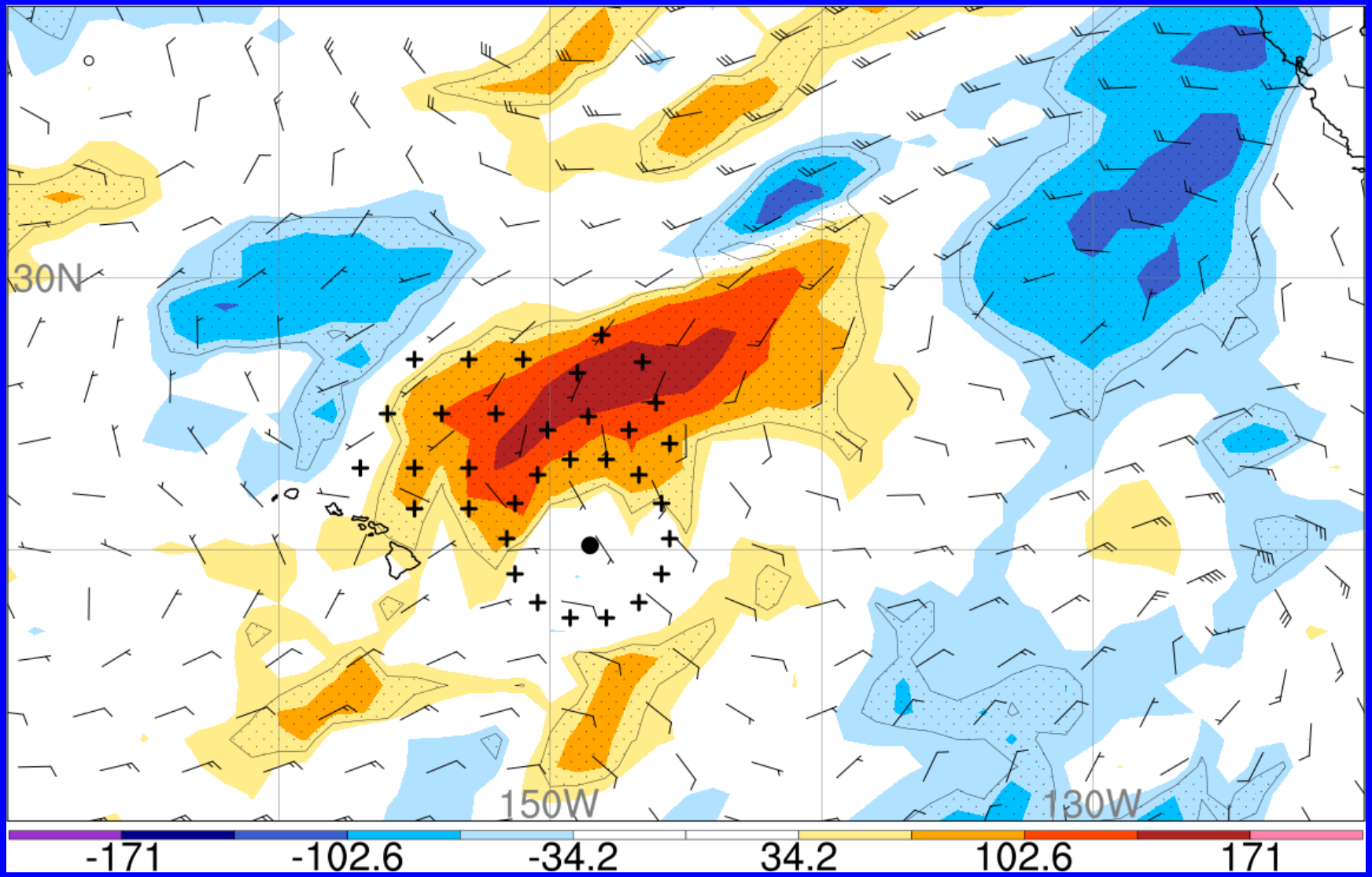



2018090400 ECMWF forecast of norman16e (ep162018)
ECMWF 0000 UTC
4 September 2018
Hurricane Norman
30N
20N
160W
150W
140W

00 UTC 6 Sept. Norman

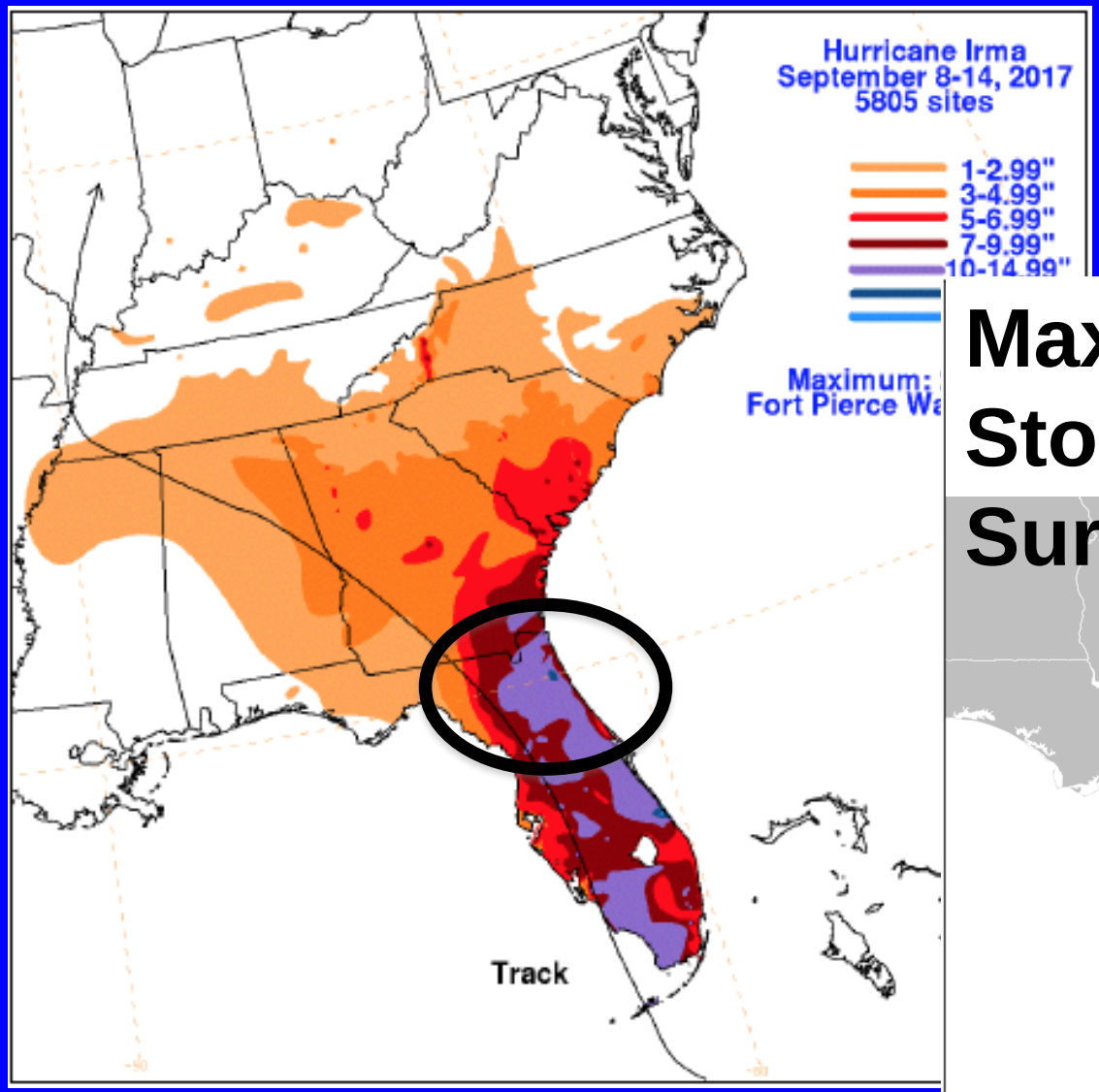


00 UTC 6 Sept. Norman



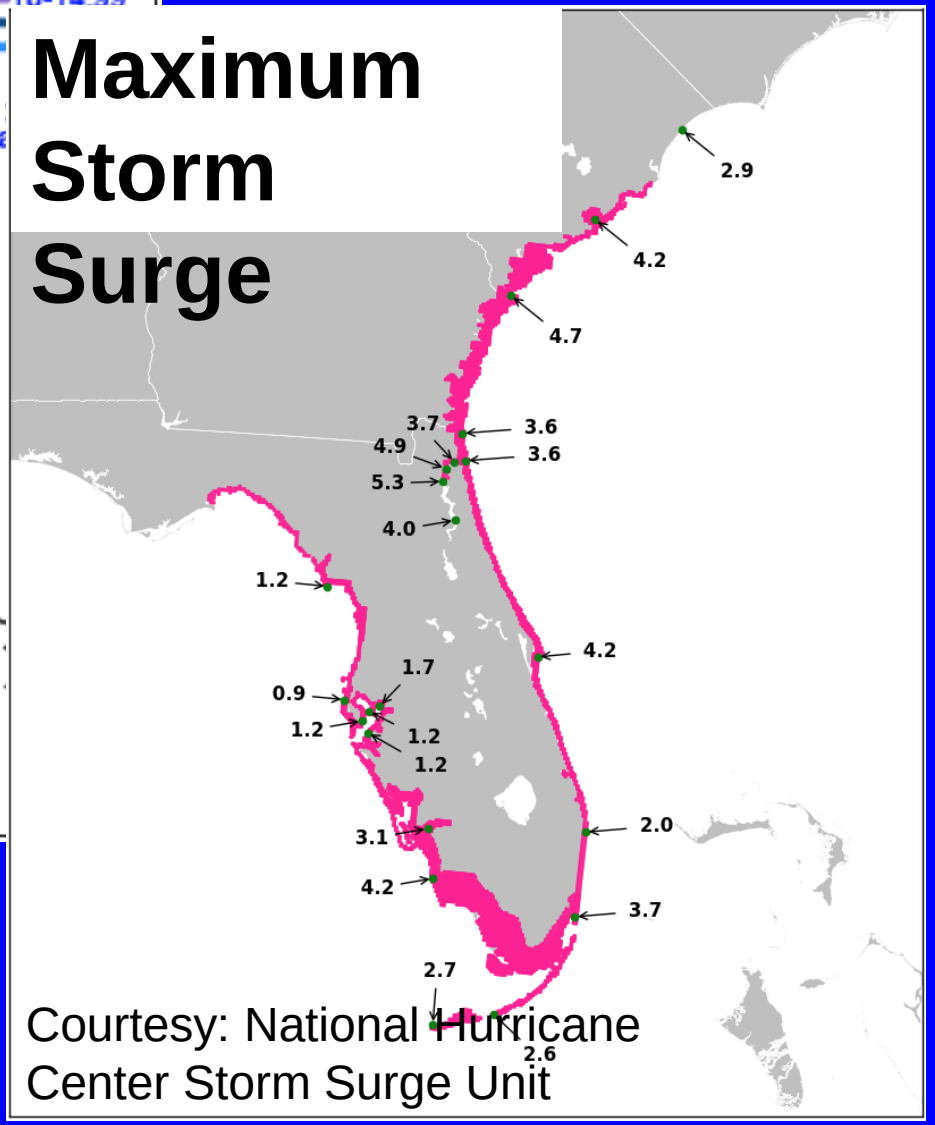
Irma Precipitation

- Technique can give useful information for more than just TC position forecasts
- Can also be applied to TC-related precipitation forecasts
- Example: Hurricane Irma (2017):



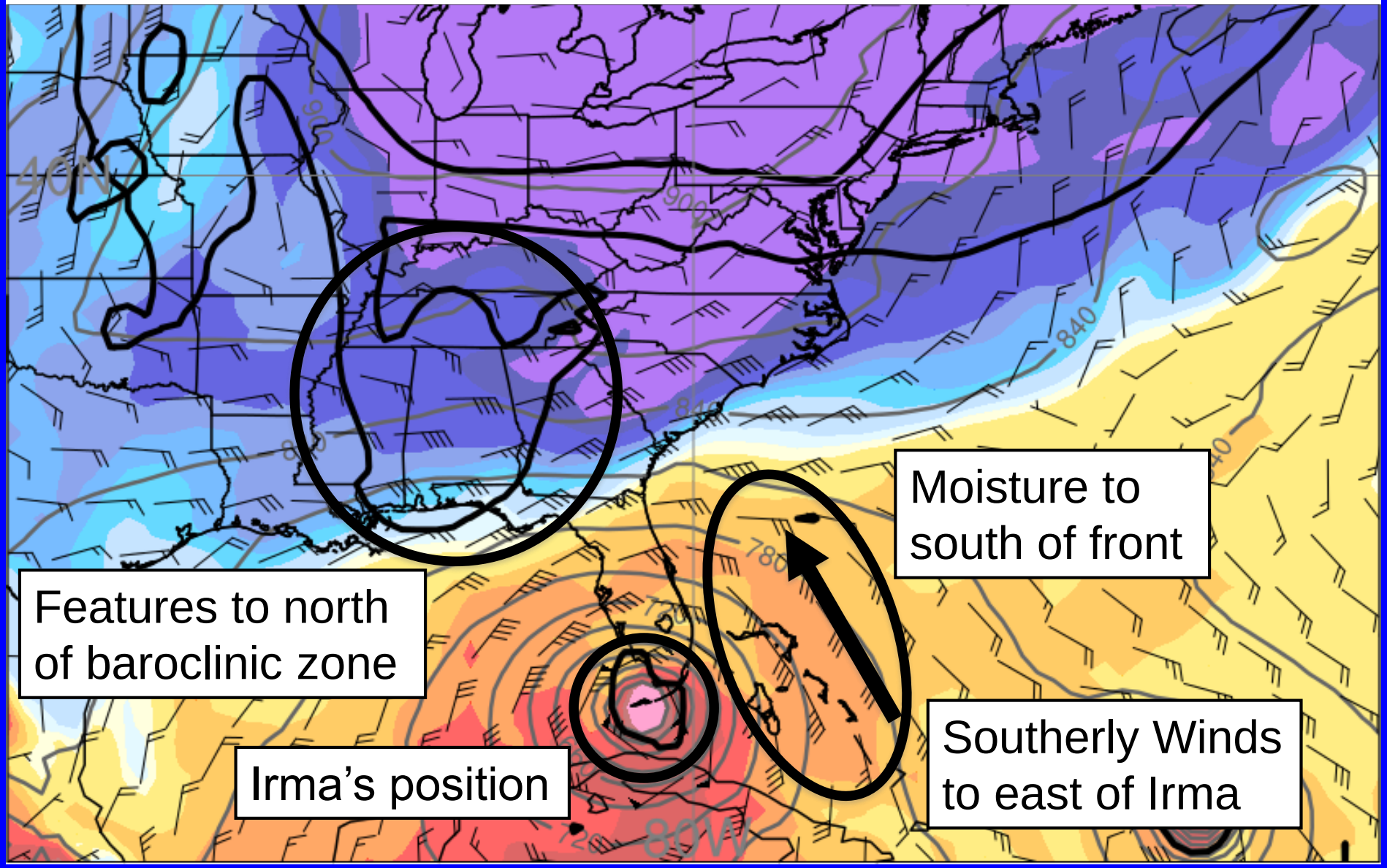
Courtesy: David Roth, NOAA/WPC

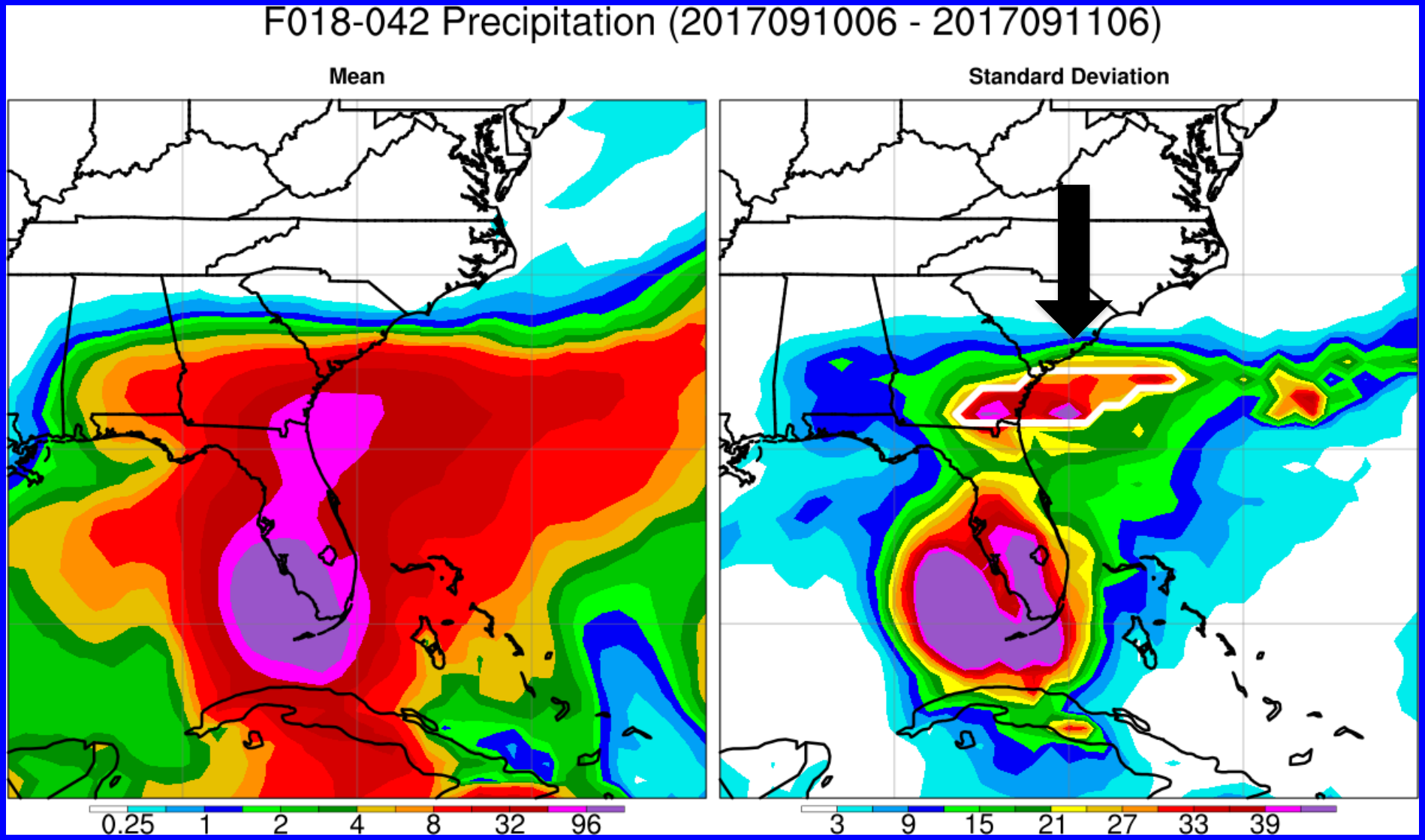
Maximum Storm Surge



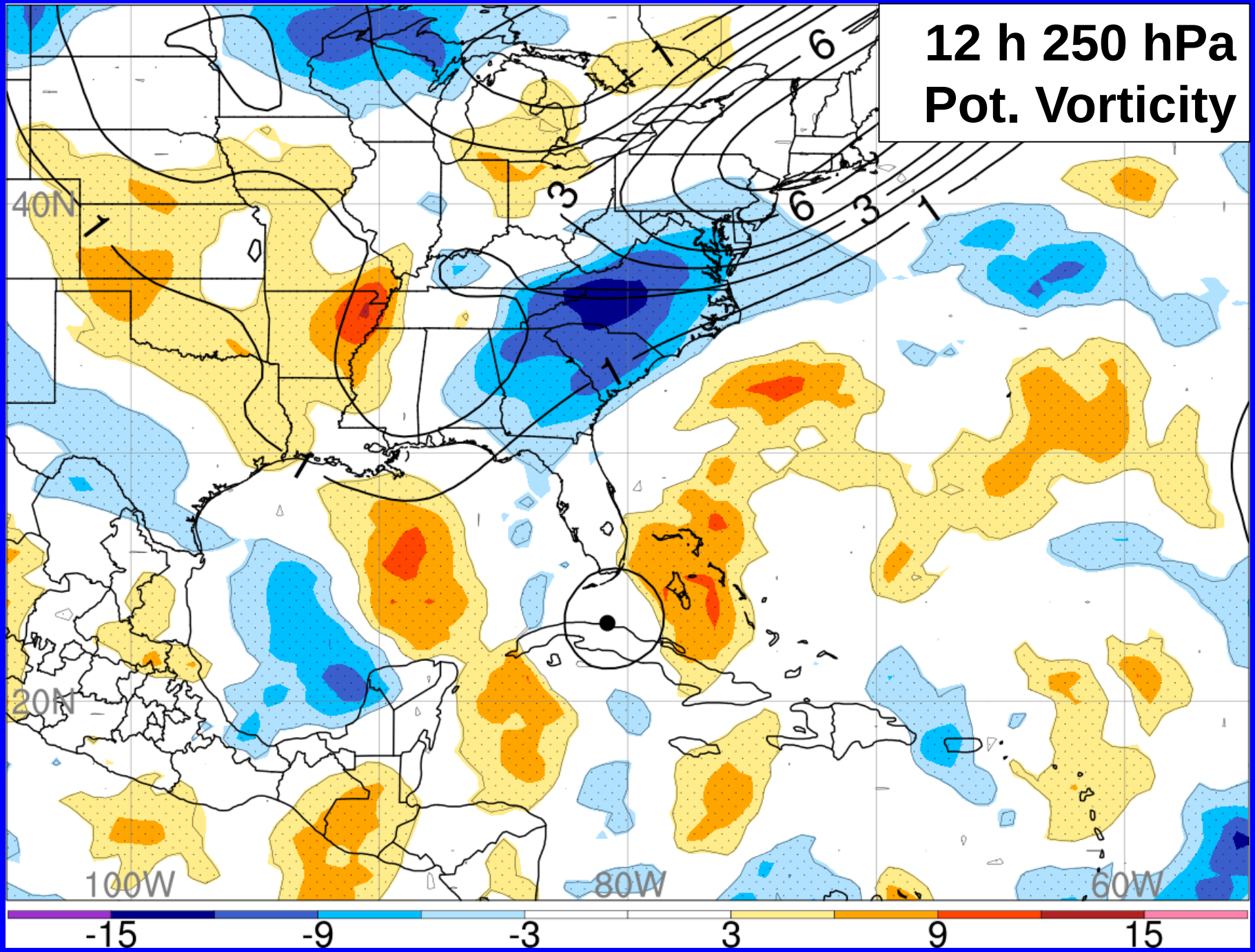
Courtesy: National Hurricane Center Storm Surge Unit

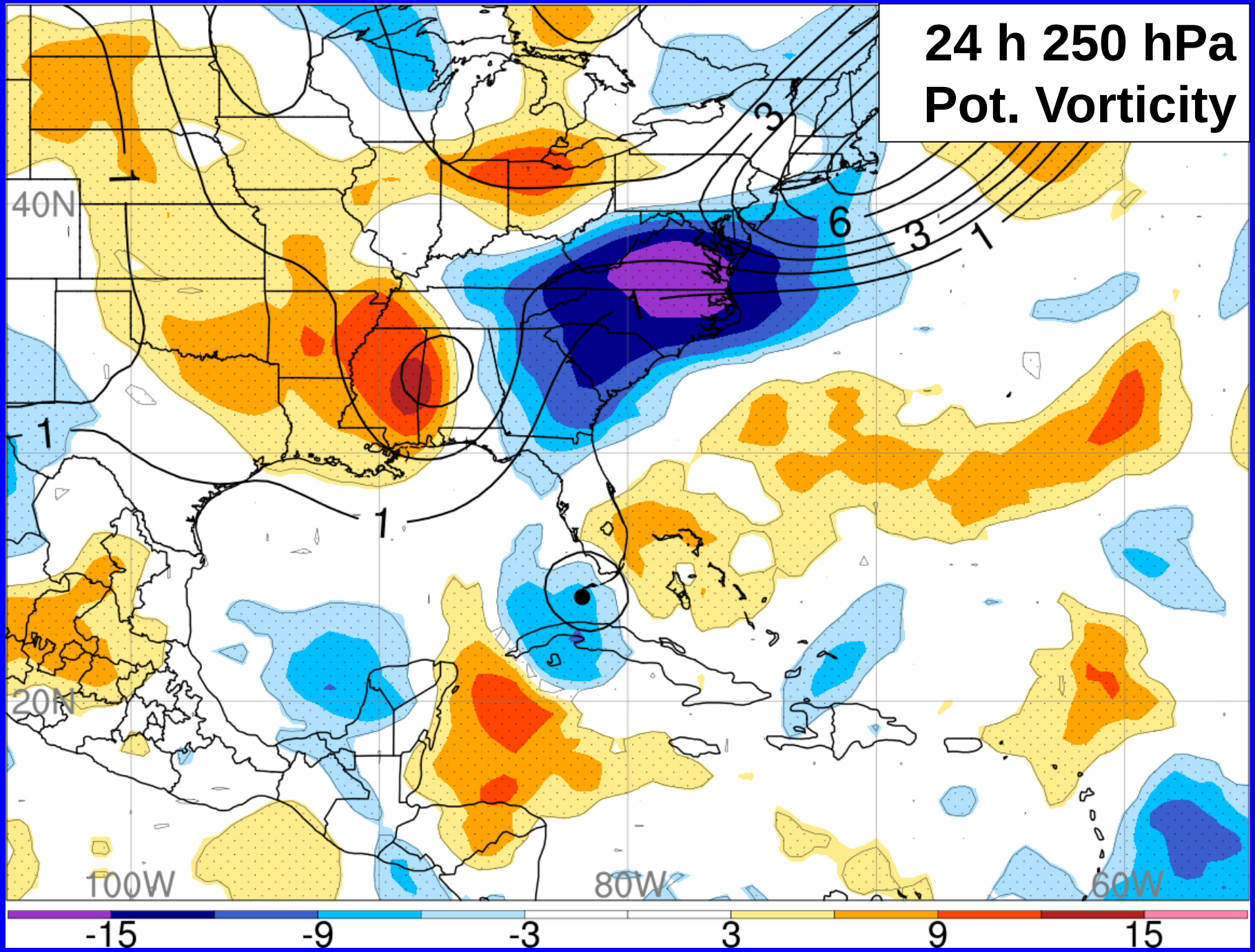
1200 UTC 10 September 2017

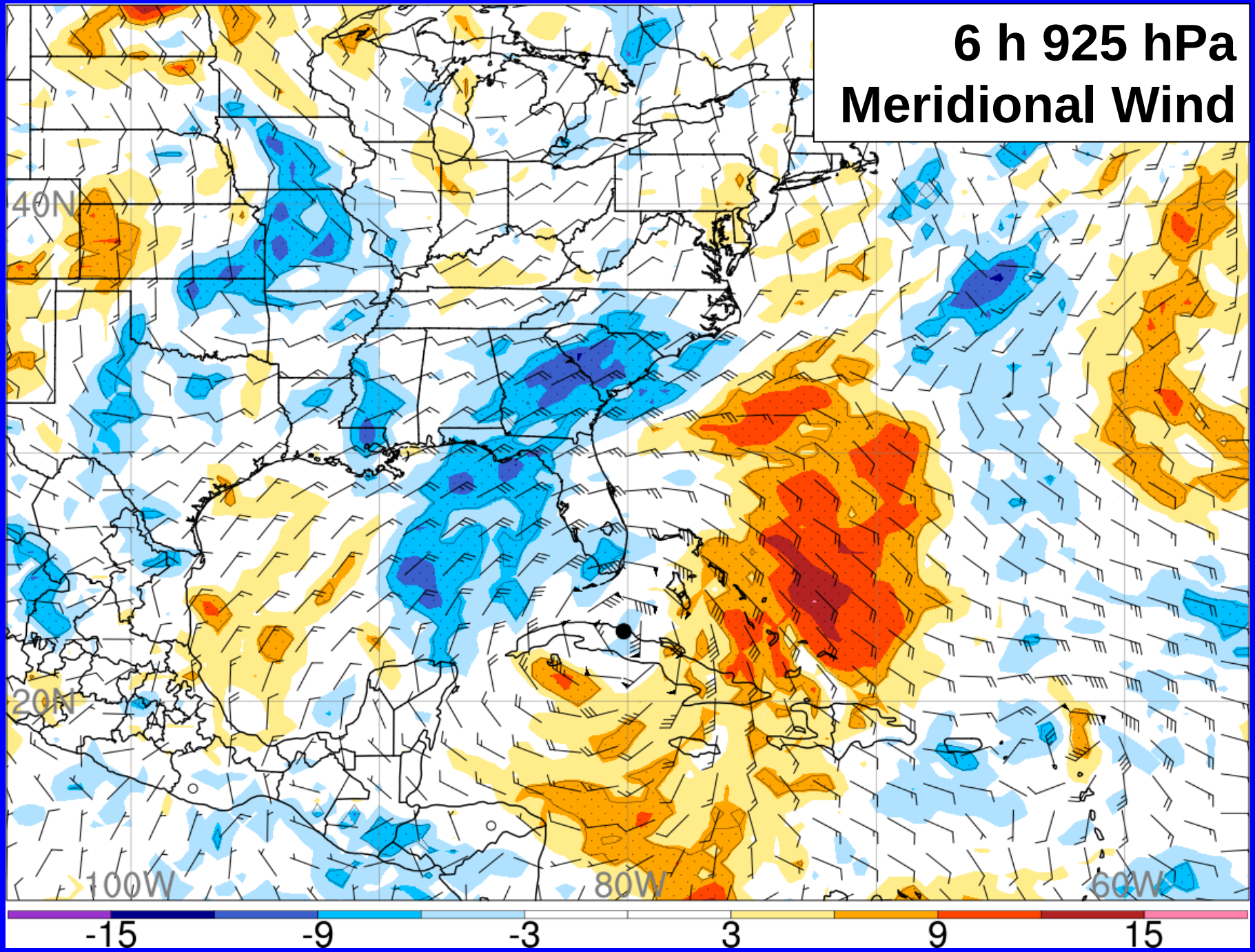


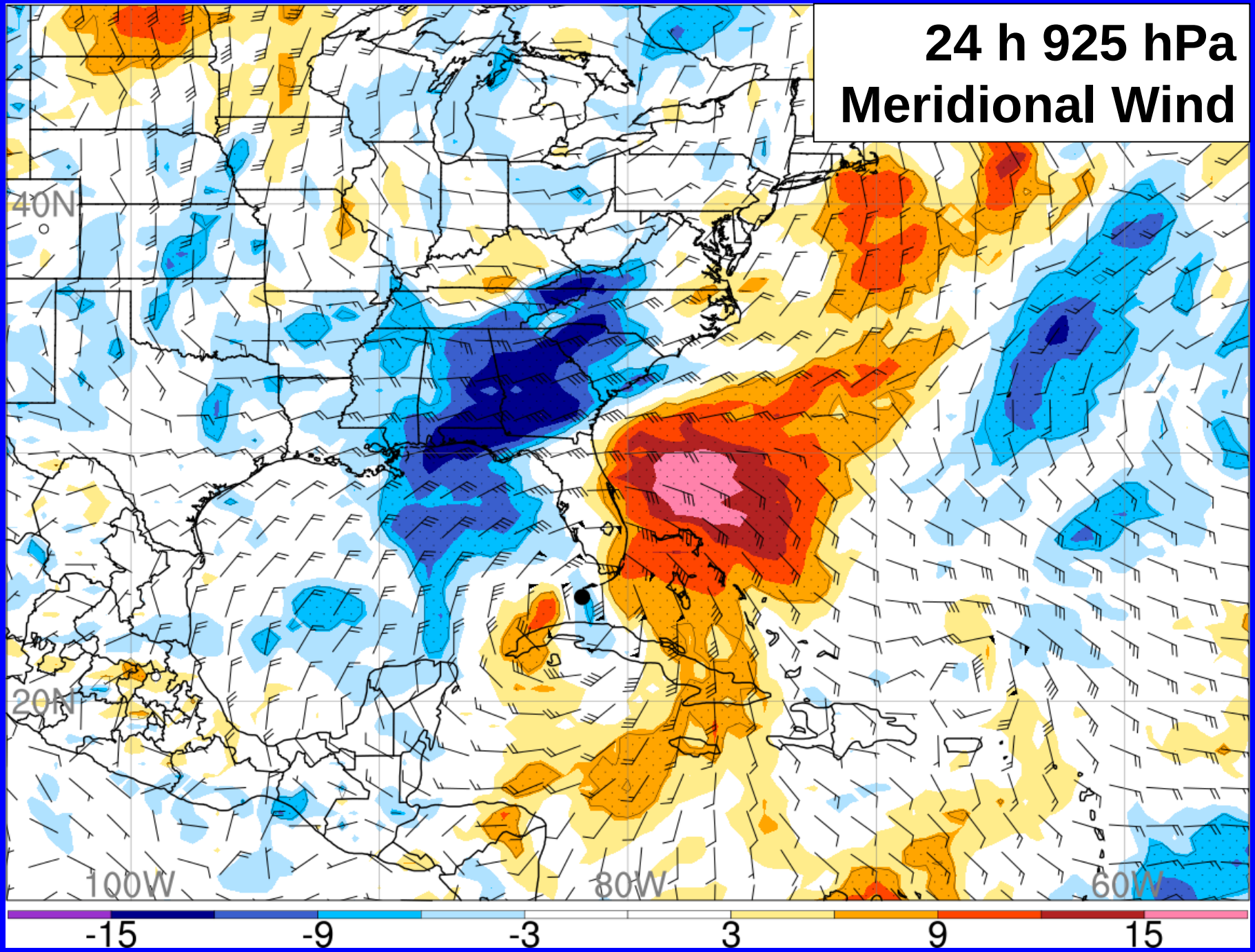


ECMWF Forecast initialized 1200 UTC 9 September 2017


12 h 250 hPa
Pot. Vorticity
40N
20N
100W
80W
60W
6
1
3
6
3
1
1
-15
-9
-3
3
9
15


24 h 250 hPa
Pot. Vorticity
40N
20N
100W
80W
60W
3
6
3
1
1
1
1
-15
-9
-3
3
9
15


6 h 925 hPa
Meridional Wind
40N
20N
100W
80W
60W
-15
-9
-3
3
9
15


24 h 925 hPa
Meridional Wind
40N
20N
100W
80W
60W
-15
-9
-3
3
9
15

Summary

- Ensemble sensitivity provides a flexible method for computing forecast sensitivity
- Computationally inexpensive assuming that forecasts already exist
- Works best when forecast metrics and fields are closely related to the model variability
- TC-related products based on this technique are currently being used in operations
- New applications are being developed (e.g., severe convection, atmospheric rivers)