Advancing Situational Awareness with RRFSe Clustering and Sensitivity Analysis Tools

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Motivation

As technology improves and NWS responsibilities expand

Forecasters have access to **more data** with simultaneously **less time** to interrogate those data

Visualization of output from convection-allowing ensemble systems can be a challenge for a number of reasons

Forecast precipitation does not follow a Gaussian distribution

Problem: The ensemble mean often washes out important nuance amongst the membership

Probability Matched Means, Spatially Aligned Means, and other post-processing approaches try to mitigate this issue

Here, we attempt to visualize the precipitation **scenarios** via **ensemble clusters**!

RRFSe Configuration

REFS Configuration used throughout most of FFaIR

| 06 UTC Cycle	00 UTC Cycle	18 UTC (D-1) Cycle	12 UTC (D-1) Cycle
m1 (ctrl) 06Z	m8 (m1 00Z)	m15 (m1 18Z Day - 1)	m22 (m1 12Z Day - 1)
m2 06Z	m9 (m2 00Z)	m16 (m2 18Z Day - 1)	m23 (m2 12Z Day - 1)
m3 06Z	m10 (m3 00Z)	m17 (m3 18Z Day - 1)	m24 (m3 12Z Day - 1)
m4 06Z	m11 (m4 00Z)	m18 (m4 18Z Day - 1)	m25 (m4 12Z Day - 1)
m5 06Z	m12 (m5 00Z)	m19 (m5 18Z Day - 1)	m26 (m5 12Z Day - 1)
m6 06Z	m13 (m6 00Z)	m20 (m6 18Z Day - 1)	m27 (m6 12Z Day - 1)
m7 HRRR 06Z	m14 HRRR 00Z	m21 HRRR 18Z (Day – 1)	m28 HRRR 12Z (Day – 1)

First, we break down the RRFSe forecast (06Z, 00Z, 18Z d-1, 12Z d-1 runs) into its leading modes of variability via EOF Analysis

EOF1 of RRFSe 6h QPF | 13% Variance Explained
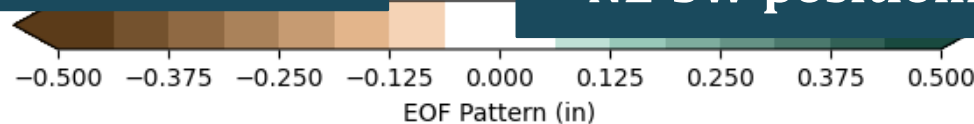Valid: 6-hrs ending 06 UTC Jun 11 2024
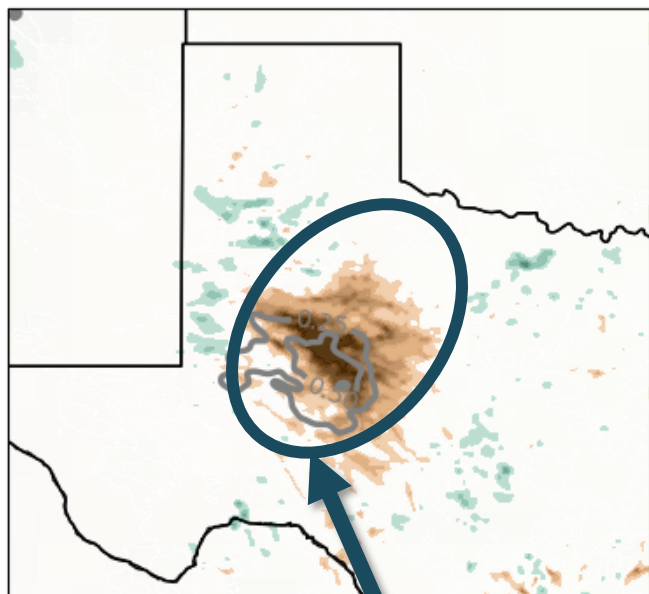
EOF2 of RRFSe 6h QPF | 10% Variance Explained
Valid: 6-hrs ending 06 UTC Jun 11 2024

Leading mode of uncertainty:
Magnitude of QPF Max

Secondary mode of uncertainty:
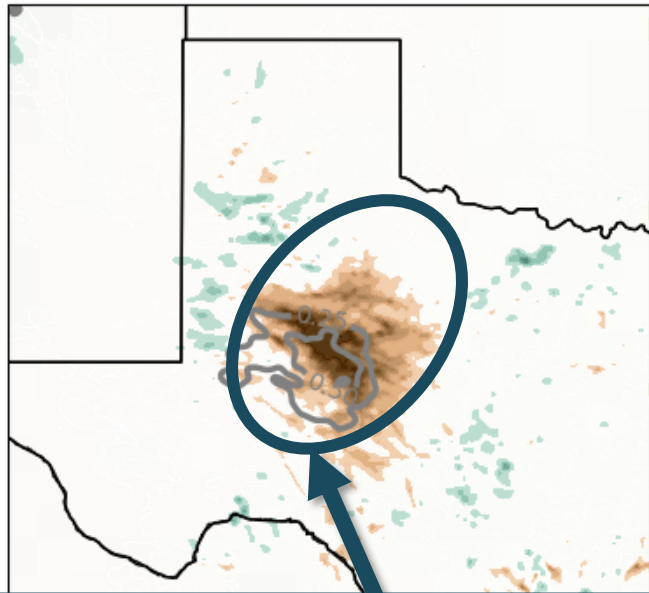**NE-SW positioning of QPF Max**

EOF Pattern (in)
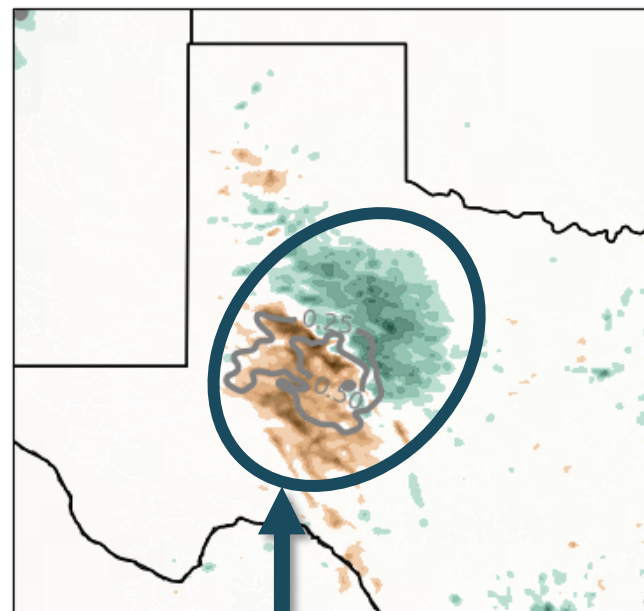
Common source of confusion:

What do the positives and negatives mean?

- Sign doesn't matter when looking at the EOFs themselves
- Only becomes important once we start clustering or looking at members in PC phase space

EOF1 of RRFSe 6h QPF | 13% Variance Explained
Valid: 6-hrs ending 06 UTC Jun 11 2024

EOF2 of RRFSe 6h QPF | 10% Variance Explained
Valid: 6-hrs ending 06 UTC Jun 11 2024

Leading mode of uncertainty:
Magnitude of QPF Max

Secondary mode of uncertainty:
NE-SW positioning of QPF Max

−0.500 −0.375 −0.250 −0.125 0.000 0.125 0.250 0.375 0.500
EOF Pattern (in)
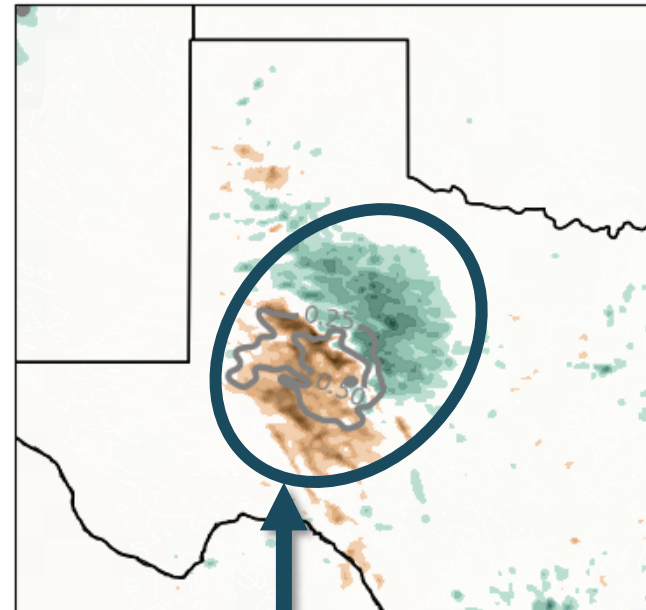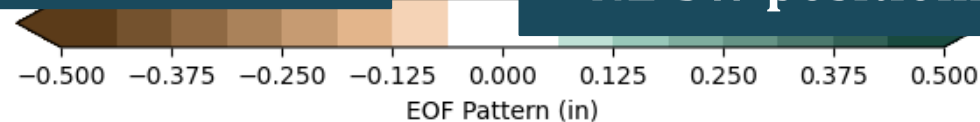
How does it work?

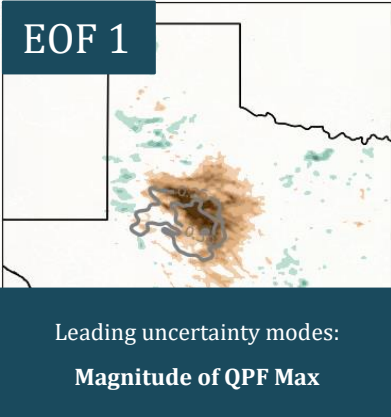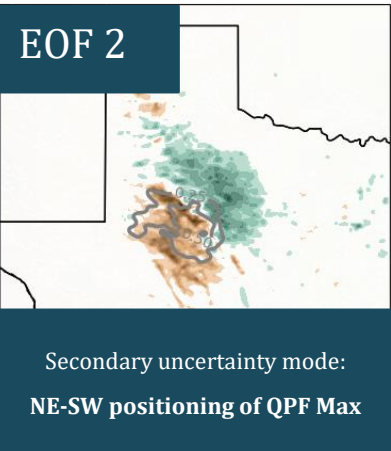Next, we group similar ensemble solutions together with clustering

First two EOFs for reference

EOF 1

Leading uncertainty modes:

Magnitude of QPF Max

EOF 2

Secondary uncertainty mode:

NE-SW positioning of QPF Max

Projecting ensemble members into PC phase space shows us the forecast scenario for each member

Members with positive PC1 will look more like EOF1 *(less QPF than the ensemble mean for west TX)*

whereas members with negative PC1 will look opposite EOF1 *(more QPF than the ensemble mean for west TX)*

K-means Clustering groups members with similar solutions based on our leading modes of uncertainty

PC1-PC2 Phase Space
Valid: 6-hrs Ending 06 UTC Jun 11 2024

00 UTC 06 UTC 12 UTC 18 UTC

Main QPF Max shifted NE

Less QPF for West TX

Cluster 2
Less QPF for West TX with a northeastward shift in the QPF Max

Cluster 3
More QPF for West TX with a northeastward shift in QPF Max

Cluster 4
More QPF for West TX with southwestward shift in the QPF Max

Cluster 1
Slightly Less QPF for West TX with a southwestward shift in the QPF Max

Main QPF Max shifted SW

More QPF for West TX

Less QPF for West TX

PC 1

Don't even need to look at EOFs or PCs to use!
Can skip straight to the cluster forecasts

Cluster 6-h 75th Percentile QPF and Difference from Full RRFSe 75th Percentile [in]
Valid: 6-hrs Ending 06 UTC Jun 11 2024

Cluster 1:
Slightly Less QPF for West TX
Southwestward shift in QPF Max

Cluster 2:
Less QPF for West TX
Northeastward shift in QPF Max

Cluster 3:
More QPF for West TX
Northeastward shift in QPF Max

Cluster 4:
More QPF for West TX
Southwestward shift in QPF Max

Full RRFSe 75th Percentile

Color-filled contours
show differences
from full ensemble
75th percentile

Don't even need to look at EOFs or PCs to use!

Can skip straight to the cluster forecasts

Cluster 6-h 75th Percentile QPF
Valid: 6-hrs Ending 06 UTC Jun 11 2024

Cluster 1:
Slightly Less QPF for West TX
Southwestward shift in QPF Max

Cluster 2:
Less QPF for West TX
Northeastward shift in QPF Max

Cluster 3:
More QPF for West TX
Northeastward shift in QPF Max

Cluster 4:
More QPF for West TX
Southwestward shift in QPF Max

Full RRFSe 75th Percentile

Color-filled contours show differences from full ensemble 75th percentile

The next day, participants subjectively verify MRTP clusters with MRMS observations

Cluster 6-h 75th Percentile QPF with 1" QPE Verification Overlaid
Valid: 6-hrs Ending 03 UTC Jun 12 2024

Cluster 1   00Z: 3=43% 06Z: 3=43% 12Z: 7=100% 18Z: 0=0% T: 13=46%   Cluster 2   00Z: 2=29% 06Z: 0=0% 12Z: 0=0% 18Z: 4=57% T: 6=21%   Cluster 3   00Z: 1=14% 06Z: 2=29% 12Z: 0=0% 18Z: 2=29% T: 5=18%

On June 11, Weather.com reported, Siesta Key "picked up 11.49 inches of rain as a small area of intense rainfall pushed ashore. Sarasota itself topped a half-foot of rain on Tuesday, with 3.93 inches of that falling in a single hour, an all-time record for that location. Flooding was reported in Sarasota, Everglades City and parts of the Miami metro," the website pointed out.

QPF [in]
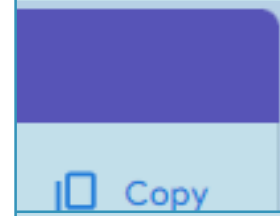
Summary of Subjective Evaluation Results (so far)!

"Clusters 1 and 4 were consistently the best performing clusters throughout the week. I don't know what is special about those two particular clusters, but they stood out to me as the most useful/helpful."

Copy

...e the second ...ster (tied with none of the clusters)

41.8%   20%

20%
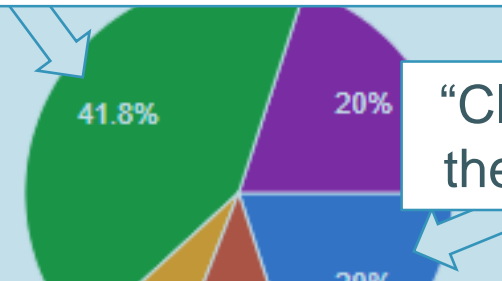
"Clusters 1 and 4 looked the best, but cluster 1 had the highest magnitudes a little too far to the south."

theoretically perform best most often

"Clusters 1 and 4 looked the best to me, but I thought cluster 1 had a slight edge as far as the structure and magnitude."

Why does Cluster 4 tend to subjectively outperform the full ensemble most often?

The 14-member REFS composed of the two most recent cycles (half the size of the RRFSe system used here) depicts more binary probabilities than the HREF*

Suggests under dispersive ensemble

*from Matt Pyle's FFaIR Seminar last week

Assuming our 28-member RRFSe system is similarly under dispersive, it makes sense that the "outlier" clusters might have a better chance of capturing the correct outcome

Relatively low spatial and magnitude variability of QPF among clusters
- Cluster 4 consists of three "extreme" members, depicting higher QPF amounts than the remaining members

Cluster 6-h 75th Percentile QPF with 1" QPE Verification Overlaid
Valid: 6-hrs Ending 03 UTC Jul 11 2024
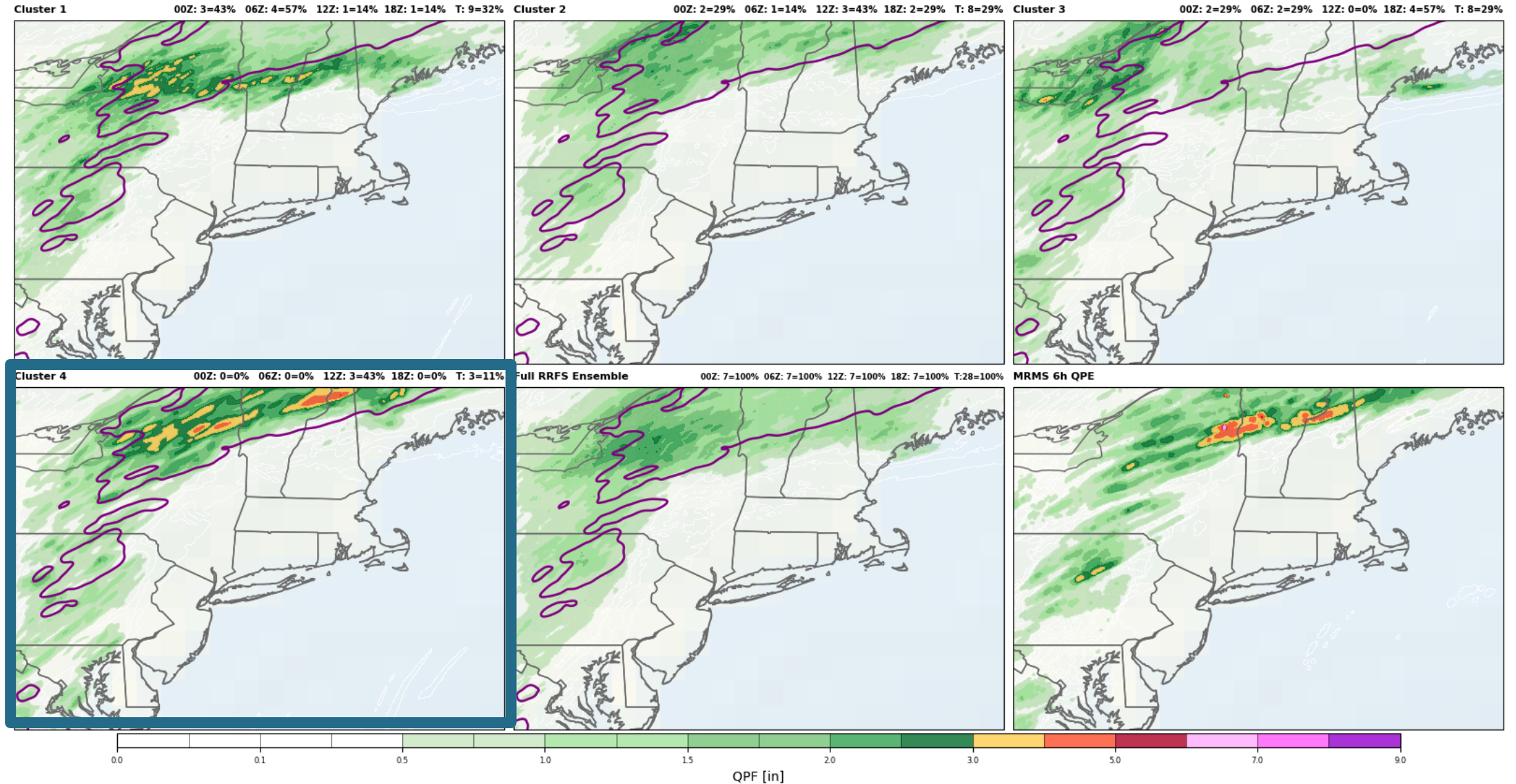
Why does Cluster 4 tend to subjectively outperform the full ensemble most often?

The 14-member[...]here) depicts more binary probabili[...]

Suggests und[...]

*from Matt P[...]

Assuming our 2[...]lusters might have a better ch[...]

"I think the finer resolution detail of cluster 4 bumps it ahead of the full ensemble, in my opinion. I want to see that higher resolution detail from a deterministic member and if it can be captured in a cluster of the ensemble, even better!"
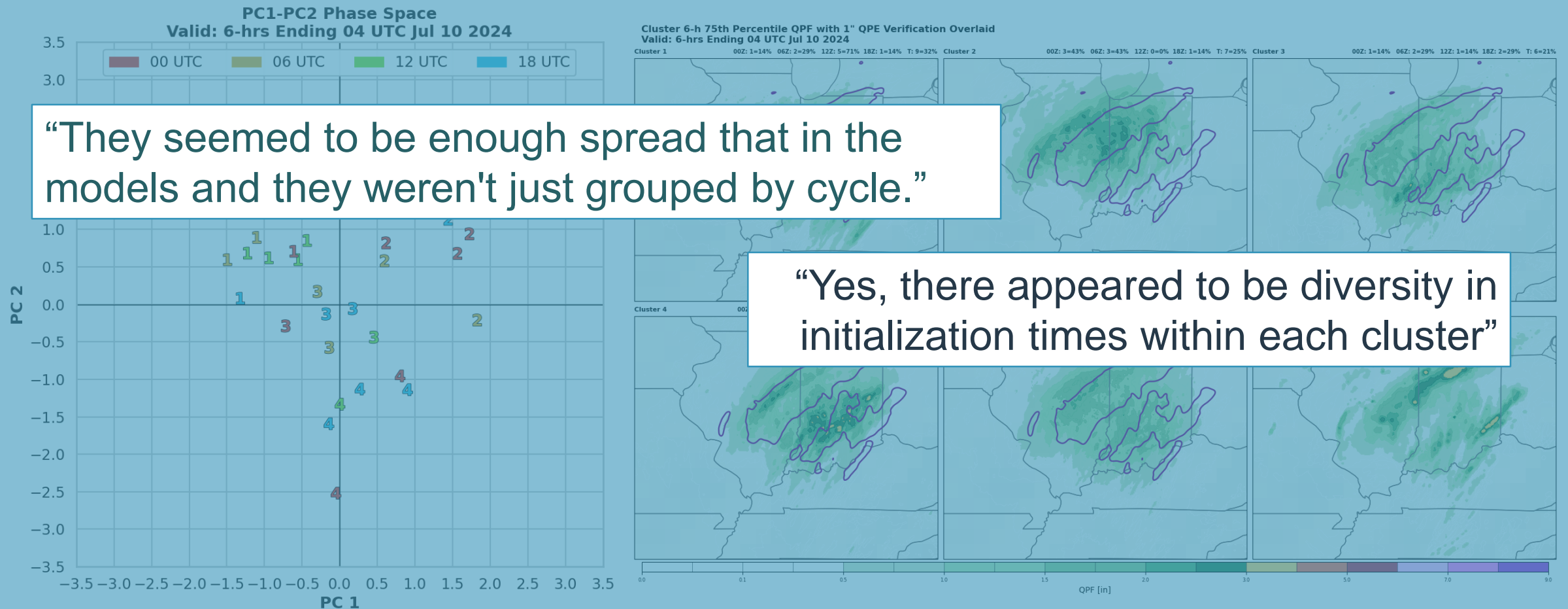
Alternatively, participants may prefer the visualization of Cluster 4 to the others due to its more deterministic appearance!

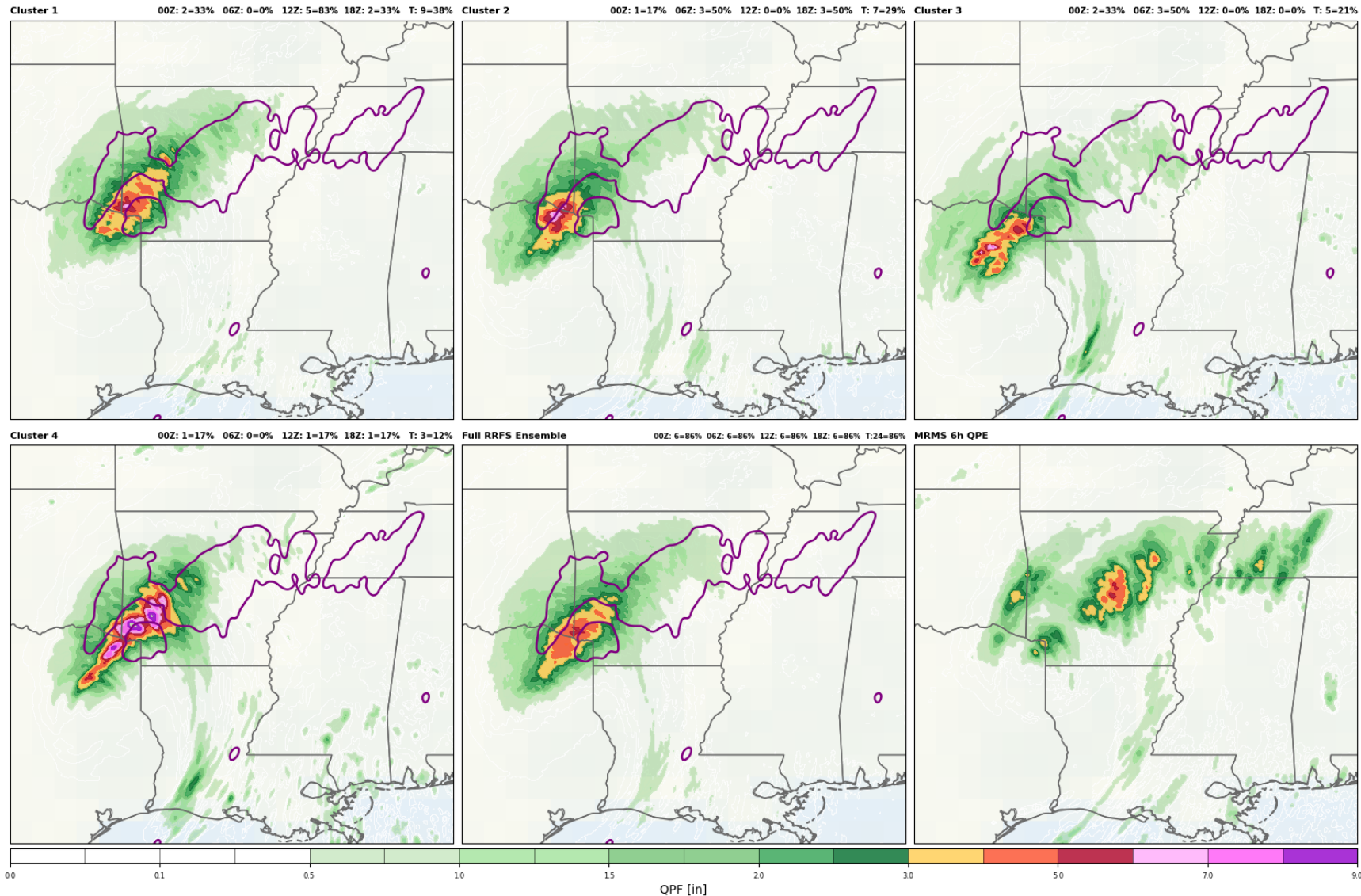**Suggests visualization could be improved for remaining clusters!**

While under dispersive as a whole, the time-lagged ensemble members seem to be represented equally amongst clusters!

"They seemed to be enough spread that in the models and they weren't just grouped by cycle."

"Yes, there appeared to be diversity in initialization times within each cluster"

Having diversity of cycles within each cluster did not always lead to diversity of scenarios!
- For post-landfall Beryl clusters, we had spread in QPF magnitudes but little spread in placement of QPF Max

Cluster 6-h 75th Percentile QPF with 1" QPE Verification Overlaid
Valid: 6-hrs Ending 08 UTC Jul 09 2024

Cluster 1   00Z: 2=33% 06Z: 0=0% 12Z: 5=83% 18Z: 2=33% T: 9=38%
Cluster 2   00Z: 1=17% 06Z: 3=50% 12Z: 0=0% 18Z: 3=50% T: 7=29%
Cluster 3   00Z: 2=33% 06Z: 3=50% 12Z: 0=0% 18Z: 0=0% T: 5=21%
Cluster 4   00Z: 1=17% 06Z: 0=0% 12Z: 1=17% 18Z: 1=17% T: 3=12%
Full RRFS Ensemble   00Z: 6=86% 06Z: 6=86% 12Z: 6=86% 18Z: 6=86% T:24=86%
MRMS 6h QPE

QPF [in]
0.0   0.1   0.5   1.0   1.5   2.0   3.0   5.0   7.0   9.0

Take-Home Points

Ensemble clustering is a quick way to distill an ensemble forecast down to its prevalent scenarios

To our knowledge, this is the first time clustering has been attempted on REFS data! Many preliminary qualitative insights from HMT FFaIR 2024 so far!

– While results herein suggest an under dispersive ensemble system, time-lagging appears to give us *useful* spread, adding confidence in viability of continuing with time-lagged RRFS approaches

   - e.g., Each cycle does not depict a completely distinct scenario from its neighboring cycles

– Subjective result that Cluster 4 typically performs the best hints at the under dispersion of the system and shows there is room for improvement with cluster visualization

   - Participants appreciate being able to see features from individual members – perhaps we could build a hover feature that depicts postage stamps of each cluster member to improve utility

   - Visualizing clusters with PMMs or SAMs will likely also improve cluster utility

In the future, we'd like to expand this product to include Ensemble Sensitivity Analysis (ESA), which diagnoses the sources of our forecast uncertainty to help us ascertain *why* our different forecast scenarios exist!

Testament to the potential of data mining ensemble systems

– As we continue to build techniques that extract information from these datasets, need to keep forecaster needs at the forefront (lots of room for great O2R/R2O, so please reach out if you have questions or ideas)! ☺

Links!

Day 3-9 500Z Clusters + Ensemble Sensitivity Analysis Page

FFaIR 2024 RRFSe QPF Clusters

Days 1-6 CONUS QPF (NBM 4.2 QMDs) Cluster Page
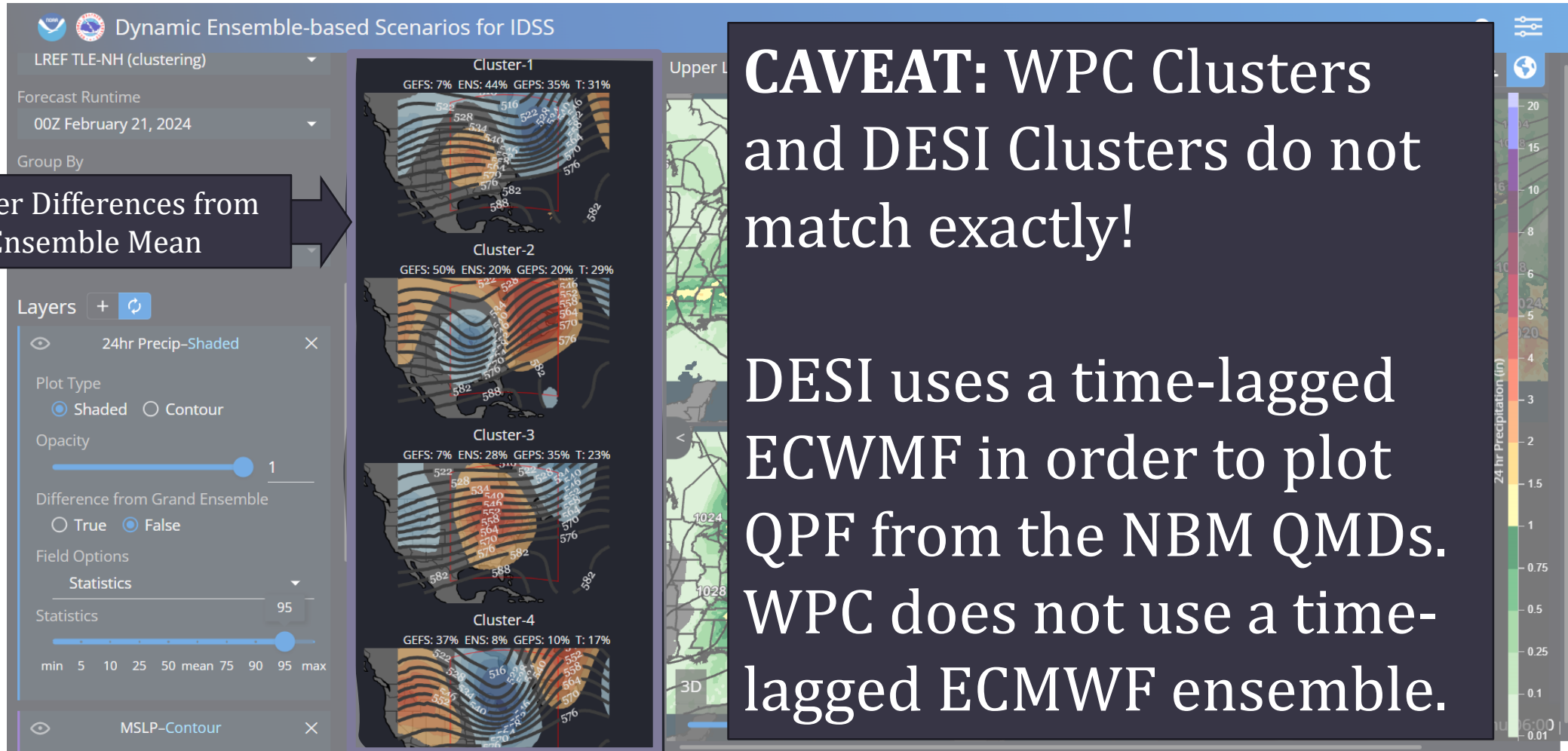
Days 3-9 500Z (CMCE+GEFS+ECMWF) Cluster Page

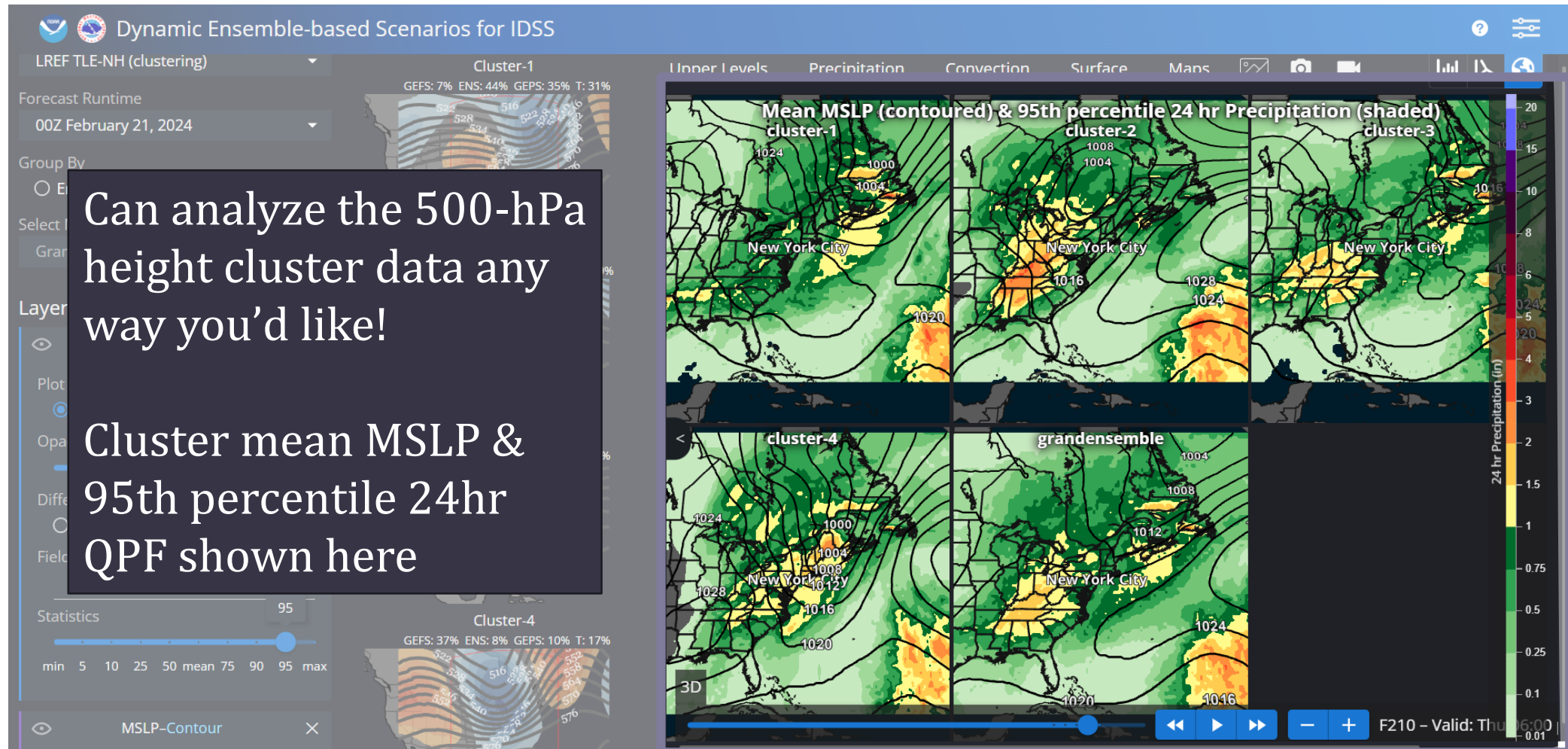Days 3-9 MSLP (CMCE+GEFS+ECMWF) Cluster Page

Bonus Slides

# You can interrogate the clusters even more effectively with the Dynamic Ensemble-based Scenarios for IDSS (DESI)!

Cluster Differences from Full Ensemble Mean

CAVEAT: WPC Clusters and DESI Clusters do not match exactly!

DESI uses a time-lagged ECWMF in order to plot QPF from the NBM QMDs. WPC does not use a time-lagged ECMWF ensemble.

You can interrogate the clusters even more effectively with the Dynamic Ensemble-based Scenarios for IDSS (DESI)!

Can analyze the 500-hPa height cluster data any way you'd like!

Cluster mean MSLP & 95th percentile 24hr QPF shown here

You can interrogate the clusters even more effectively with the Dynamic Ensemble-based Scenarios for IDSS (DESI)!

What early forecast differences are responsible for all this forecast uncertainty?
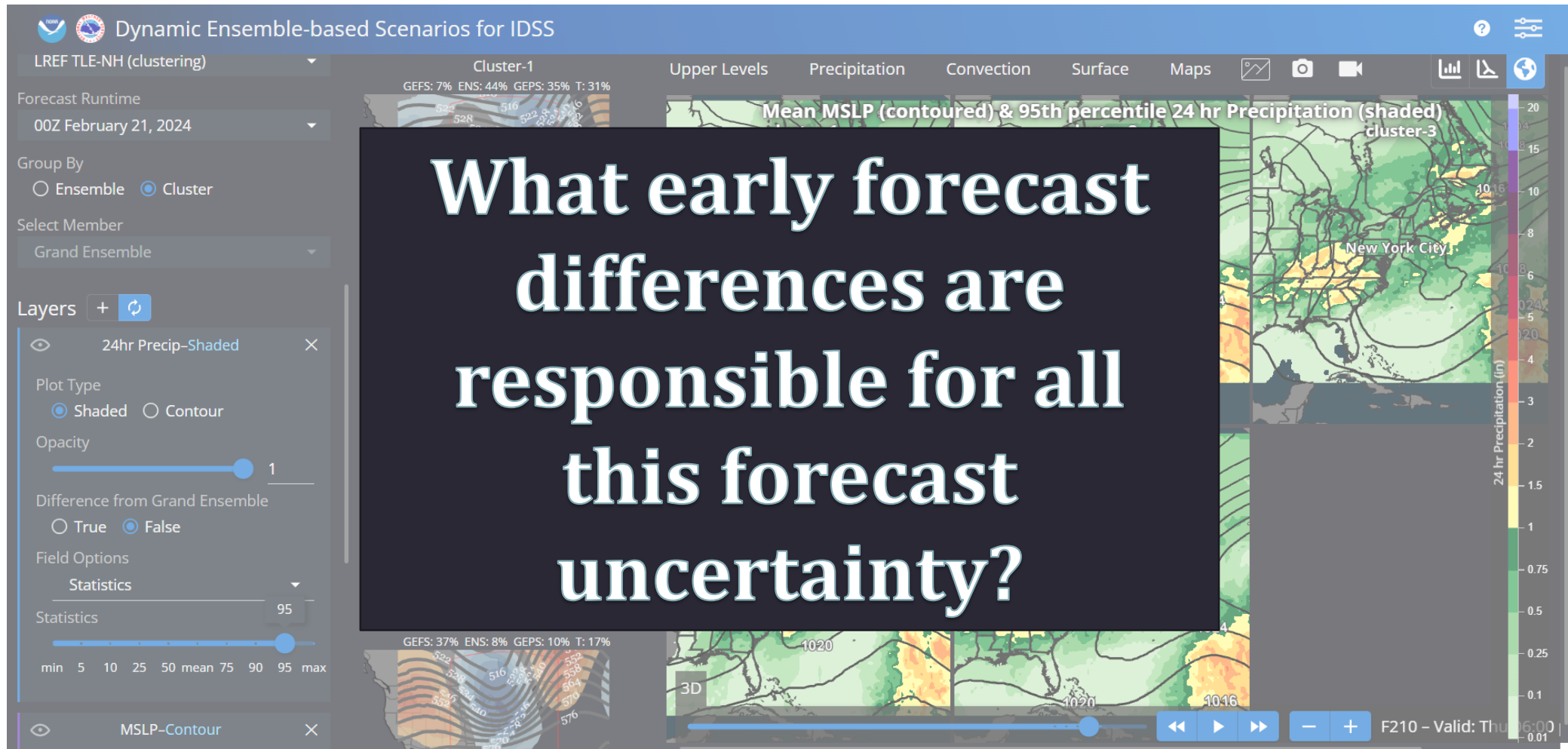
What is Ensemble Sensitivity Analysis?

Reveals how meteorological conditions early in the forecast (**sensitivity variable**) are linked to the evolution of a chosen high-impact forecast feature (**response function**)
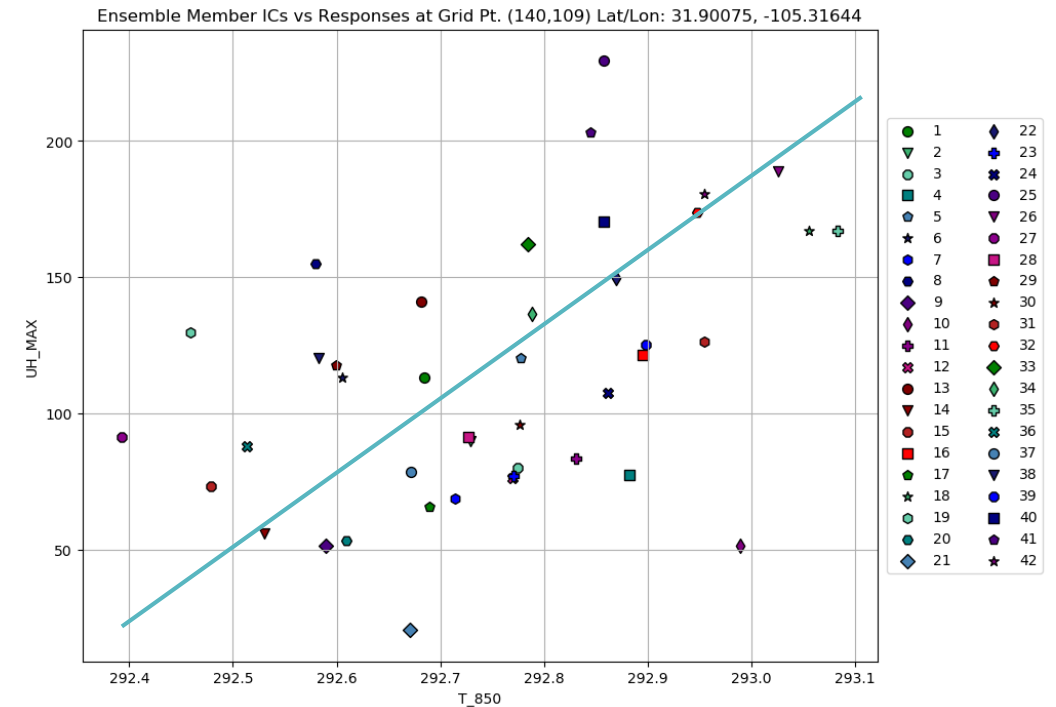
(Hakim and Torn 2008, Ancell and Hakim 2007, Torn and Hakim 2008)

Simply the slope of a linear regression line:

$$\frac{\partial J}{\partial x_0}$$

$J \equiv response\ function$
$x_0 \equiv sensitivity\ variable$

Ensemble Sensitivity ≡ Slope of the Linear Regression

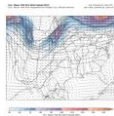**Member 1-hour UH Max at f25 (Response Function = J)**

Member 850 hPa Temperature at f6 (Sensitivity Variable = x_0)

Ensemble Sensitivity Fields

Powerful tool: Sensitivity fields show us which early forecast features the ensemble "cares" most about in predicting high-impact weather!

More Examples of Sensitivity Variables and Response Functions:

Sensitivity Variables
(Predictors)

Response Functions
(High-Impact Forecast Features)

- 2m Temperature
- SLP
- 850 hPa Temperature
- 850 hPa Moisture
- 700 hPa Temperature
- 500 hPa GPH
- 300 hPa U, V

- **Magnitude Responses**
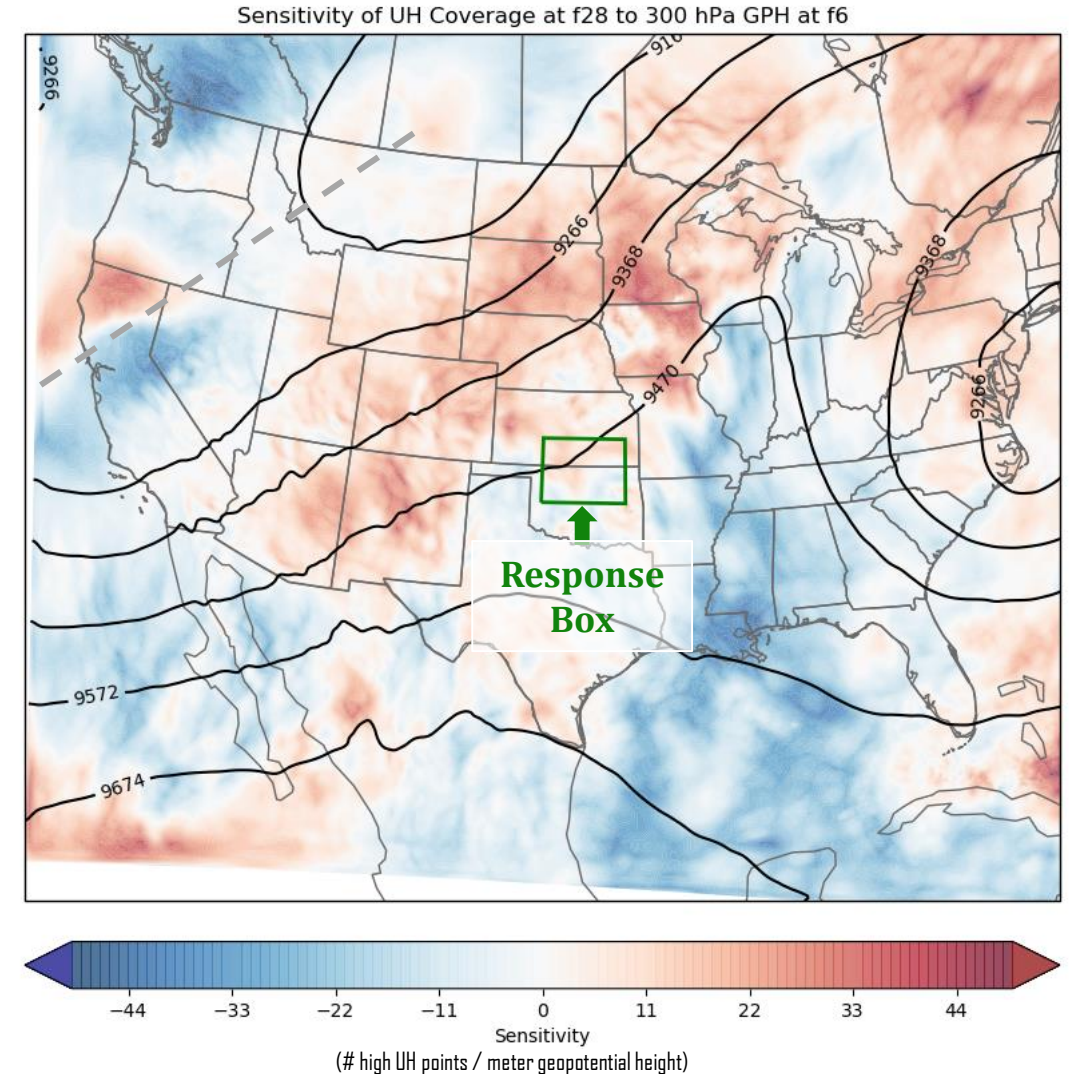 - Max Simulated Reflectivity
  - Max Precipitation Accumulation
  - Max 10m Wind Speed

- **Coverage Responses**
  - High Reflectivity (>40 dBZ) Coverage
  - High 24hr QPF (>2") Coverage
  - High 10m Wind Speed (>40 mph) Coverage

Sensitivity time (early) → Response time (later)

Sensitivity of UH Coverage at f28 to 300 hPa GPH at f6

Response Box

Sensitivity

(# high UH points / meter geopotential height)

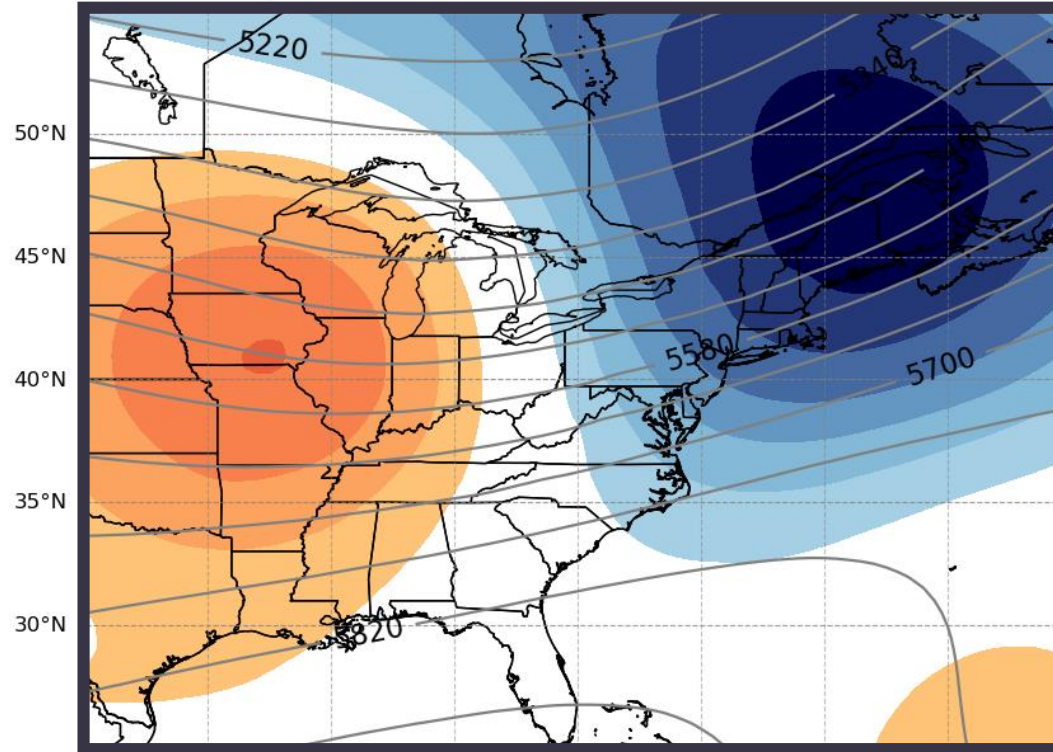In our use case, ESA tells us how the atmosphere needs to evolve early on in order to look like a given EOF!

Let's regress the phase speed uncertainty of the pattern back onto the early 500-hPa height field

EOFs of 24-hour Mean 500-hPa Heights [meters]
Init: 00Z Wed Feb 21 2024 --> Valid: 24-hours Ending 0OZ Fri Mar 1 2024
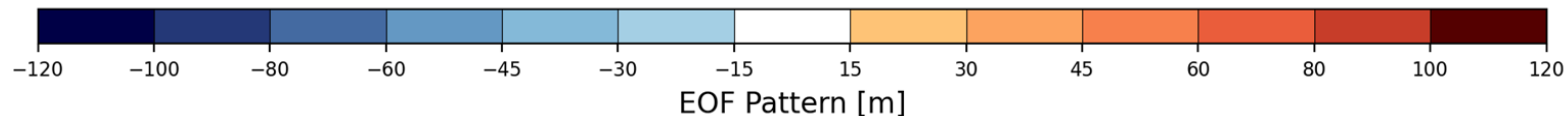

EOF1 of Day 8 500 hPa HGT   Percent Variance = 49.0%

Uncertainty: Position of trough relative to full ensemble mean (phase speed)
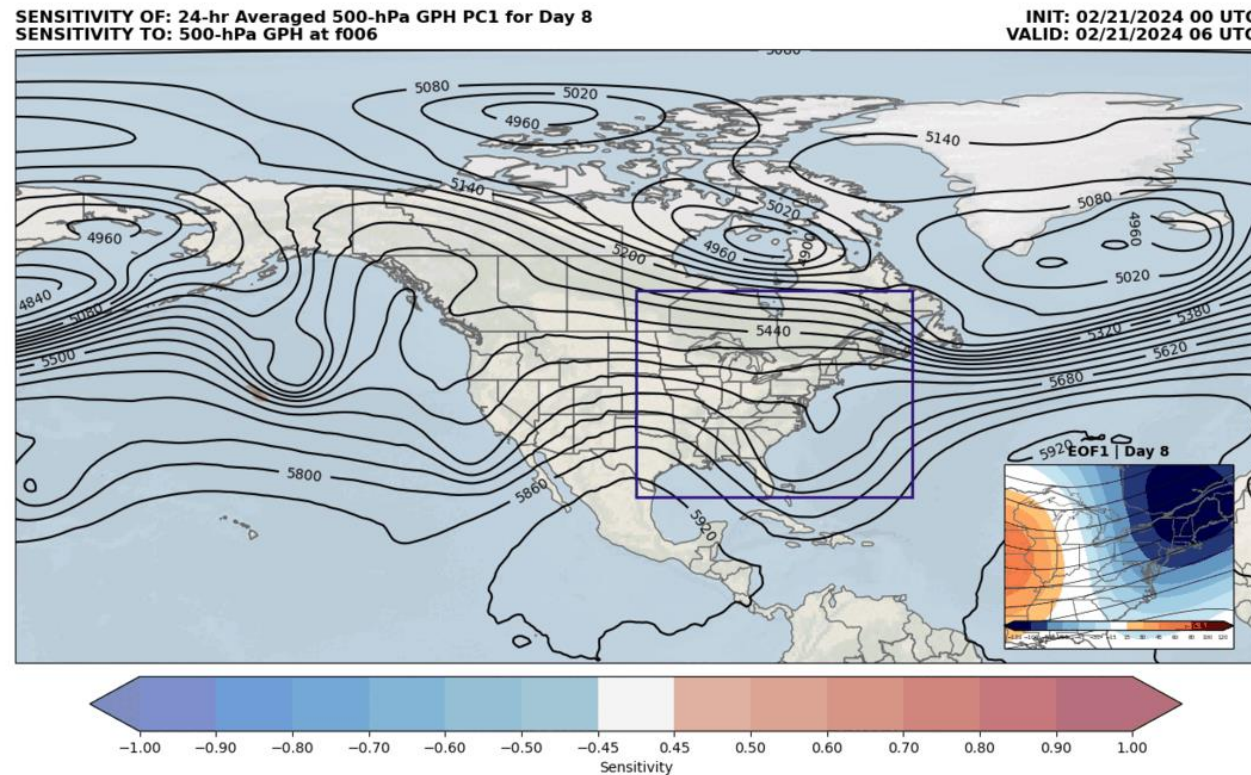
+ PC1 means trough shifted to the NE

- PC1 means trough shifted to the SW

ESA shows us what the ensemble "cares about" most when predicting the position of the trough at Day 8

When we calculate the standardized sensitivity of PC values to the early forecast state, *the slope of the linear regression line becomes a **correlation**!*
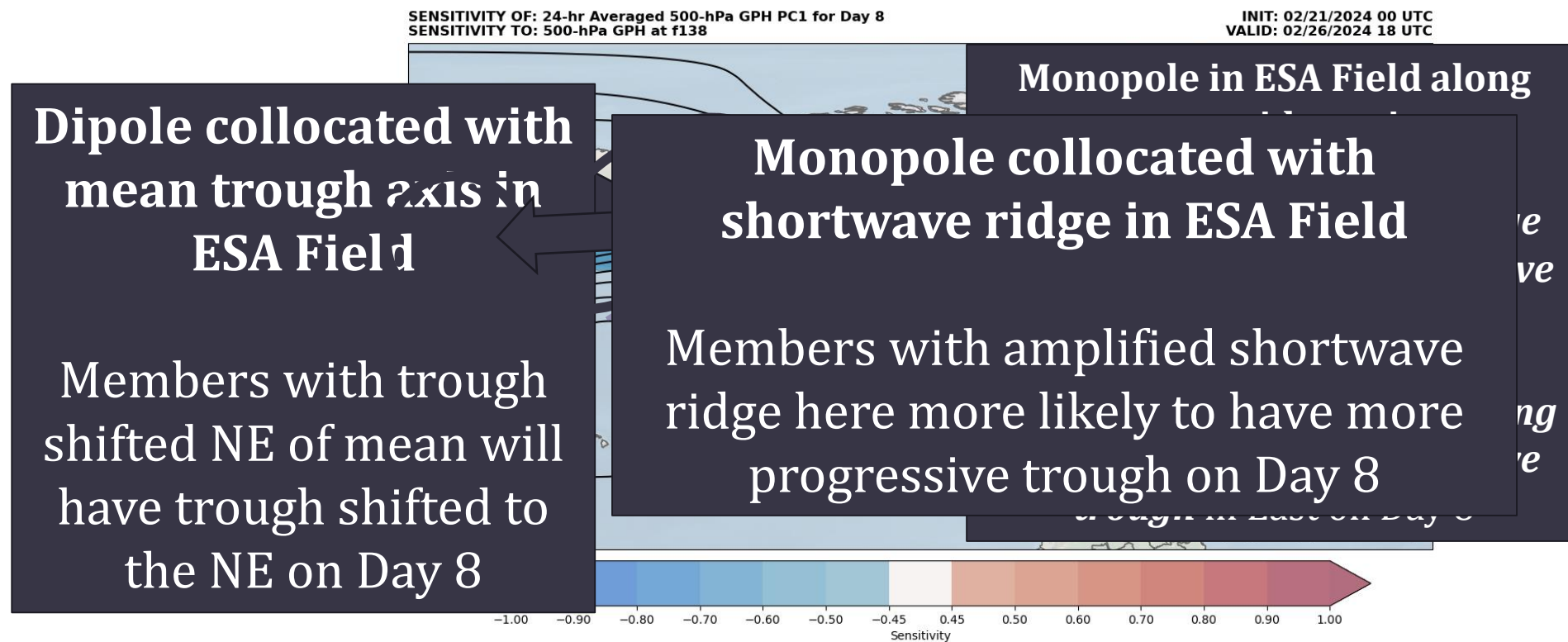
ESA shows us what the ensemble "cares about" most when predicting the position of the trough at Day 8

When we calculate the standardized sensitivity of PC values to the early forecast state, *the slope of the linear regression line becomes a **correlation**!*

SENSITIVITY OF: 24-hr Averaged 500-hPa GPH PC1 for Day 8
SENSITIVITY TO: 500-hPa GPH at f138

INIT: 02/21/2024 00 UTC
VALID: 02/26/2024 18 UTC

Dipole collocated with mean trough axis in ESA Field

Members with trough shifted NE of mean will have trough shifted to the NE on Day 8

Monopole in ESA Field along

Monopole collocated with shortwave ridge in ESA Field

Members with amplified shortwave ridge here more likely to have more progressive trough on Day 8

We can also conduct sensitivities of *MSLP PCs* back to the early forecast 500-hPa height field

This product could be particularly useful during the hurricane season for tropical cyclone sensitivity fields

SENSITIVITY OF: 24-hr Averaged MSLP PC1 for Day 8
SENSITIVITY TO: 500-hPa GPH at f138

INIT: 02/21/2024 00 UTC
VALID: 02/26/2024 18 UTC

Members with a *deeper trough than average here*
Members with a *shallower trough than average here* more likely to have a *stronger and more progressive surface low on Day 8*
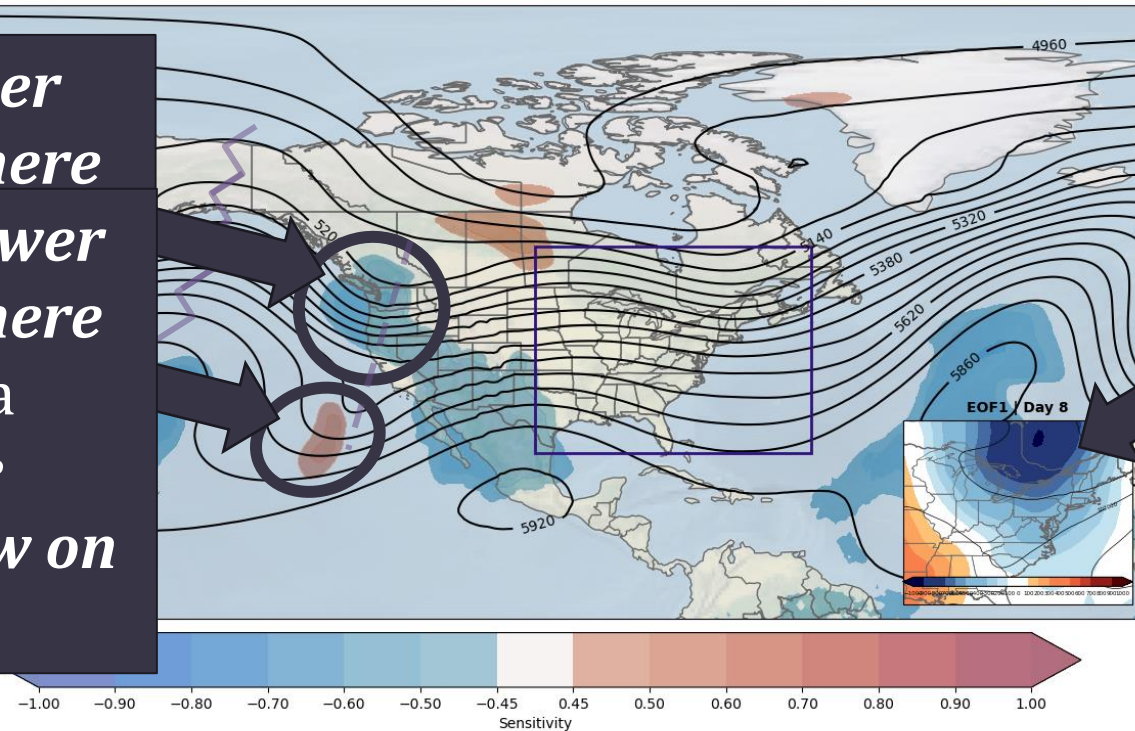
Main Uncertainty: Depth & Position of Surface Low

EOF1 / Day 8