Better Use of Ensembles in Operations Through Clustering and Ensemble Sensitivity Analysis

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Motivation

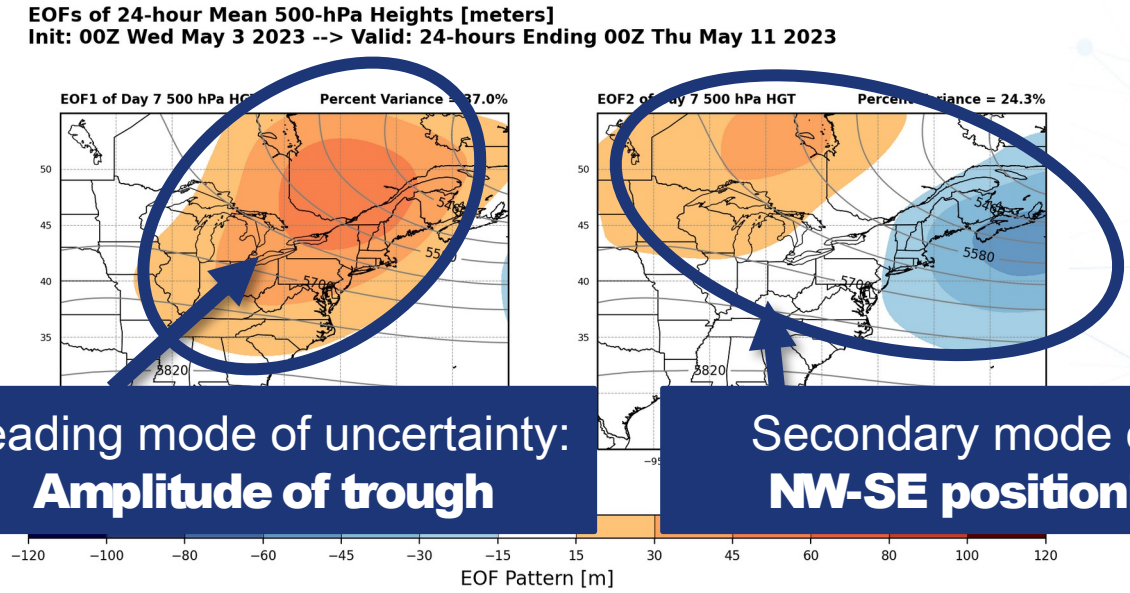
- As technology improves and NWS responsibilities expand
  - Forecasters have access to more data with simultaneously less time to interrogate those data
- The National Blend of Models (NBM) is frequently used as a first-guess for said forecasts
  - Blends a large amount of forecast data, but can be seen as a black box
  - Forecasters desire more information about what makes up the NBM
- Ensemble mean of NBM's sub-ensemble systems (CMCE, GEFS, and ECMWF) is one way to quickly summarize solutions
  - Problem: it often washes out important nuance amongst ensemble membership

Solution? Develop a clustering approach to break down an ensemble forecast into its most prevalent scenarios!

Inspired by and in collaboration with fuzzy clustering work conducted at Stony Brook

How does it work?

First, we break down the forecast (super-ensemble of CMCE, GEFS, & ECMWF) into its leading modes of variability via EOF Analysis (traditionally known as PCA)



Leading mode of uncertainty:
Amplitude of trough

Secondary mode of uncertainty:
NW-SE positioning of trough

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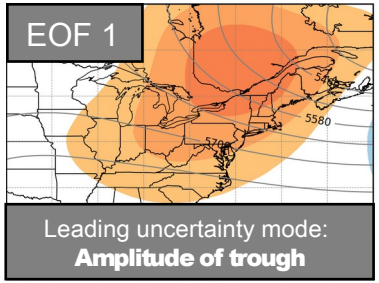
How does it work?

Next, we use k-means clustering to assign members to cluster scenarios

First two EOFs for reference

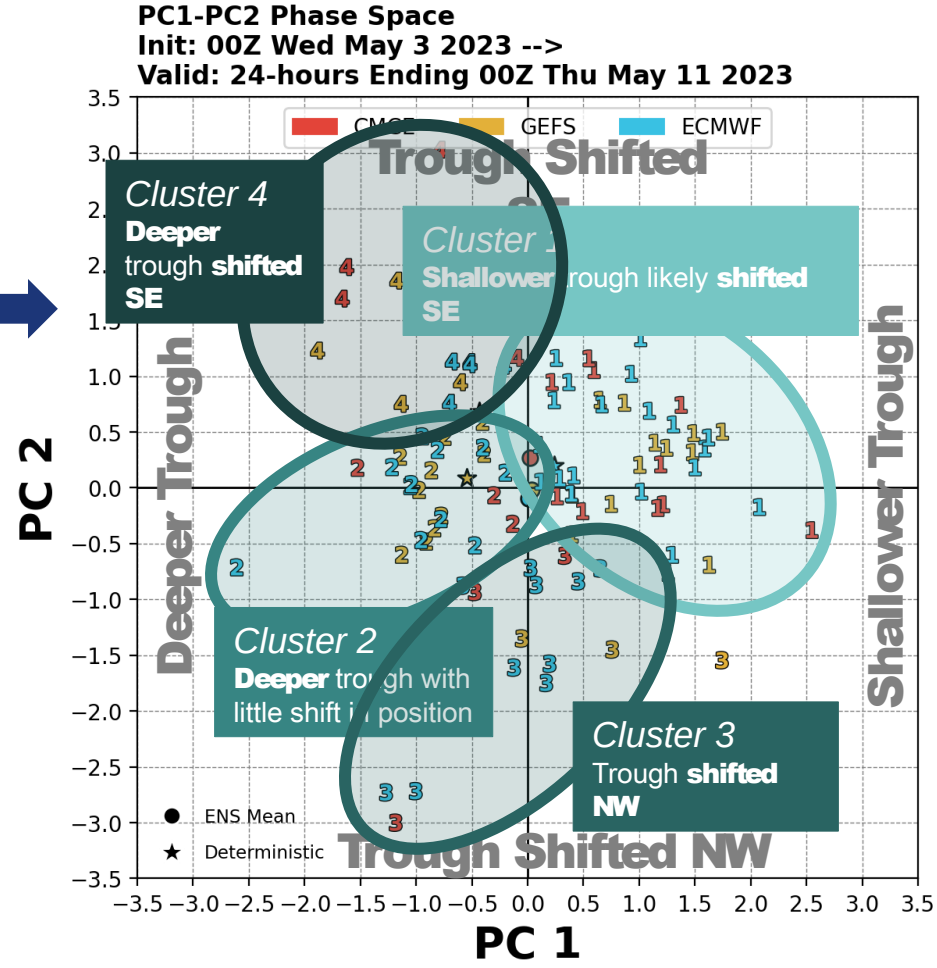


Principal component (PC) phase space shows us the forecast scenario for each ensemble member (and system)

Members with positive PC1 will look more like EOF1 whereas members with negative PC1 will look opposite EOF1

K-means clustering groups members with similar scenarios

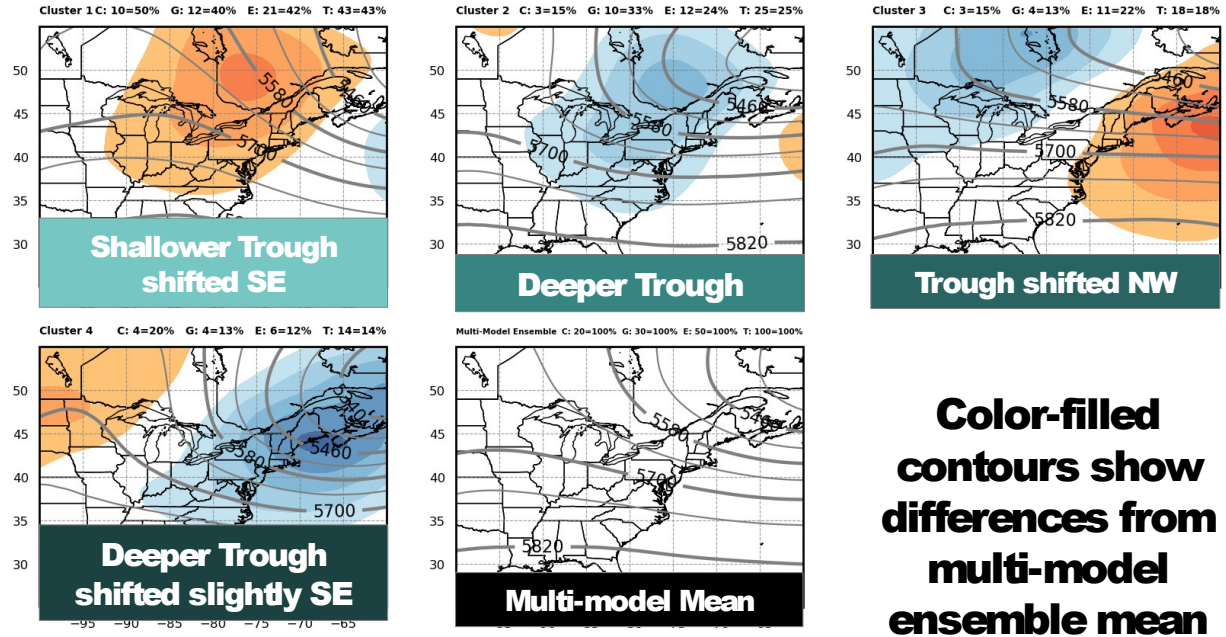
(WPC pg keeps # clusters fixed at 4)



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

Can skip straight to the cluster forecasts (of 500-hPa heights in this case)

Cluster Mean 24-hour Mean 500-hPa Heights and Difference from Multi-Model Mean [m]
Init: 00Z Wed May 3 2023 --> Valid: 24-hours Ending 00Z Thu May 11 2023



Color-filled contours show differences from multi-model ensemble mean

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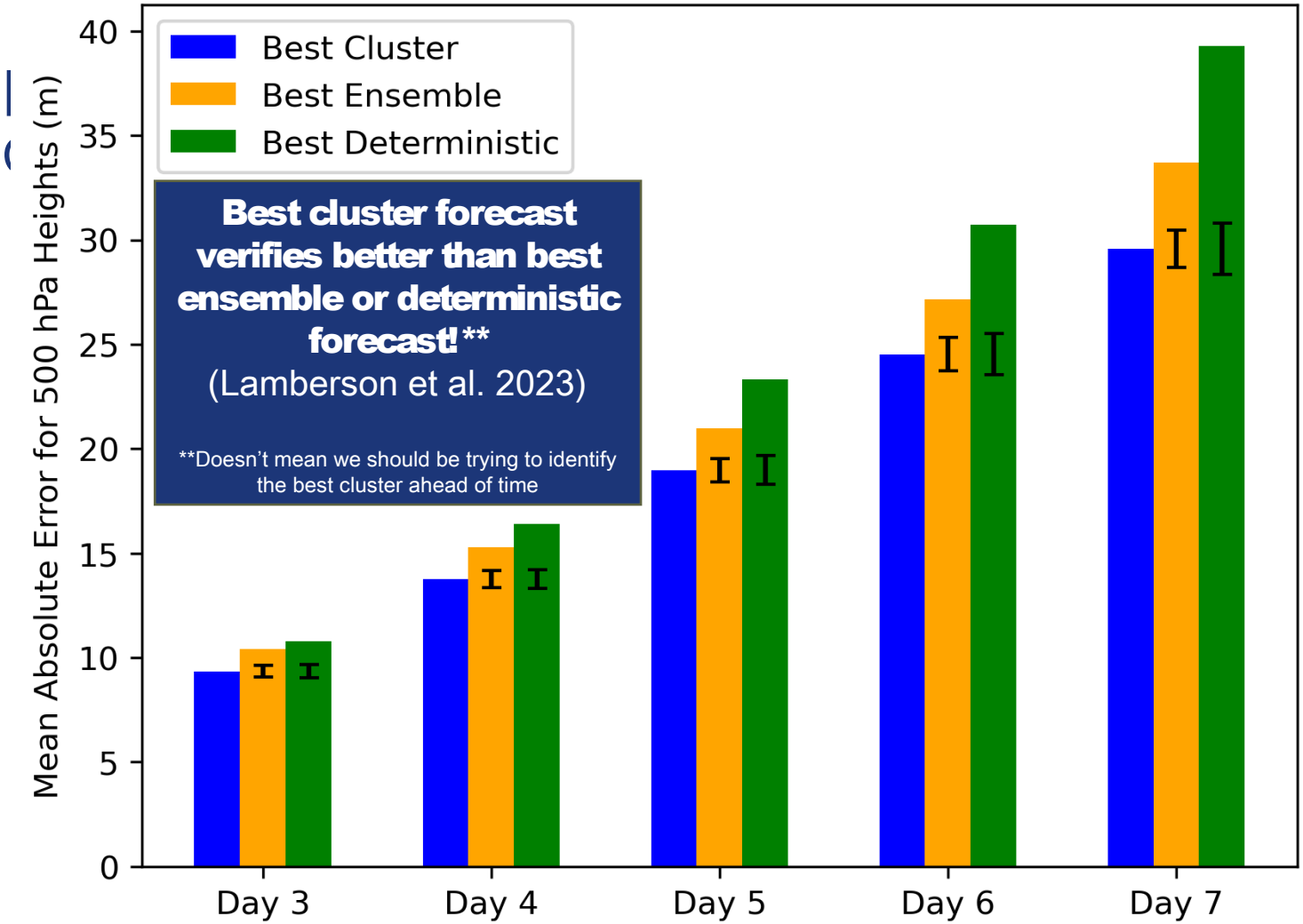
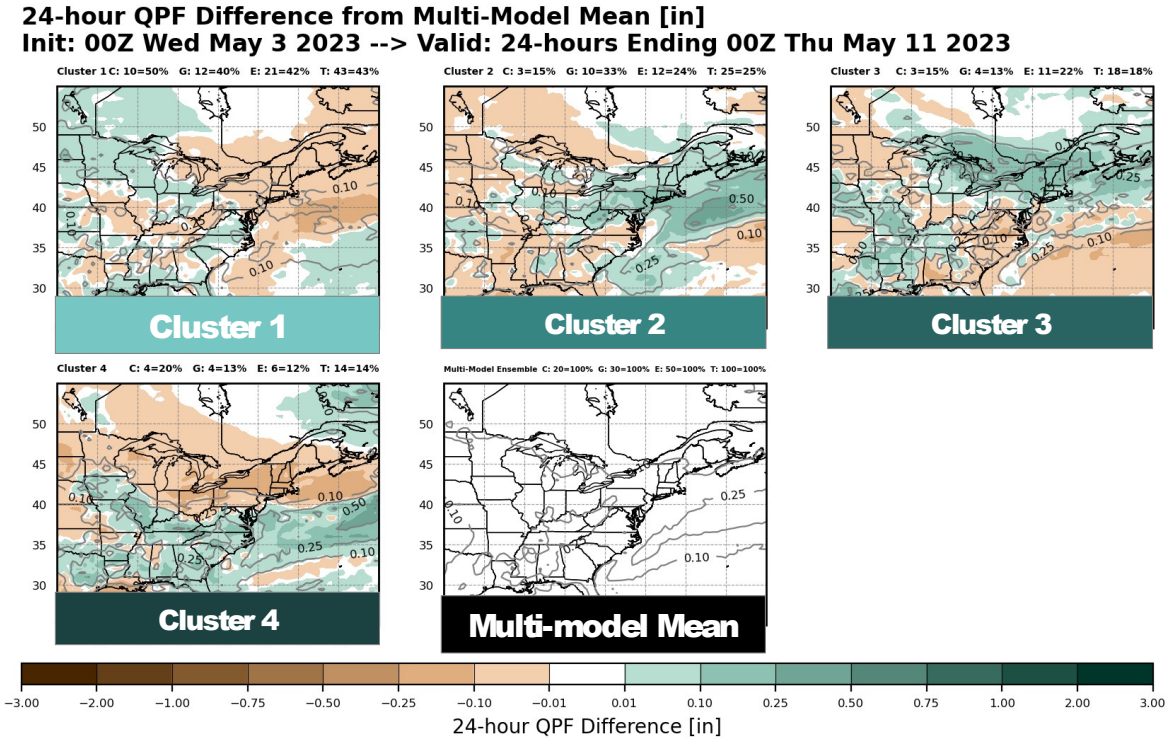

Best Cluster
Best Ensemble
Best Deterministic
Best cluster forecast verifies better than best ensemble or deterministic forecast!**
(Lamberson et al. 2023)
**Doesn't mean we should be trying to identify the best cluster ahead of time
Mean Absolute Error for 500 hPa Heights (m)
0
5
10
15
20
25
30
35
40
Day 3
Day 4
Day 5
Day 6
Day 7

Can use 500-hPa height clusters to predict other fields

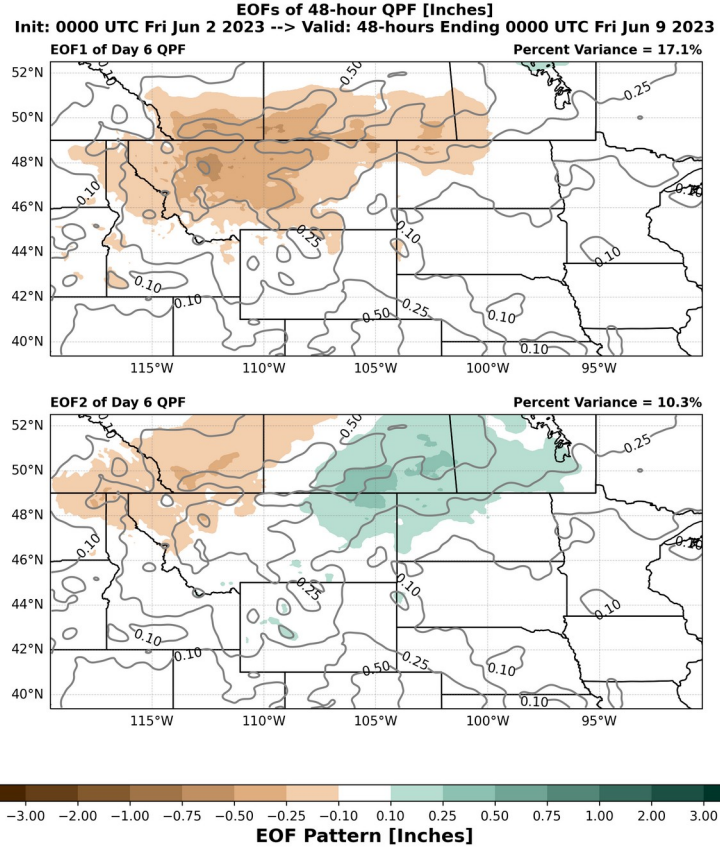
24-hr QPF



We also have a page that clusters on QPF uncertainty!

Based on NBM QMDs (100 members)

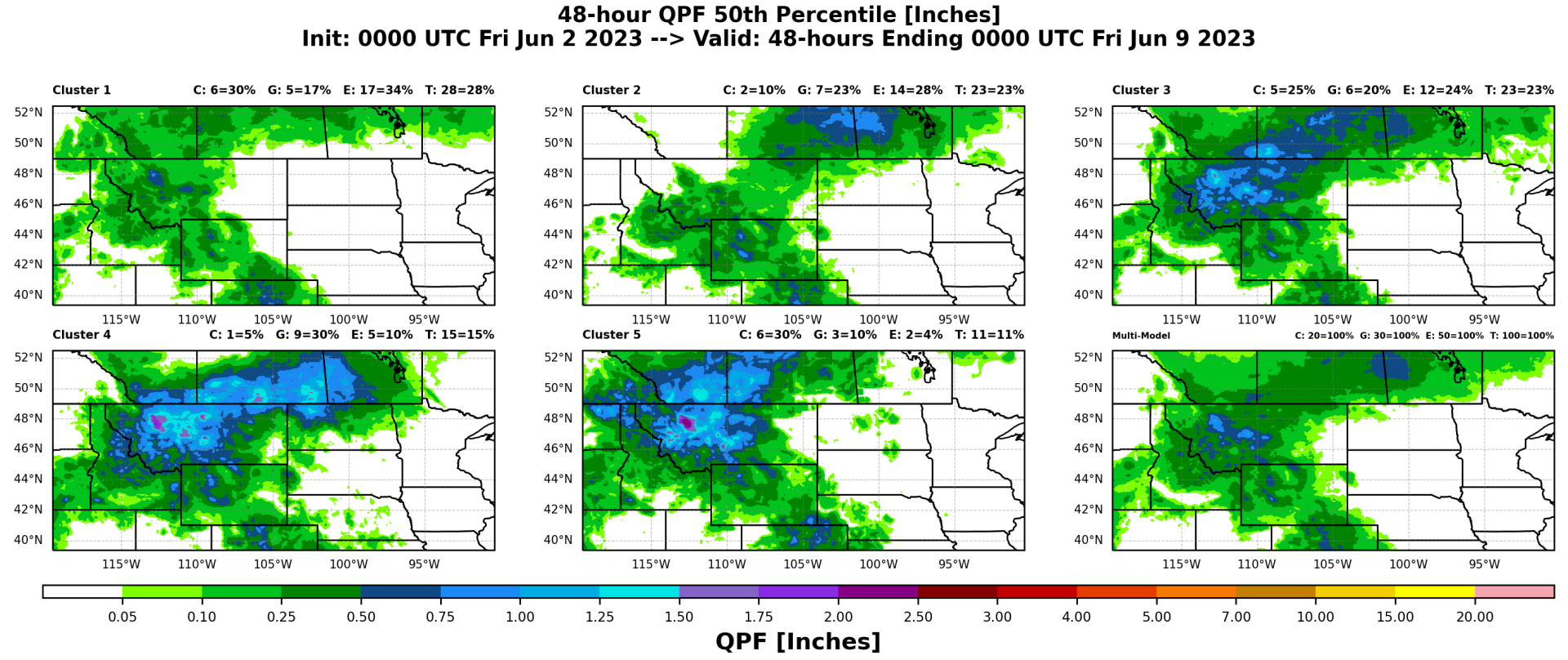
Leading mode of 48hr QPF uncertainty is precipitation amounts



Secondary mode of 48hr QPF uncertainty is position of precipitation max

We also have a page that clusters on QPF uncertainty!

48-hr QPF 50th Percentile by Cluster



Forecasters regularly use this guidance!

- Clustering technique has quickly gained popularity within the NWS (largely due to Western & Central Region championing it!)
  - In 2019, ensemble clustering tool was mentioned **38x** in NWS AFDs
  - By 2021, it was referenced over **3,600x** in AFDs
- Clustering also used as a centerpiece of the experimental ensemble visualization platform known as the Dynamic Ensemble-based Scenarios for IDSS (DESI)
  - As part of DESI, the clustering technique is used as both a scientific forecasting tool and a communication tool

But they want more context about how the different clusters came to be…

…Cue ensemble sensitivity analysis (ESA)!

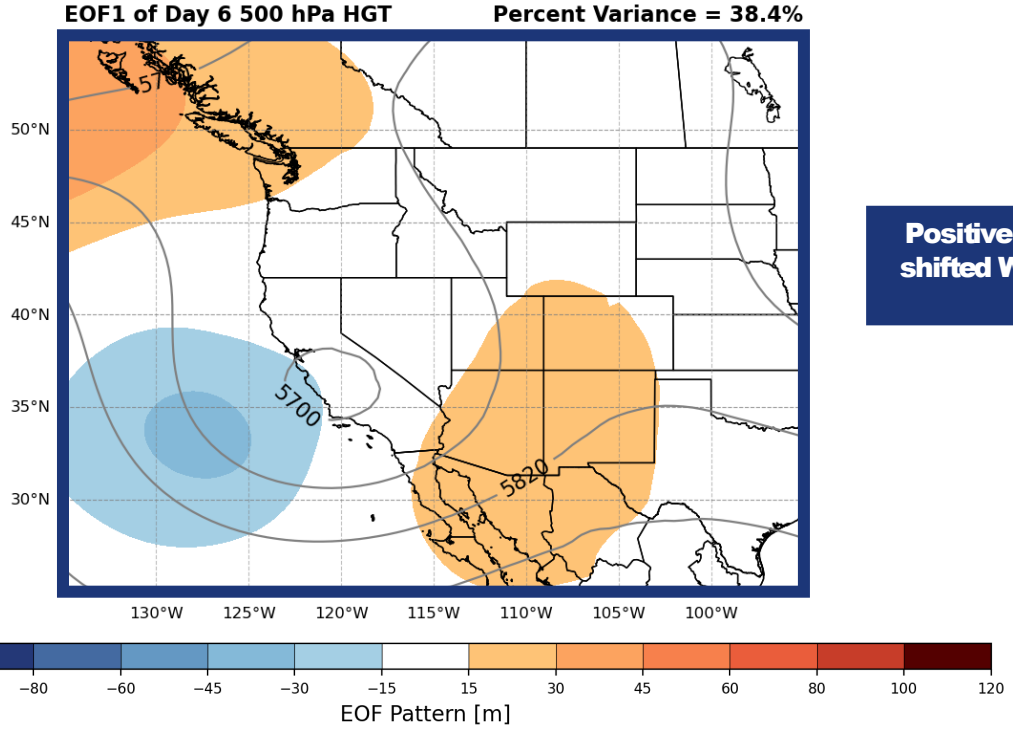
- Clusters tell you the different prevalent forecast outcomes, but don't provide any context on what leads to those outcomes
  - Forecasters can look at the forecast evolution of each cluster and infer which early forecast differences lead to different outcomes, but takes a lot of time/energy and can be tricky
  - Ensemble sensitivity analysis relates the possible forecast outcomes back to the early forecast state – quantifies which early features are most relevant to scenario
  - **Clustering describes the "what", and ensemble sensitivity explains the "why"**
- Forecasters often ask for the "why" in DESI feedback surveys
- Actively developing this product as a web-based tool (should be available on the main WPC cluster page in the next few weeks)

Also in collaboration with Brian Colle at Stony Brook

ESA tells us how the atmosphere needs to evolve early on in order to look like a given EOF!

Response Function: PC Values (in this case, positioning of the cut-off low)

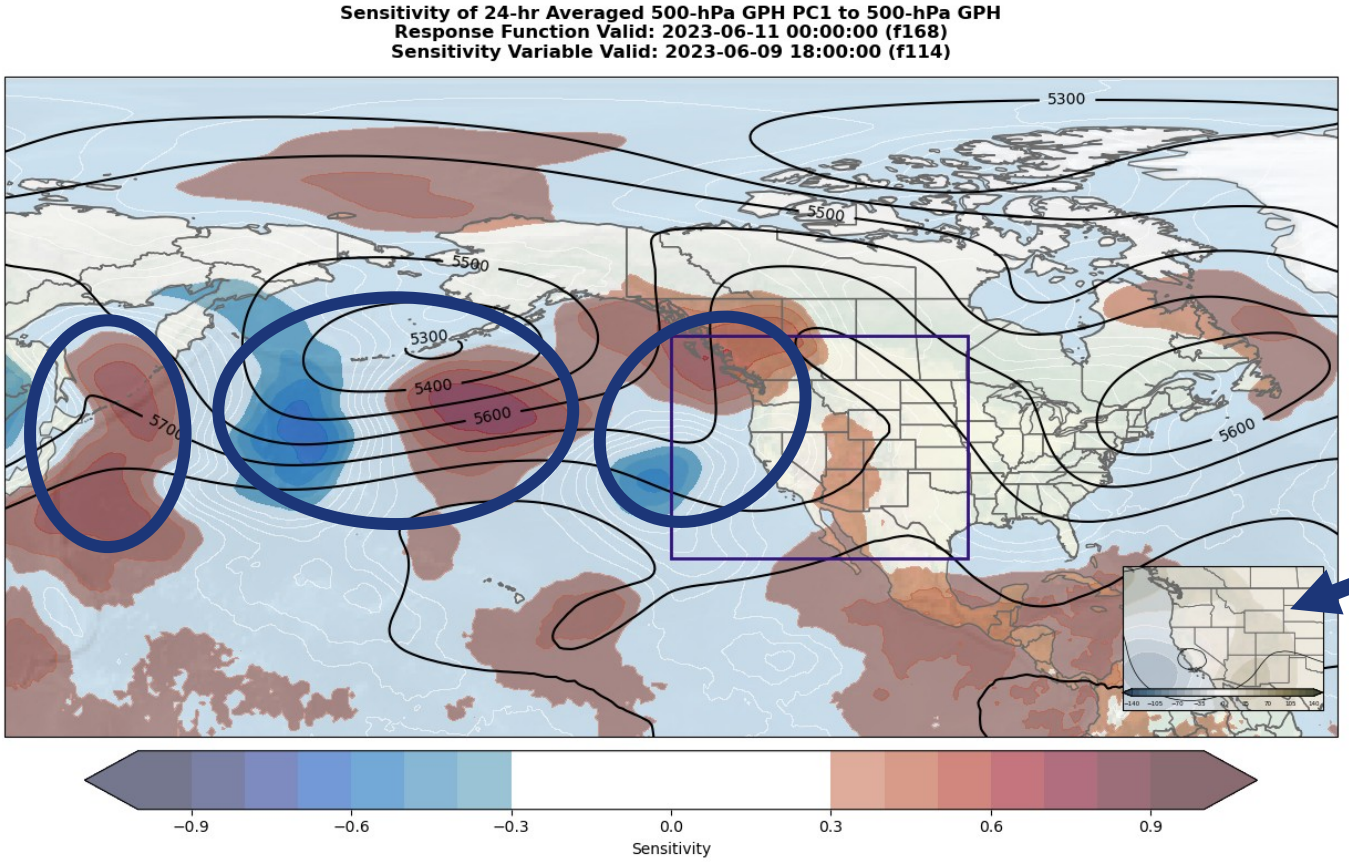
EOFs of 24-hour Mean 500-hPa Heights [meters]
Init: 00Z Mon Jun 5 2023 --> Valid: 24-hours Ending 00Z Mon Jun 12 2023



Primary Uncertainty:
Position of Cutoff Low & Amplitude of Pattern over Pacific NW

Positive PC1 means **cut-off low shifted West** and **higher heights for Pacific NW**

ESA tells us how the atmosphere needs to evolve early on in order to look like a given EOF!



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EOF1 for reference

Take-Home Points

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

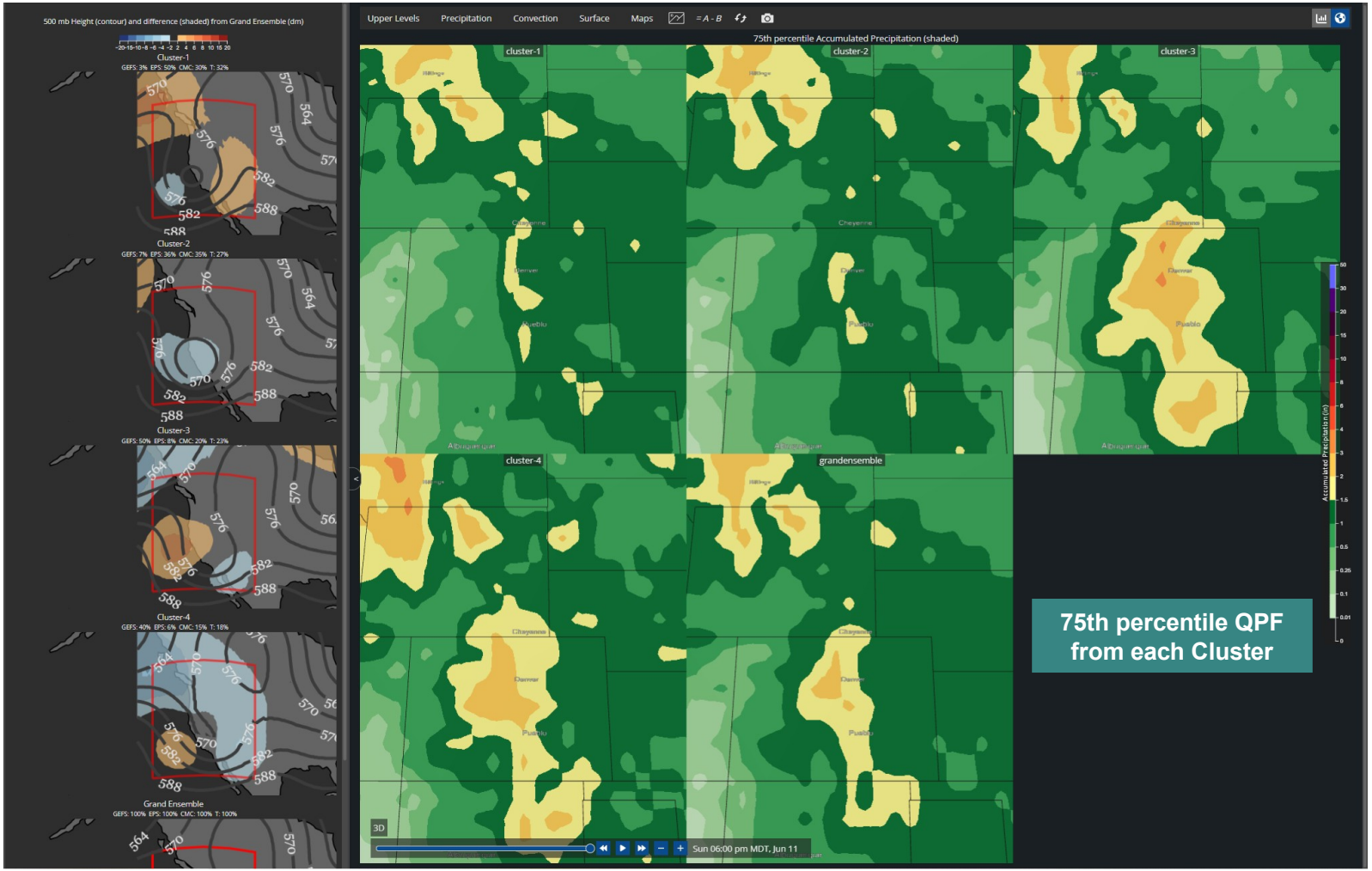
- Lots of potential as a scientific tool (best cluster verifies better than best deterministic or best ensemble mean forecast)
- Feedback suggests utility as a communication tool as well

Ensemble sensitivity analysis (ESA) provides context on how the atmosphere must evolve to lead to different cluster scenarios

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 O2R/R2O in these spaces)!

Bonus Slides


500 mb Height (contour) and difference (shaded) from Grand Ensemble (dm)
Cluster-1
GEFS: 3% EPS: 50% CMC: 30% T: 32%
Cluster-2
GEFS: 7% EPS: 36% CMC: 35% T: 27%
Cluster-3
GEFS: 50% EPS: 8% CMC: 20% T: 23%
Cluster-4
GEFS: 40% EPS: 6% CMC: 15% T: 18%
Grand Ensemble
GEFS: 100% EPS: 100% CMC: 100% T: 100%
Upper Levels
Precipitation
Convection
Surface
Maps
75th percentile Accumulated Precipitation (shaded)
cluster-1
cluster-2
cluster-3
cluster-4
grandensemble
Accumulated Precipitation (in)
3D
Sun 06:00 pm MDT, Jun 11
75th percentile QPF from each Cluster

Forecaster Feedback on Clustering in DESI as a Communication Tool

"Helps the forecaster determine why uncertainty exists which can be passed along to the core partner which helps build trust."

"Aids in communicating with our partners and the public. Cluster information gives me a better idea of where there is lots of uncertainty, and in those cases I avoid speaking in terms of absolutes."

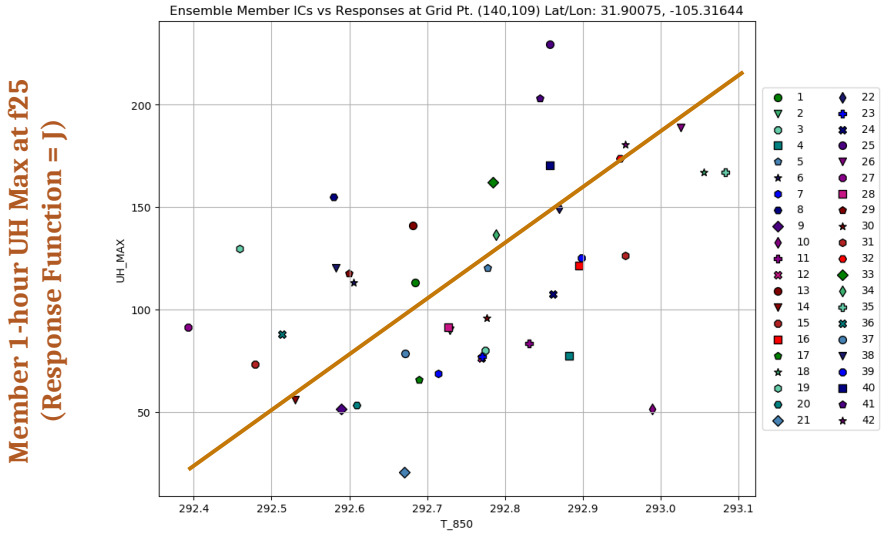
How does Ensemble Sensitivity Analysis work?

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:

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)

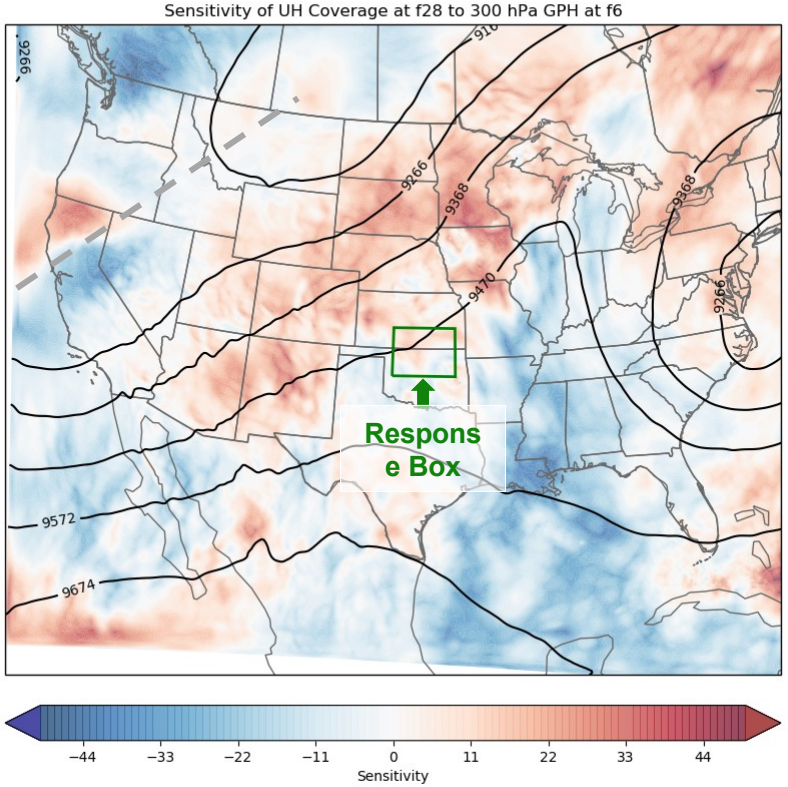
Ensemble Sensitivity Fields

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

More Examples of (Traditional) Sensitivity Variables and Response Functions:

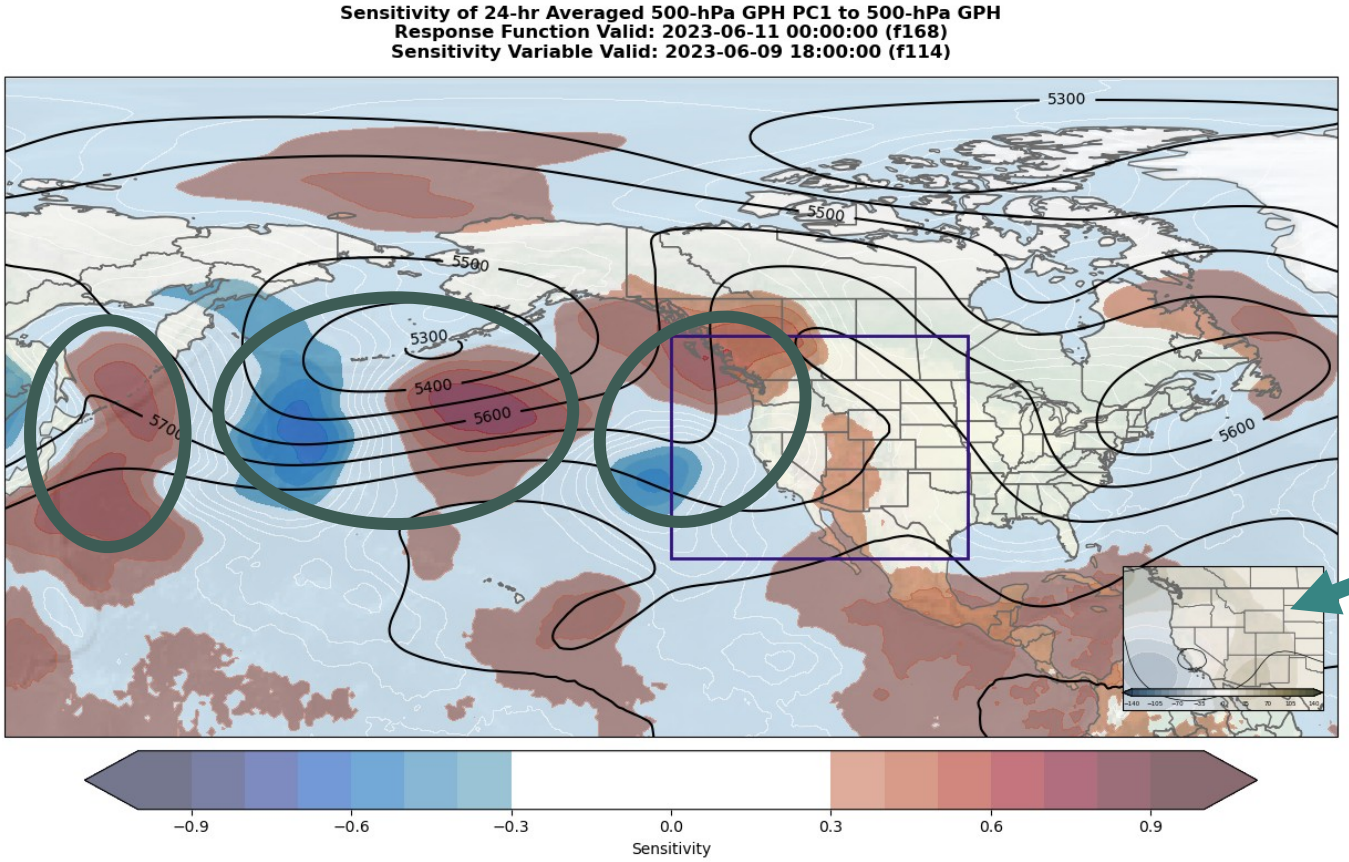
Sensitiv	Response
• 2m Temperature • SLP	**Magnitude Responses** • Max Updraft Helicity

Sensitivity time (early) → Response time (later)



(# high UH points / meter geopotential height)

Can use ESA and truth at early forecast times to hedge your bets on a particular cluster verifying



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