Extreme Rainfall in NYC from Ida: Insights from a High-Resolution Forecast Model

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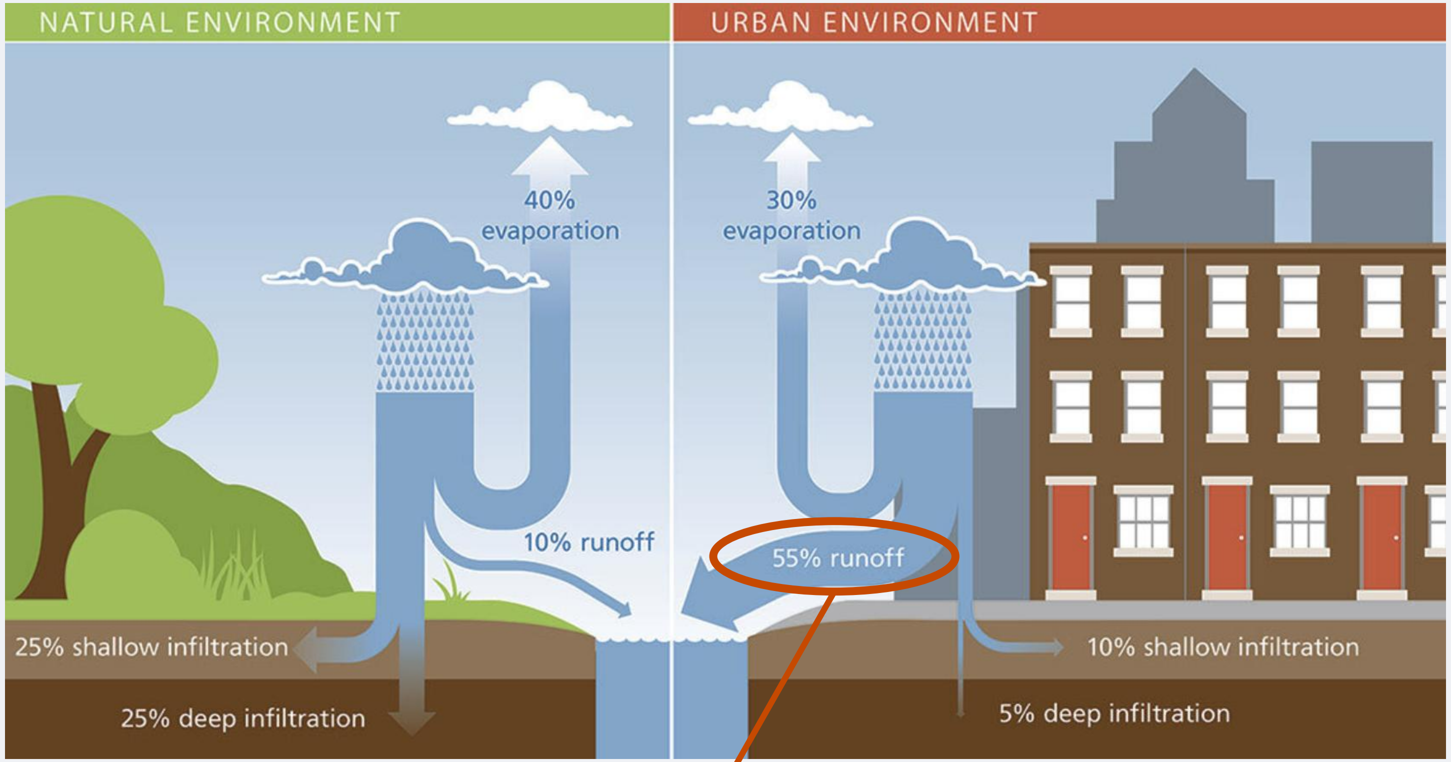
Background & Motivation

Urban Areas are Susceptible to Flash Flooding

- Permeable soil
- Vegetation to intercept and absorb water
- Only ~10% runoff



The Nature Conservancy

Stormwater Drainage System

- Impervious concrete & asphalt
- Little vegetation
- 55% runoff on average

Hourly Rainfall in NYC

- **Hourly rainfall** → main metric for flash flood risk
- NYC infrastructure designed for a **5-year storm** (20% chance any year)
- **Threshold: 1.75 inches per hour**

Central Park ASOS Hourly Rainfall Amounts

Statistica

Note: These values are from only <u>one</u> weather station and regular hourly METARs

Consider these **lowball** measurements.

2021 was already anomalously wet

- 2021: NYC's **second wettest summer on record**
- 21 August 2021: Hurricane Henri brings 1.94"/hr

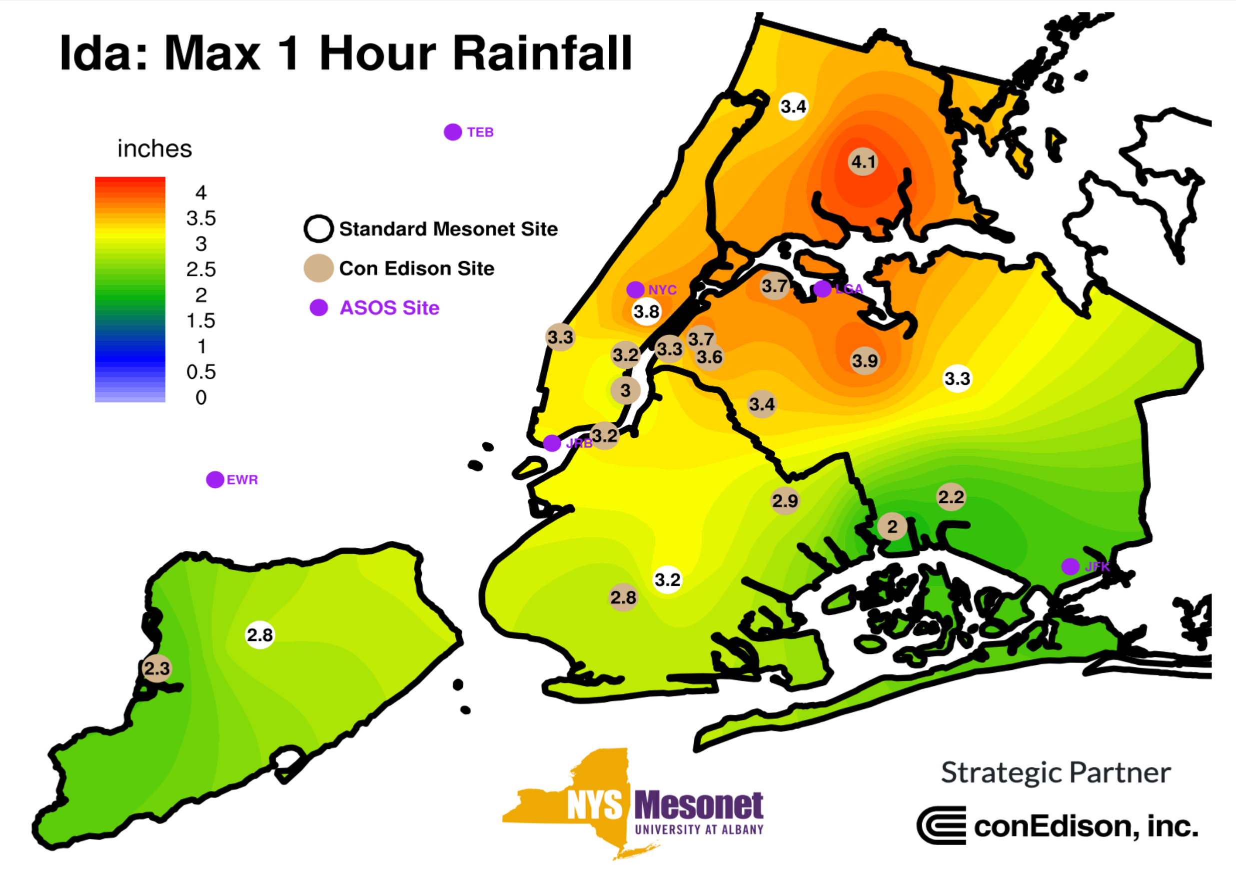
New York Post

Central Park ASOS Hourly Rainfall Amounts

Statistica

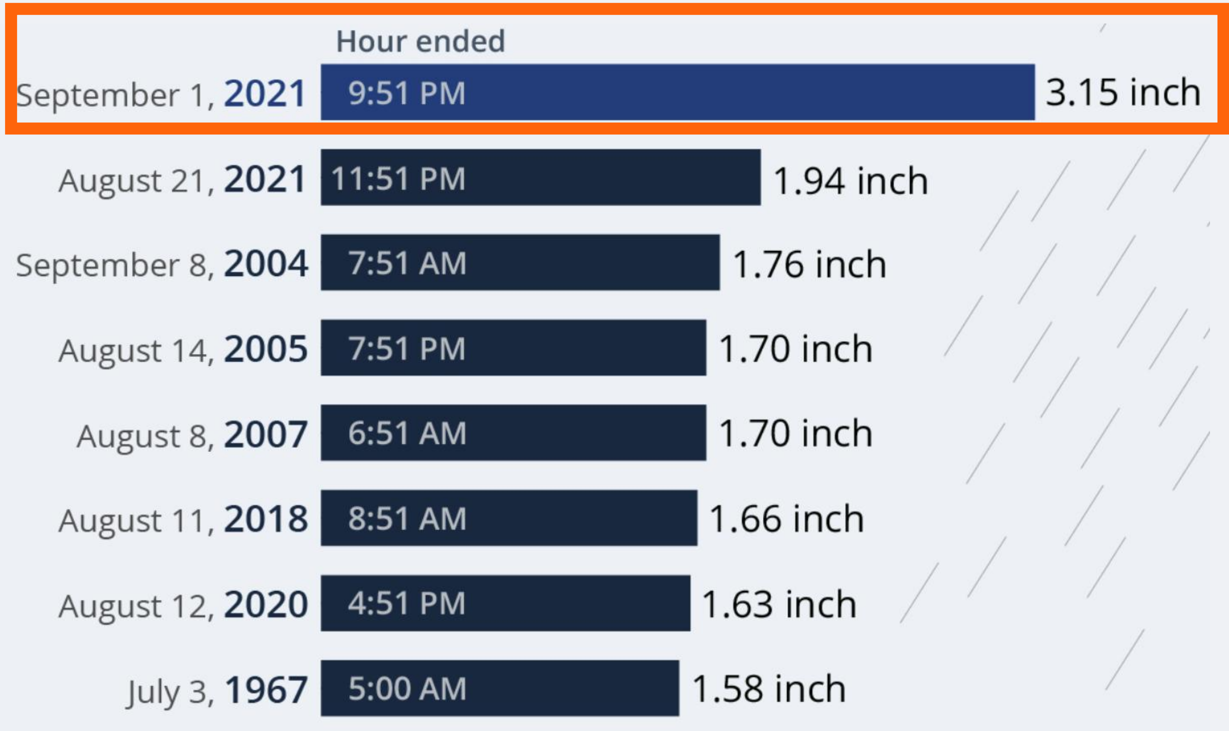
Ida shatters previous records

NYC Micronet Rainfall Measurements



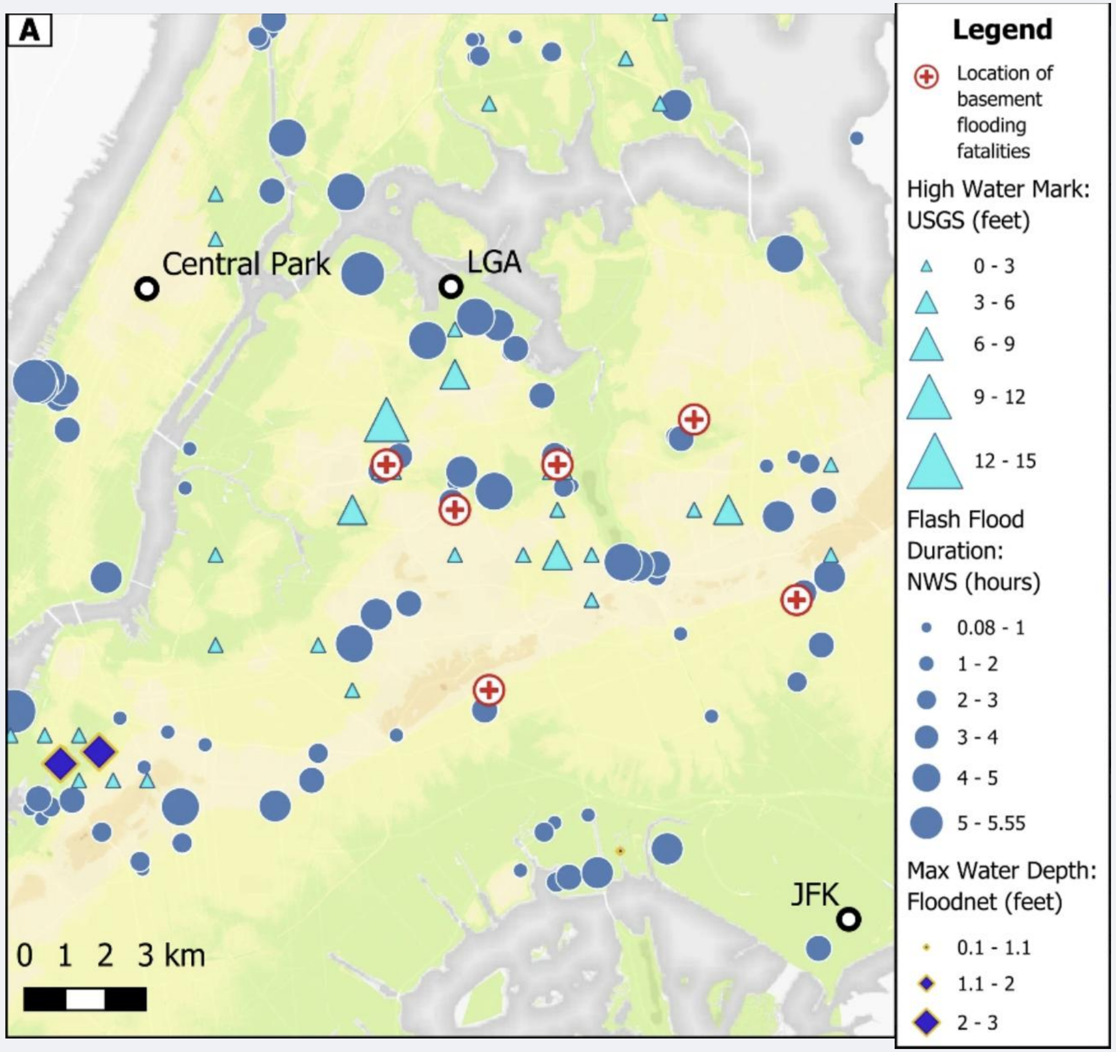
NYS Mesonet

Central Park ASOS Hourly Rainfall Amounts



Statistica

Impact: Flash Flooding



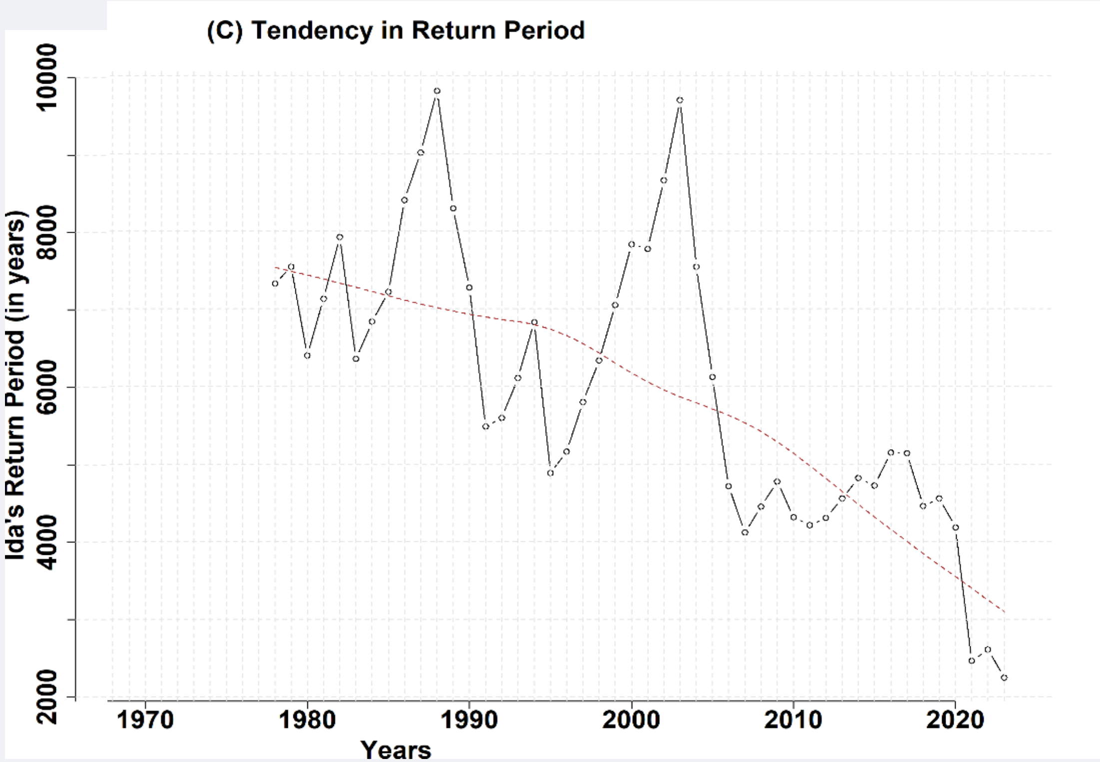
Adapted from Fig. 1 of Mossel et al. (2024)

- Hours-long flash flooding
- 13 dead in NYC
  - 11 from basement flooding
- Billions of dollars of damage
- Different from past storms: affected **inland neighborhoods** instead of coasts

Events like Ida have and will become more common

- Mossel et al. (2024) found that the return period of Ida-like events **has decreased over past 4 decades**
- Trend likely to continue and accelerate with **climate change**
- **Despite increasing likelihood, Ida-like events are super rare**

Return Period (inverse of likelihood) of Ida-like hourly rainfall



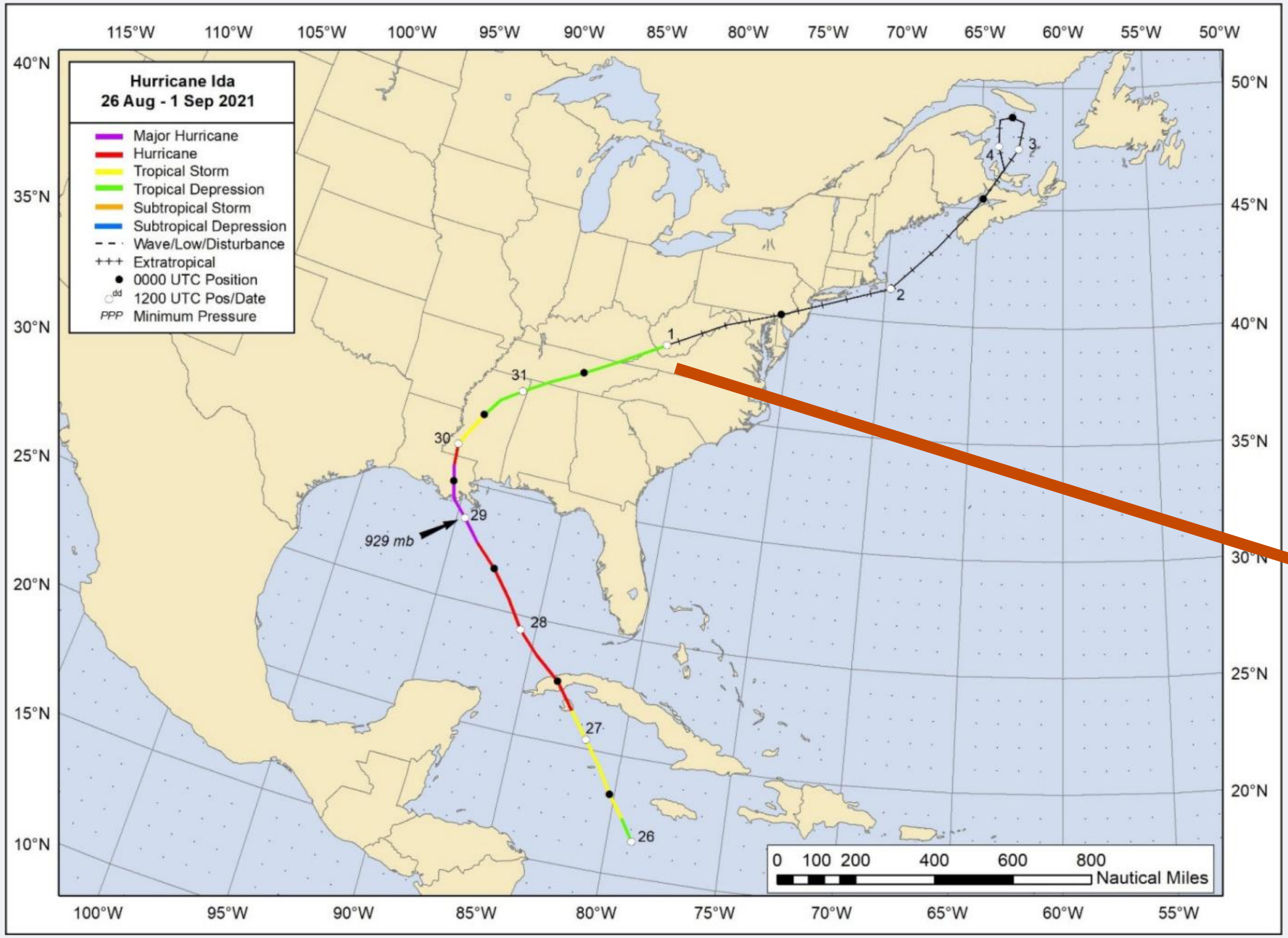
Adapted from Fig. 2 of Mossel et al. (2024)

Meteorological History

What exactly happened?

Hurricane Ida Track & Transition

Hurricane Ida Dated Track & Classifications



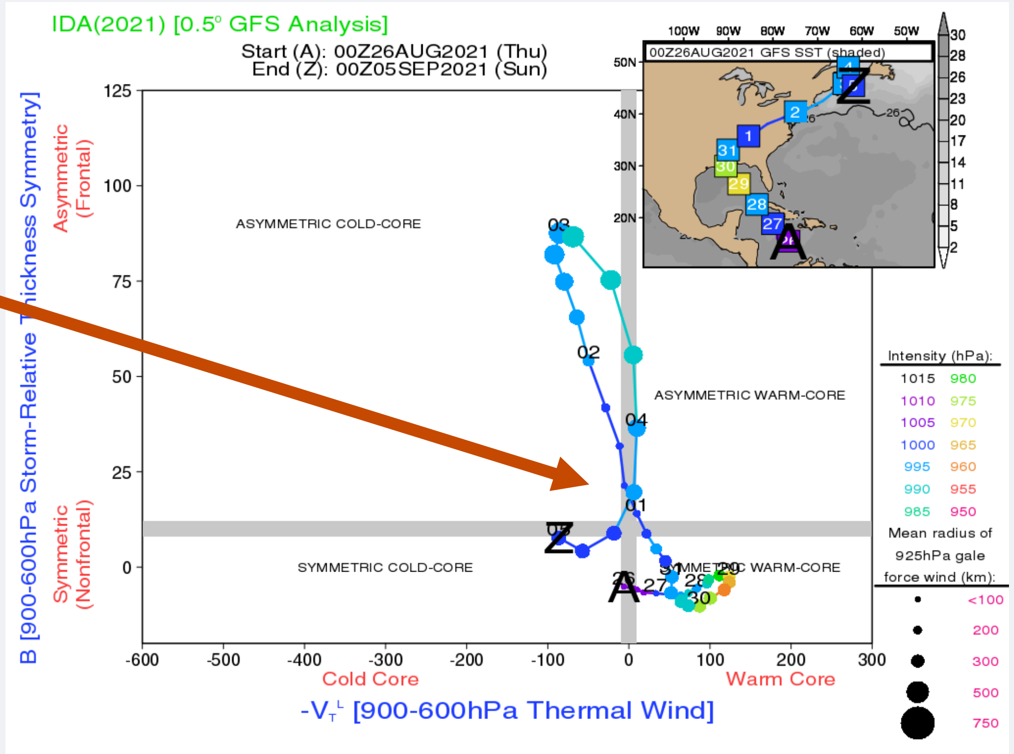
NOAA National Hurricane Center

Formed: Aug 26, 2021

ET Transition: Sep 1, 2021

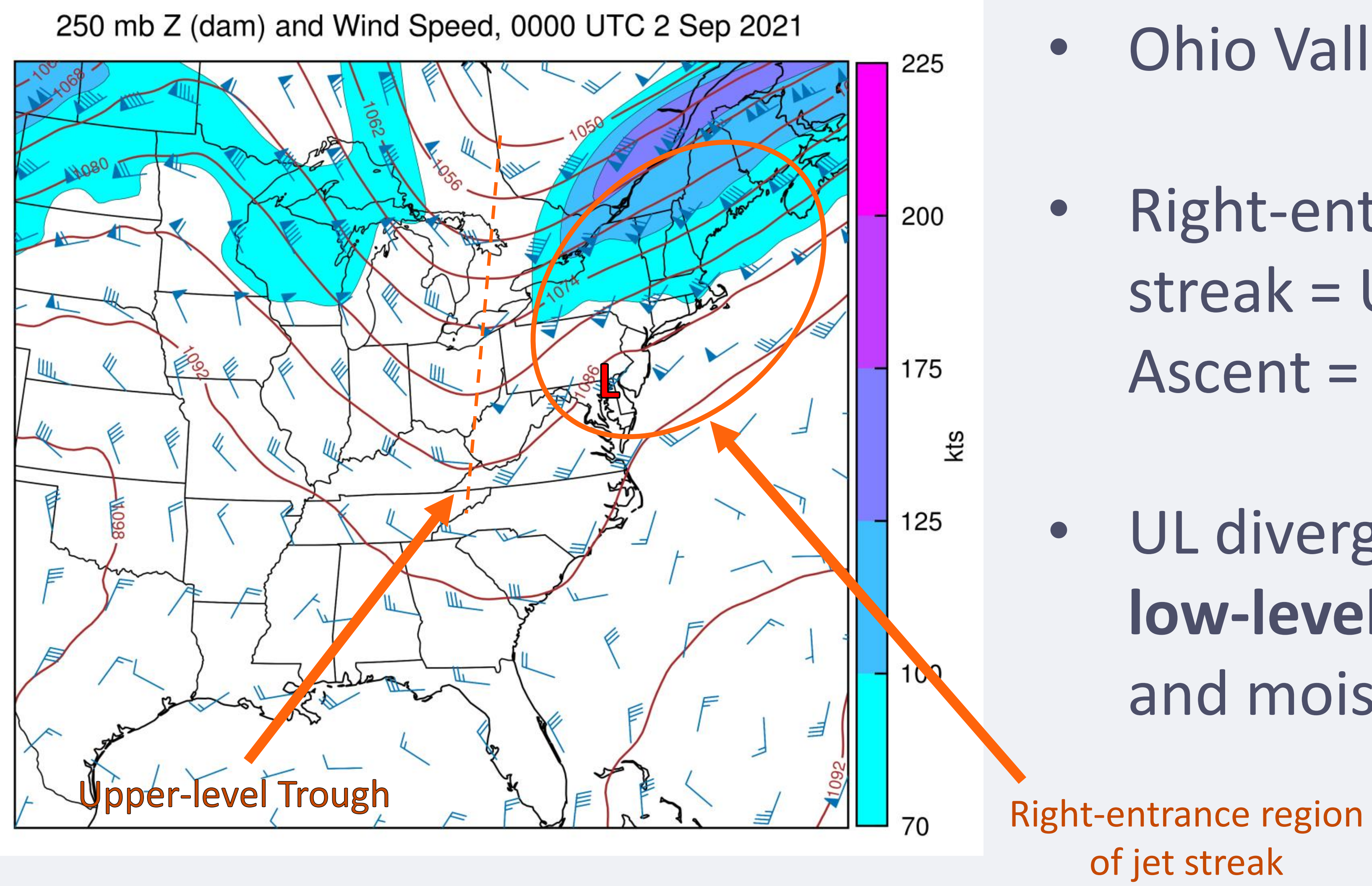
Dissipated: Sep 4, 2021

Hurricane Ida Phase Space Diagram



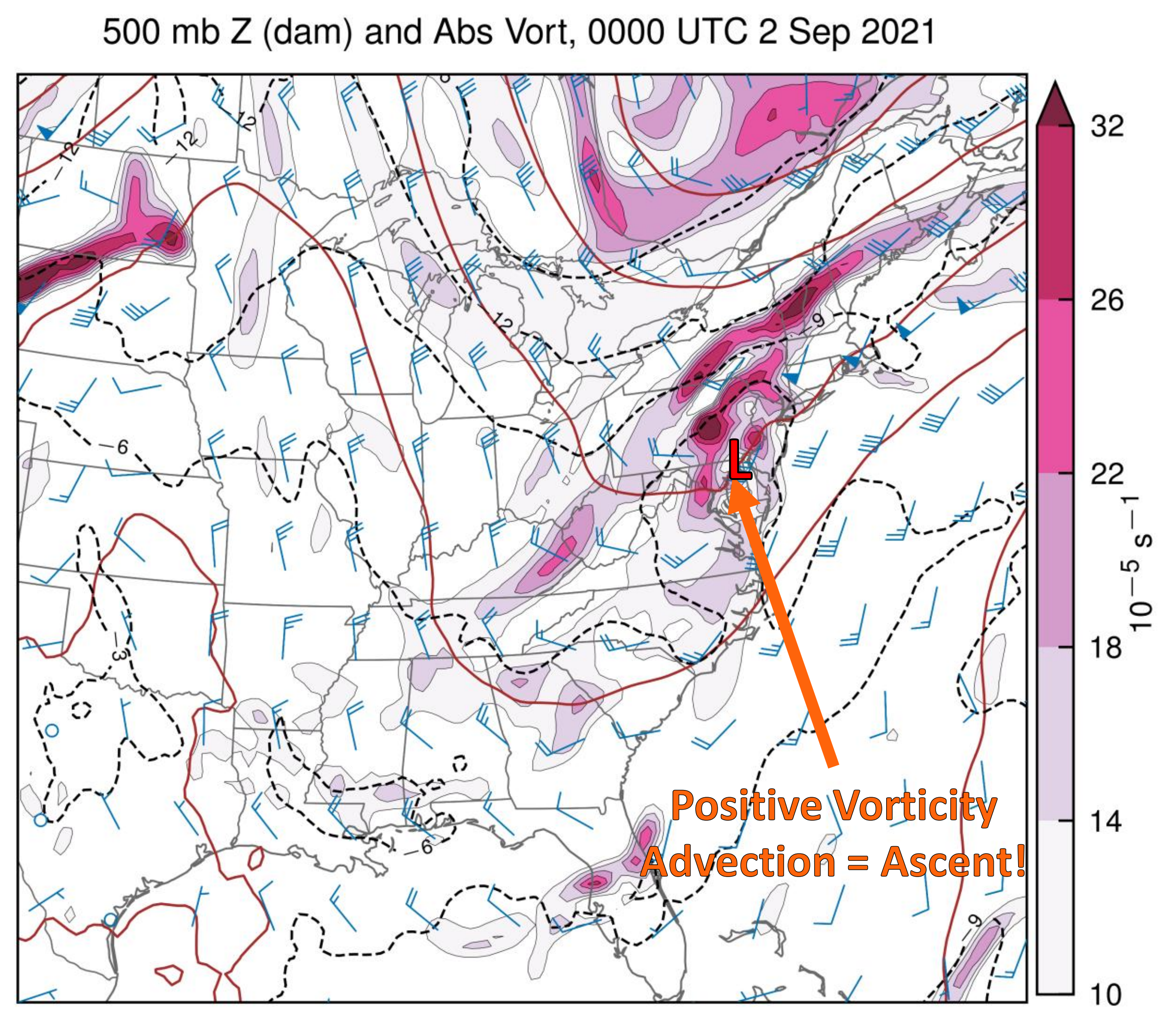
Source: Hart & Evans

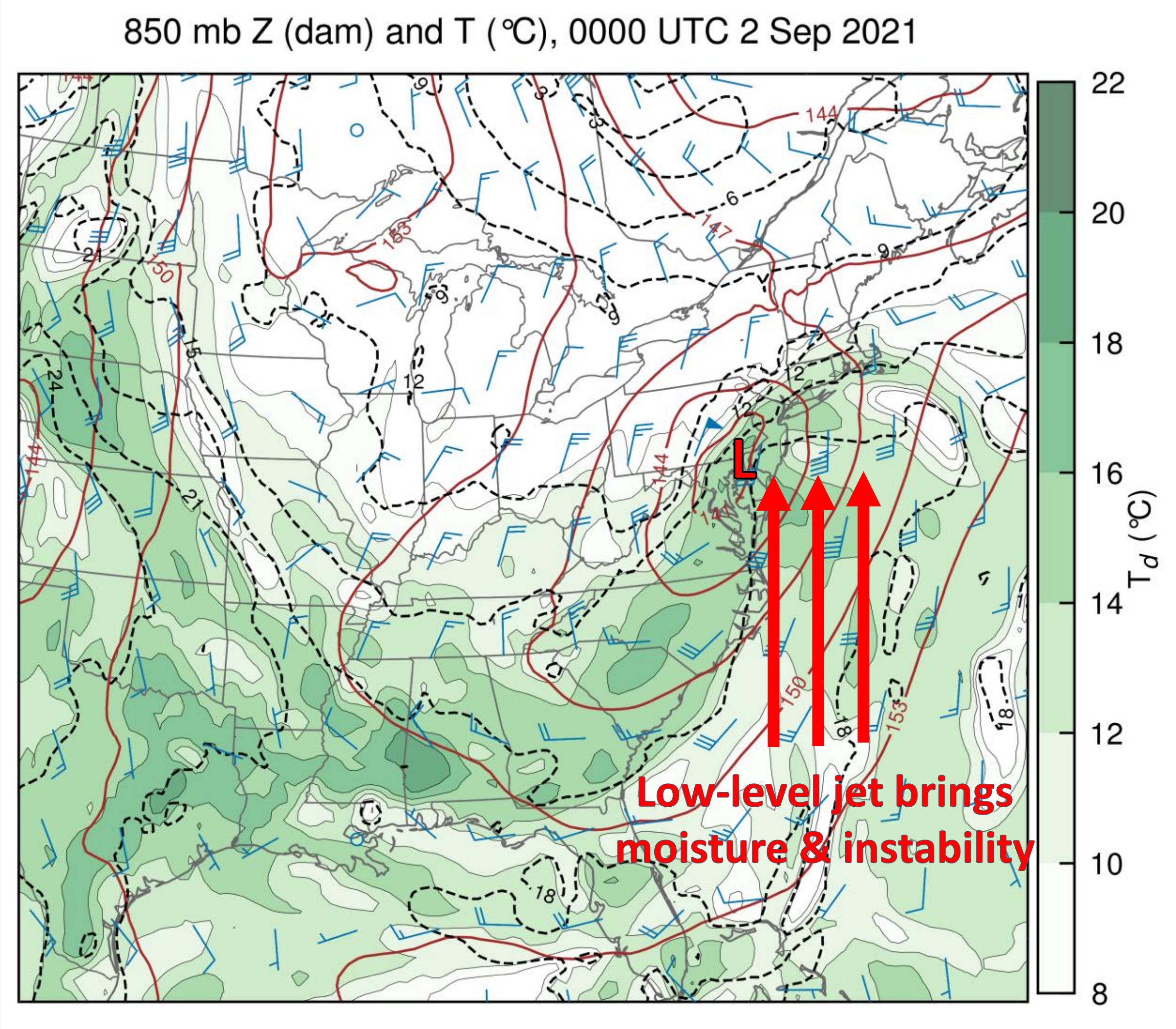
Upper-level support



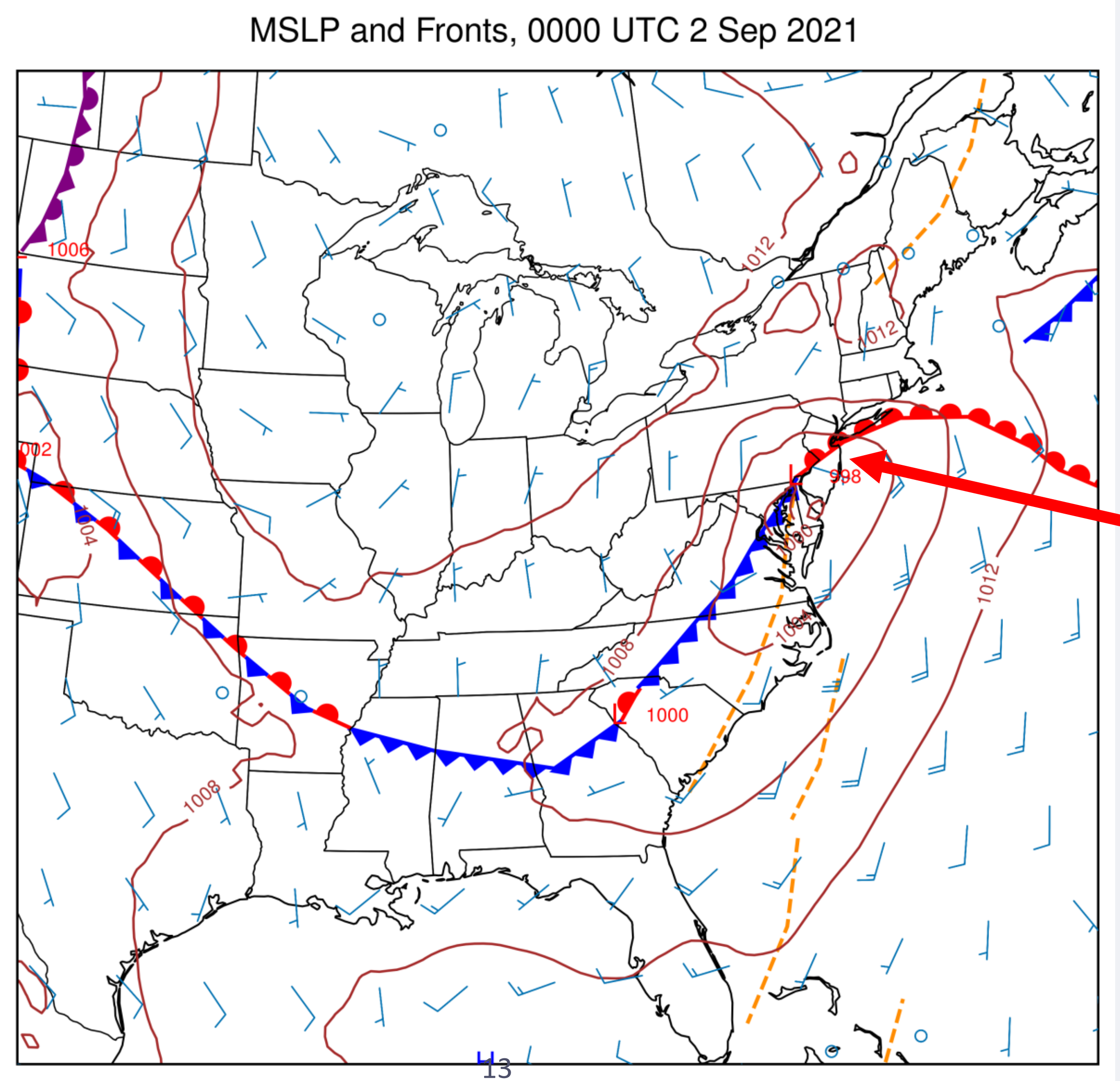
- Ohio Valley trough @ 250 mb
- Right-entrance region of jet streak = UL Divergence = Ascent = **Precipitation!**
- UL divergence also supports a **low-level jet** to bring energy and moisture

Mid-level Support





Surface Analysis

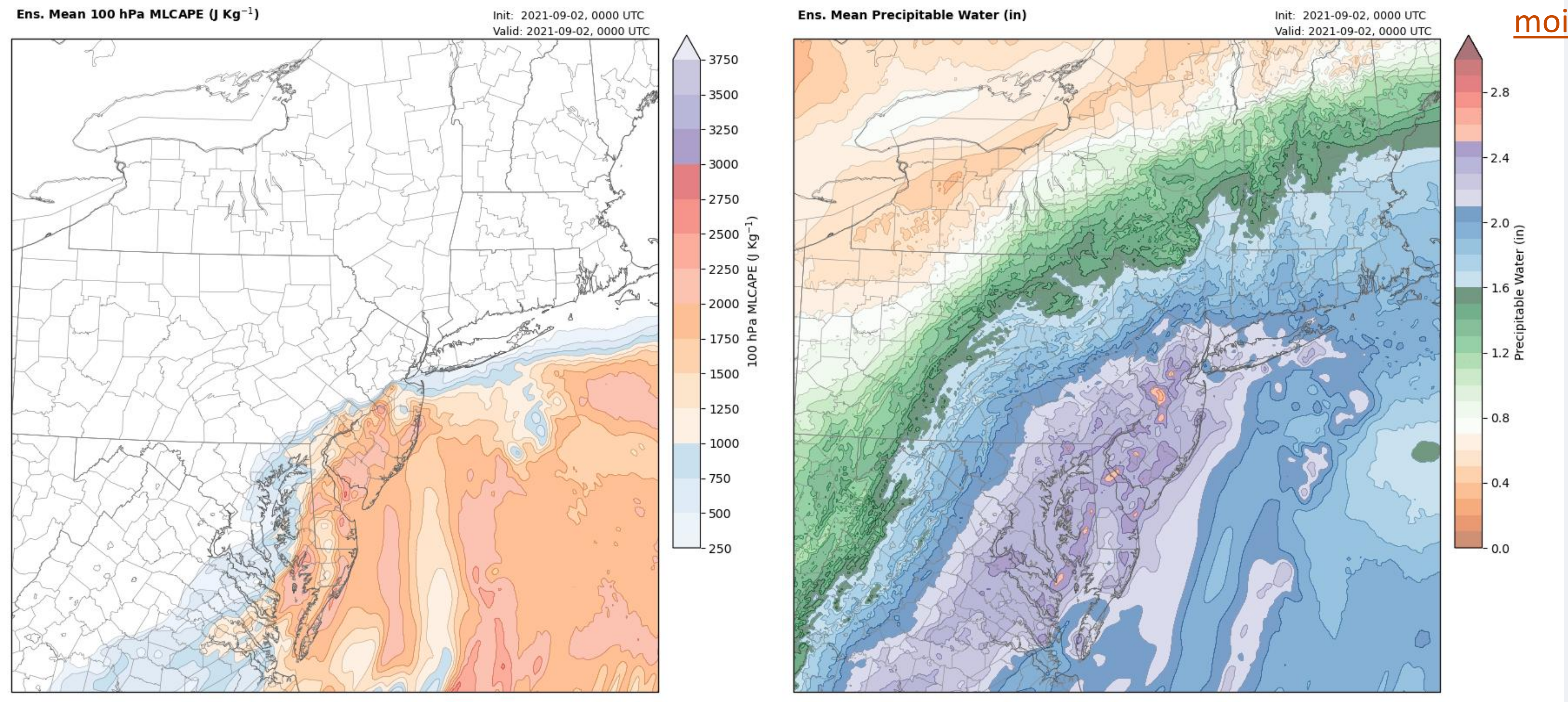


Warm front responsible for heavy NYC rainfall

Mixed-Layer CAPE & Precipitable Water

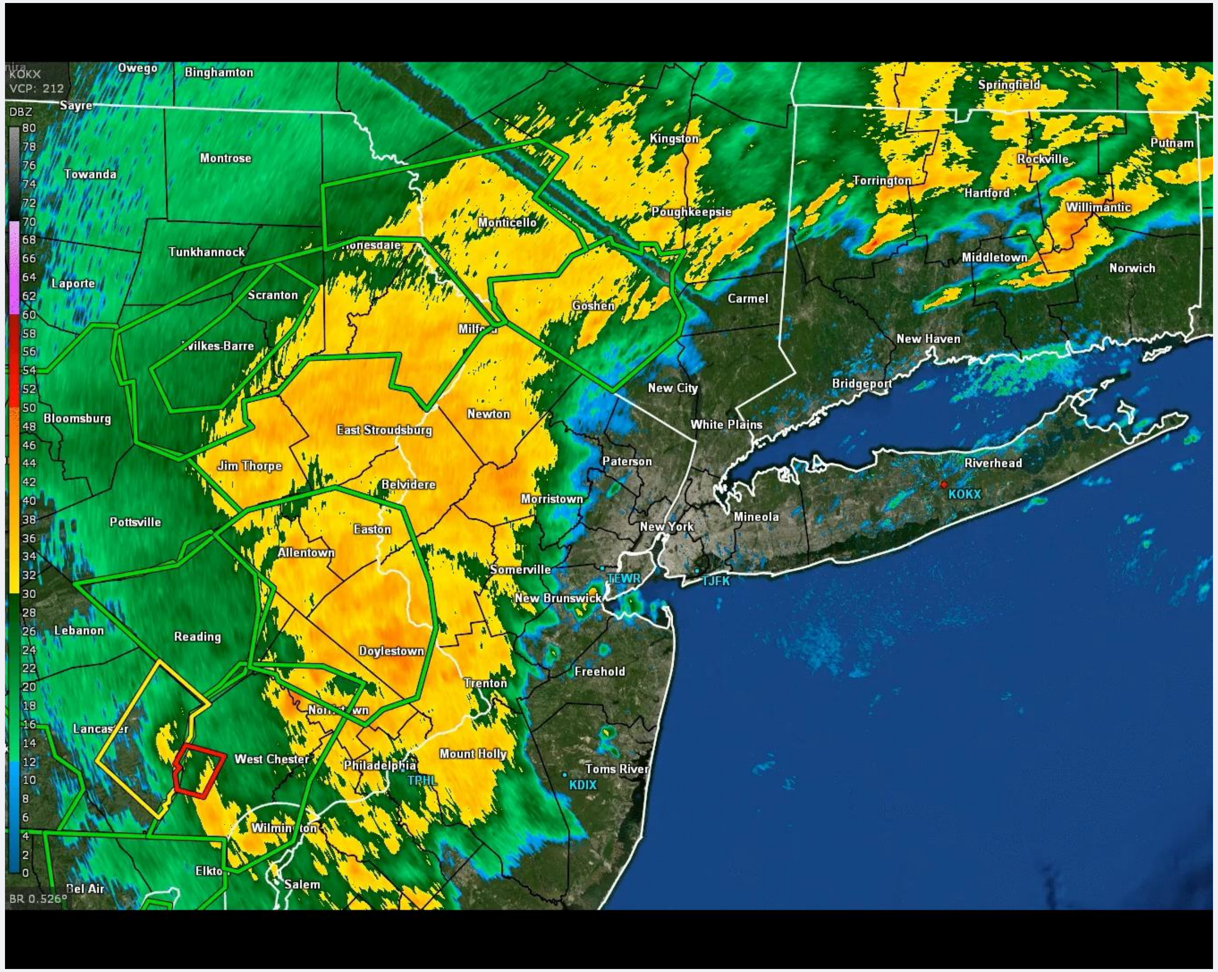
Precipitable water is a measure of <u>moisture</u>

Mixed-Layer CAPE is a measure of <u>instability</u>



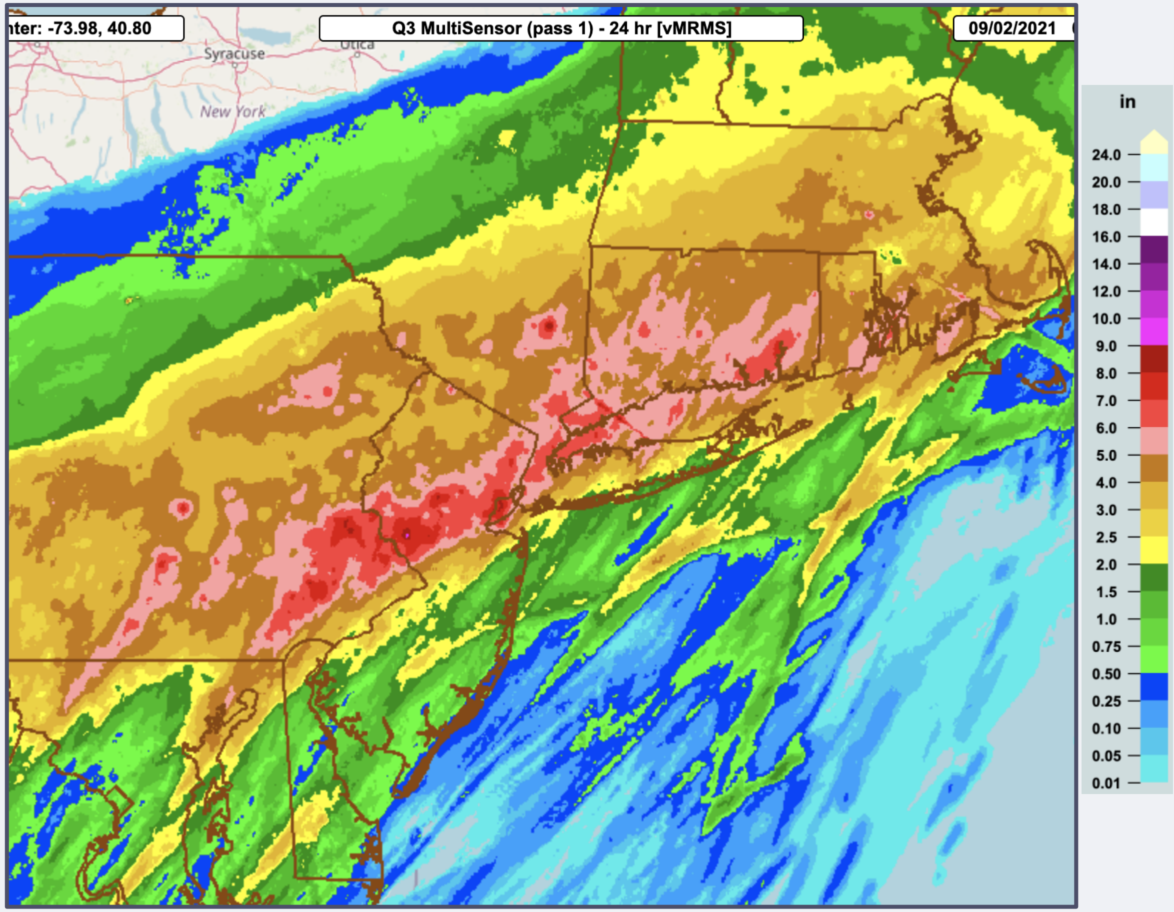
Radar Loop and 24 hr Rainfall

KOKX Radar & NWS Watches/Warnings



Valid 2030 UTC 1 Sep 2021–0310 UTC 2 Sep 2021

MRMS Q3 Multisensor 24-hour Rainfall



Period Ending 0900 UTC 2 Sep 2021

Summary & what's next

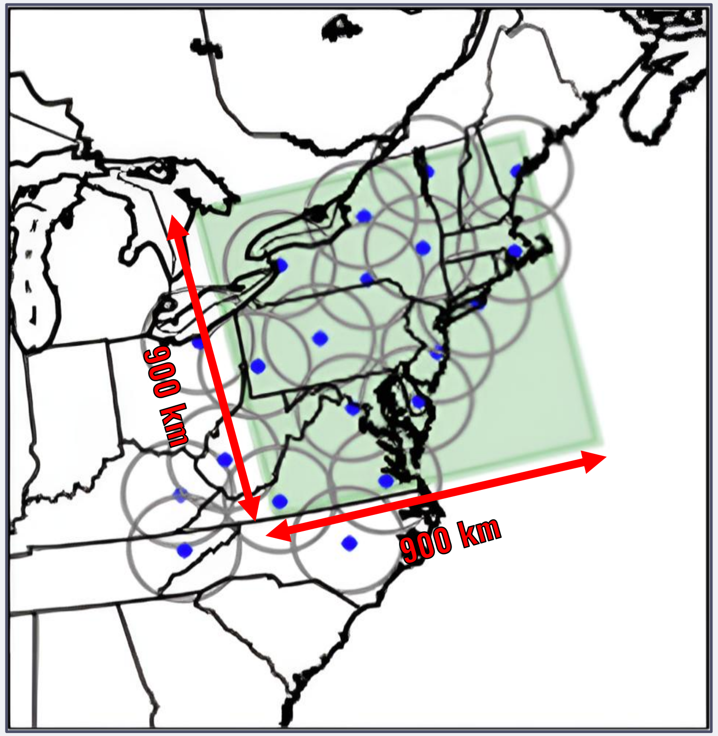
- The confluence of many factors <u>across spatial scales</u> made Ida so destructive
  - Trough and jet streak placement
  - Positive vorticity advection
  - Low-level jet
  - Slow-moving front
  - Ample moisture and instability
  - Training supercells
- **Which of these offers the most predictability for Ida and future extreme rainfall events?**

Results with the Warn-on-Forecast System

Model: Warn-on-Forecast System (WoFS)

- 18-member ensemble analysis and forecast system
  - 3 km horizontal resolution; 51 vertical levels
  - Based on WRF-ARW
- Movable domain!
- Data assimilation every 15 minutes
  - Radar (WSR-88D)
  - Satellite (GOES)
  - Surface observations
- 6-hour-long simulations initialized hourly 1700–0300 UTC
- Physics and initial conditions (EnKF) differ between members

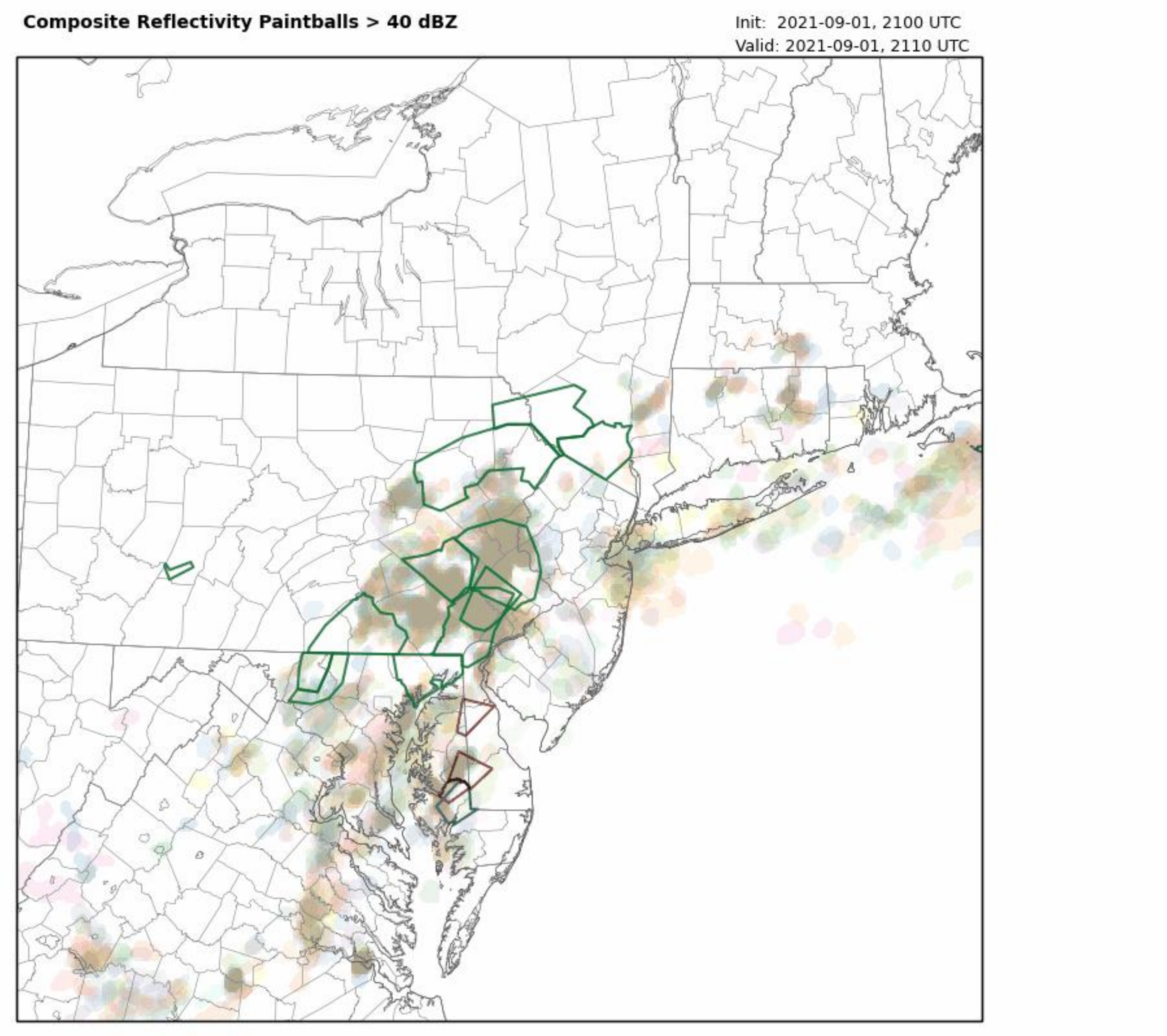
WoFS Grid on 1 Sep 2021



Radar locations (◆) with 150 km range rings

2100 Initialization of WoFS

Paintball plot of reflectivity values > 40 dBZ

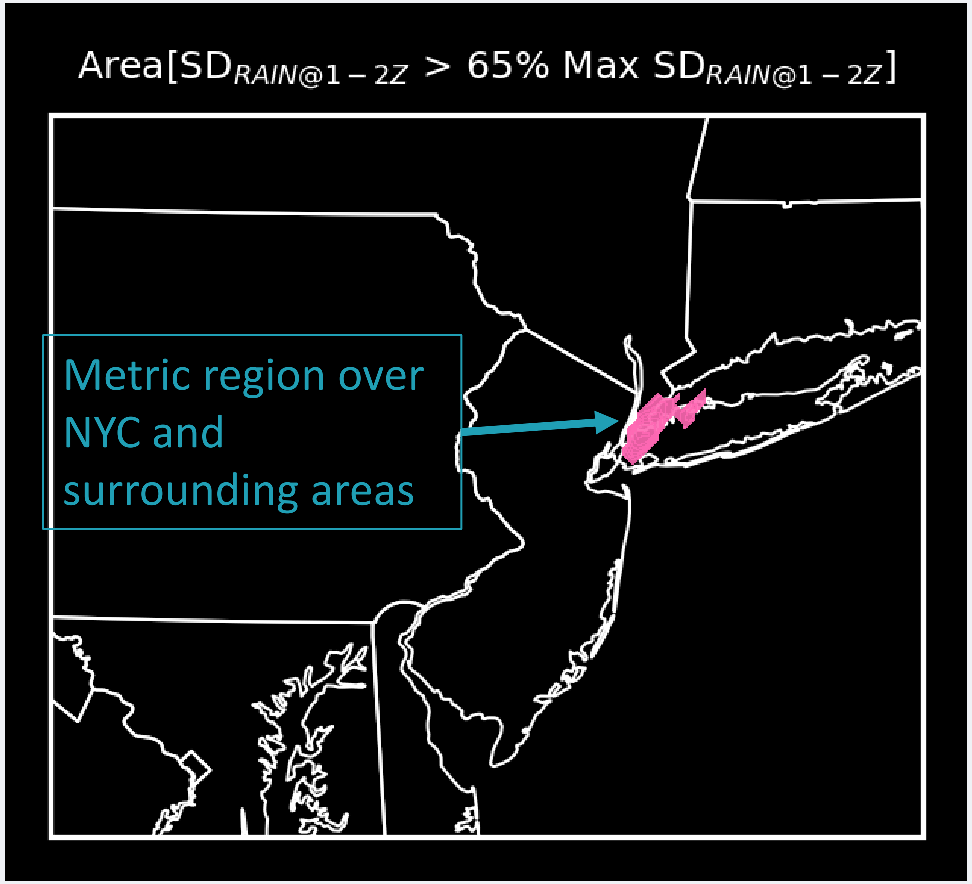


Green = flash flood warning

Red = Tornado warning

Blue = Severe Thunderstorm Warning

Region and rainfall metric



"**NYC**" = region where 72-member ensemble SD of hourly rainfall ≥65% of domain-maximum SD

WoFS Output: Hourly initializations from 2000–2300 UTC 1 Sep 2021

- 4 initializations × 18 members = 72-member ensemble

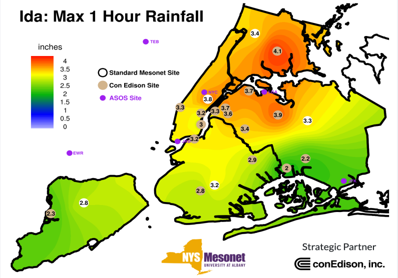
Rainfall metric: 0100–0200* UTC rainfall in NYC = $\mathbf{RAIN_{1\text{-}2,NYC}}$

- Corresponds to observed maximum rainfall rates in Manhattan

*Results are relatively insensitive to hour chosen

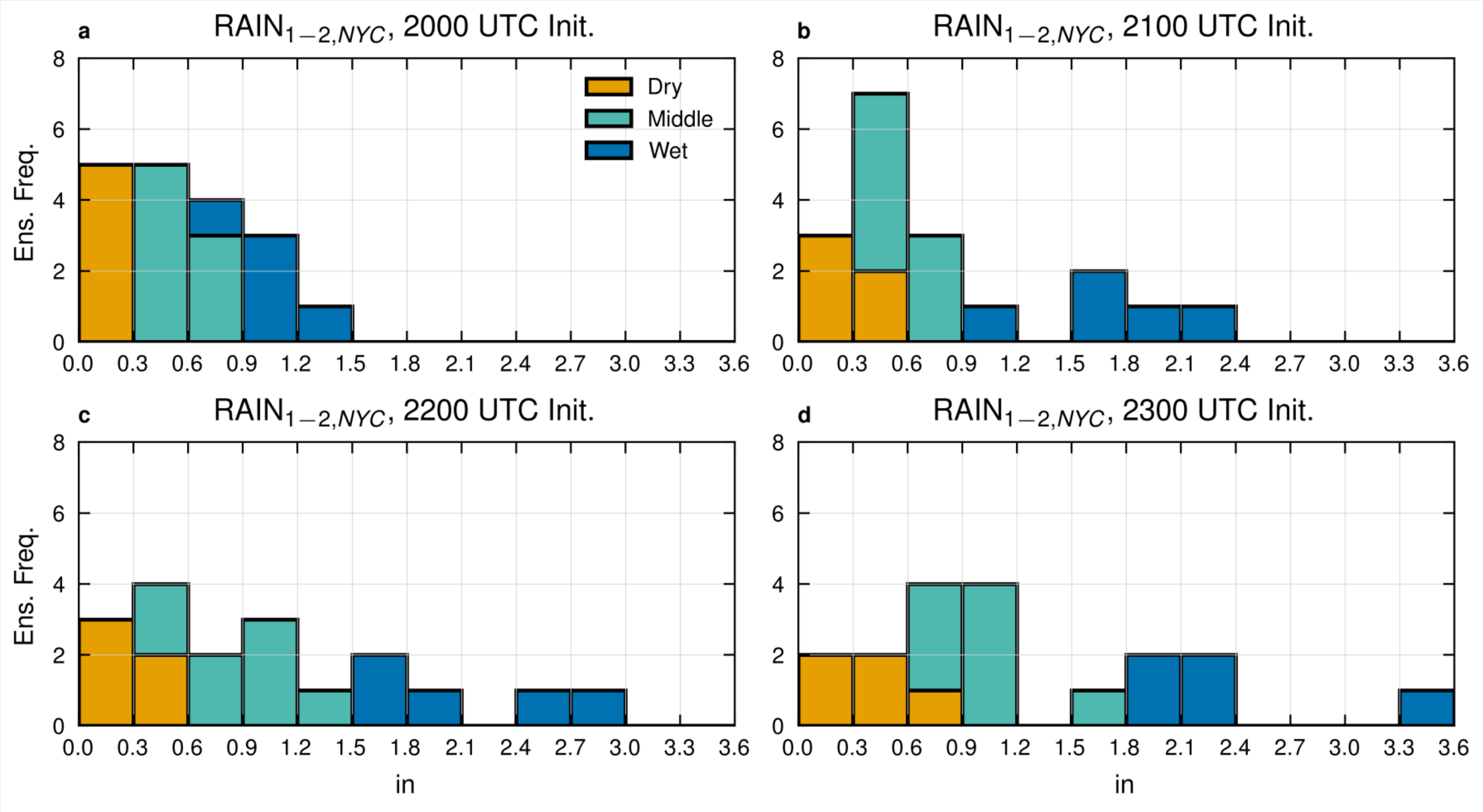
Huge ensemble spread in NYC rainfall!

Few ensemble members come close to matching observations!



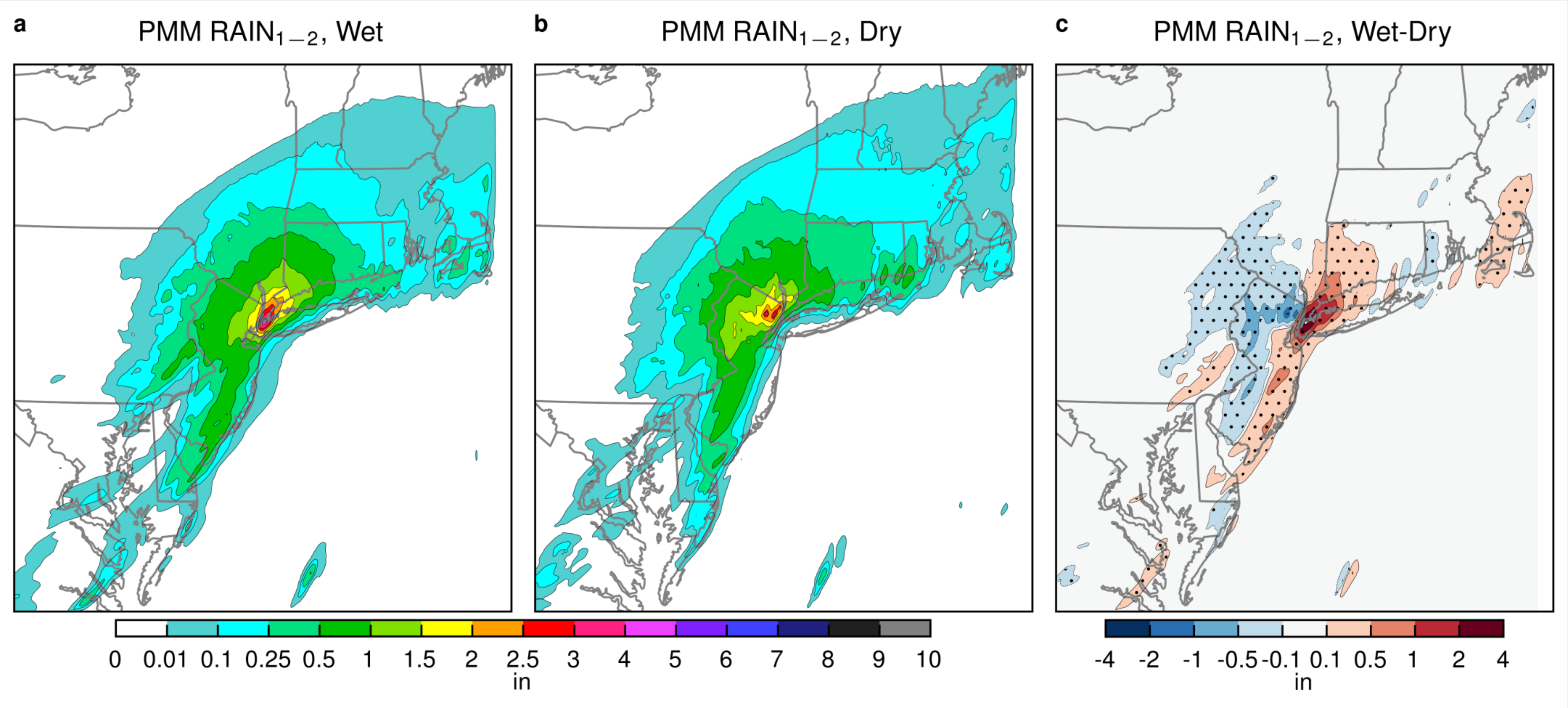
Approach #1: Compare the 5 wettest and 5 driest ensemble members from each initialization → Wet & Dry Subsets (n=20)

Histograms of the 0100-0200 UTC NYC Rainfall in each WoFS initialization



Dry subset has less rain, shifted NW

Probability Matched Mean* of 0100–0200 UTC Rainfall

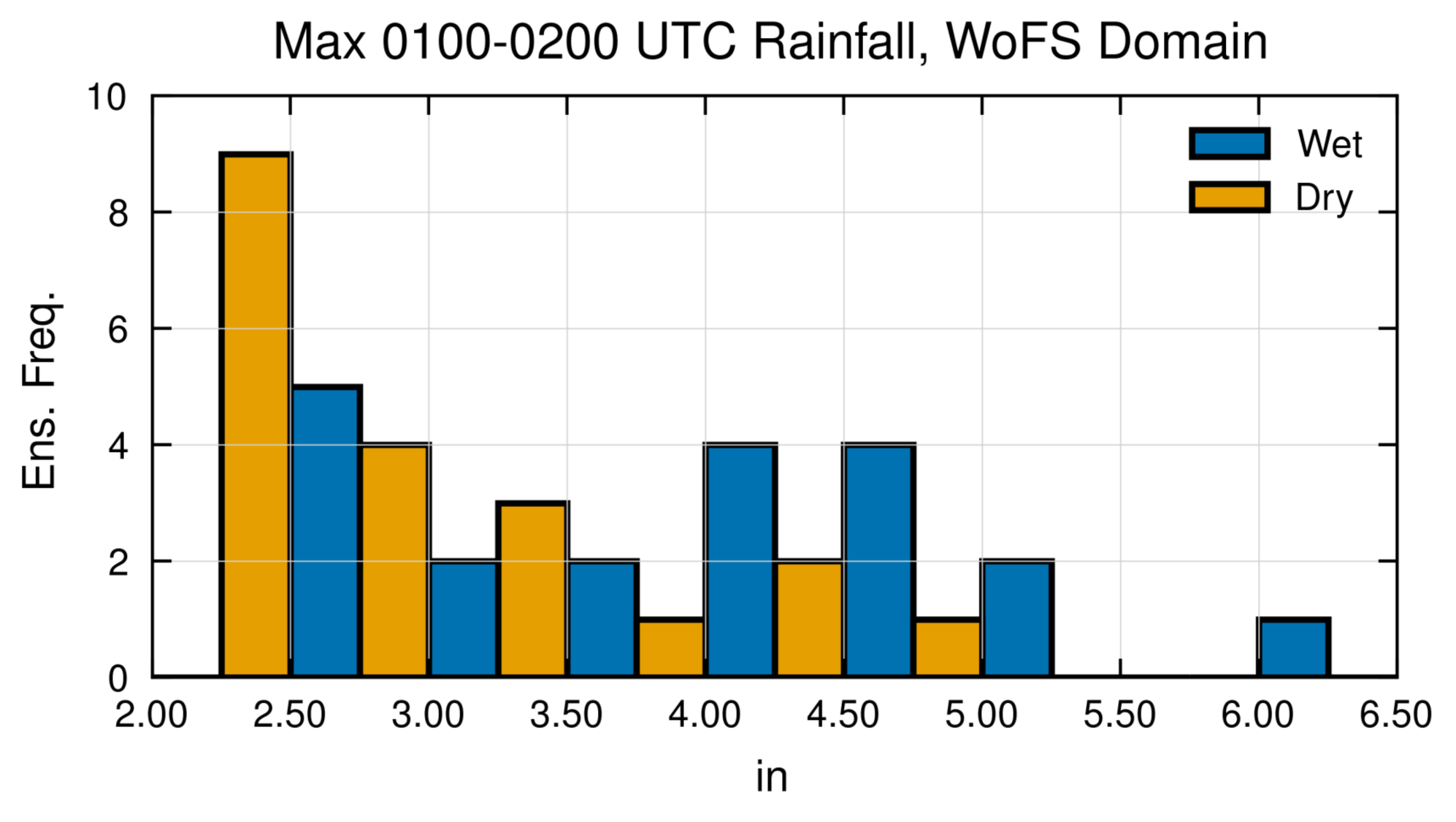


*Probability matched mean → similar to ensemble mean, but retains extreme values

Dotted = statically significant

Wet subset has higher maximum rainfall over entire WoFS domain

Histogram of the Max 0100-0200 UTC Rainfall over all ensemble members and WoFS domain



Ensemble Sensitivity Analysis

Ensemble Sensitivity Analysis = **a linear regression of a forecast metric against the atmosphere at an earlier time**

$$\boxed{\frac{\partial RAIN_{1-2,NYC}}{\partial x}} = \boxed{\frac{cov(\boldsymbol{\partial RAIN_{1-2,NYC}},\boldsymbol{x})}{var(\boldsymbol{x})}} \times \boxed{SD(\boldsymbol{x})}$$

Sensitivity

Slope of linear regression

StDev of predictor

Here, $\boldsymbol{\partial RAIN_{1-2,NYC}}$ (0100-0200 UTC NYC Rainfall) is our **forecast metric**, while $\boldsymbol{x}$ is our **predictor** (geopotential heights, winds, etc.)

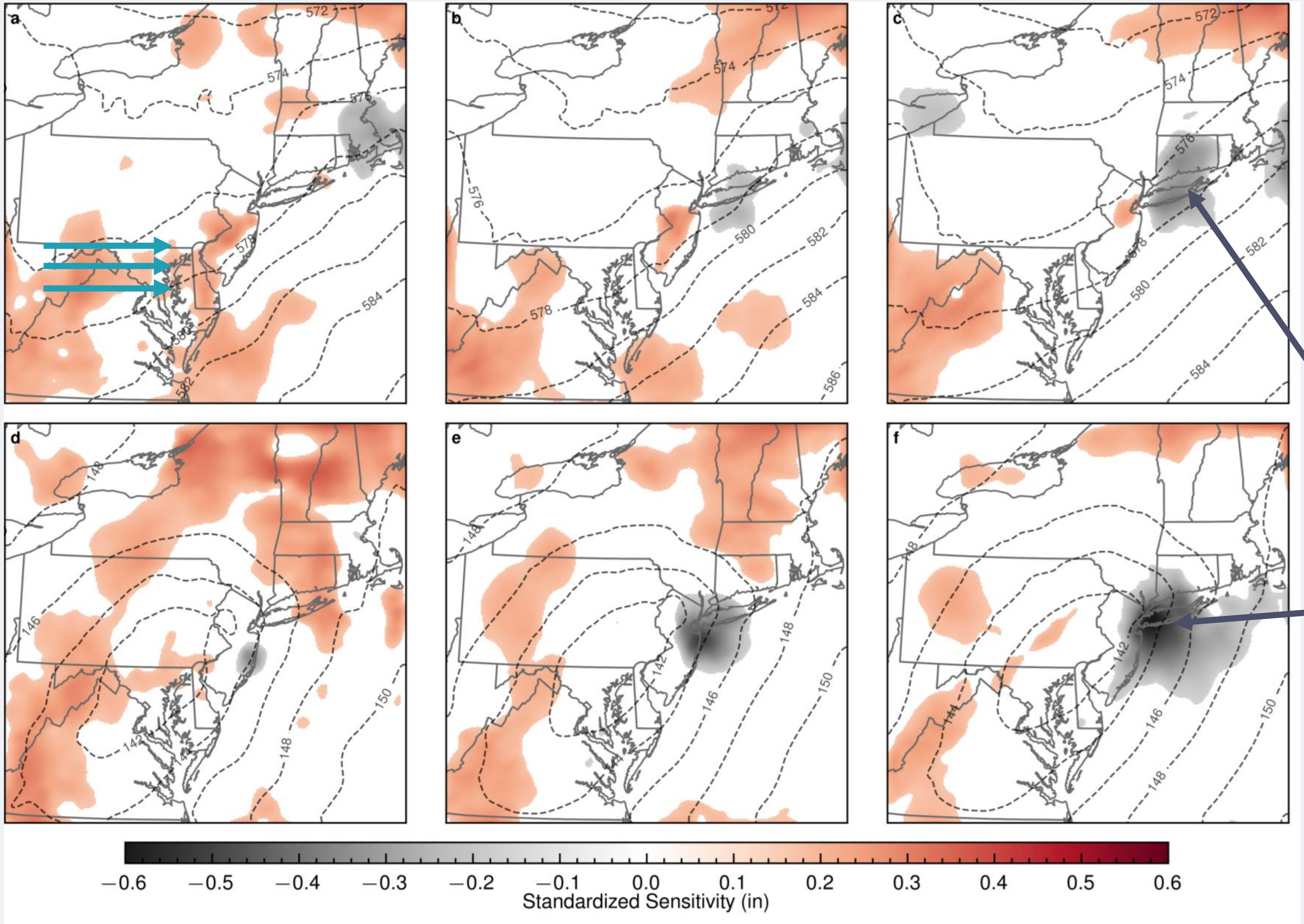
Resulting values = expected change in $\partial RAIN_{1-2,NYC}$ given a one-standard deviation change in x

Sensitivity of RAIN$_{1\text{-}2,NYC}$ to Geopotential Heights

2300 UTC | 0000 UTC | 0100 UTC

500 mb Heights

850 mb Heights



Higher heights to N and SW impact **steering flow direction and speed** of supercells!

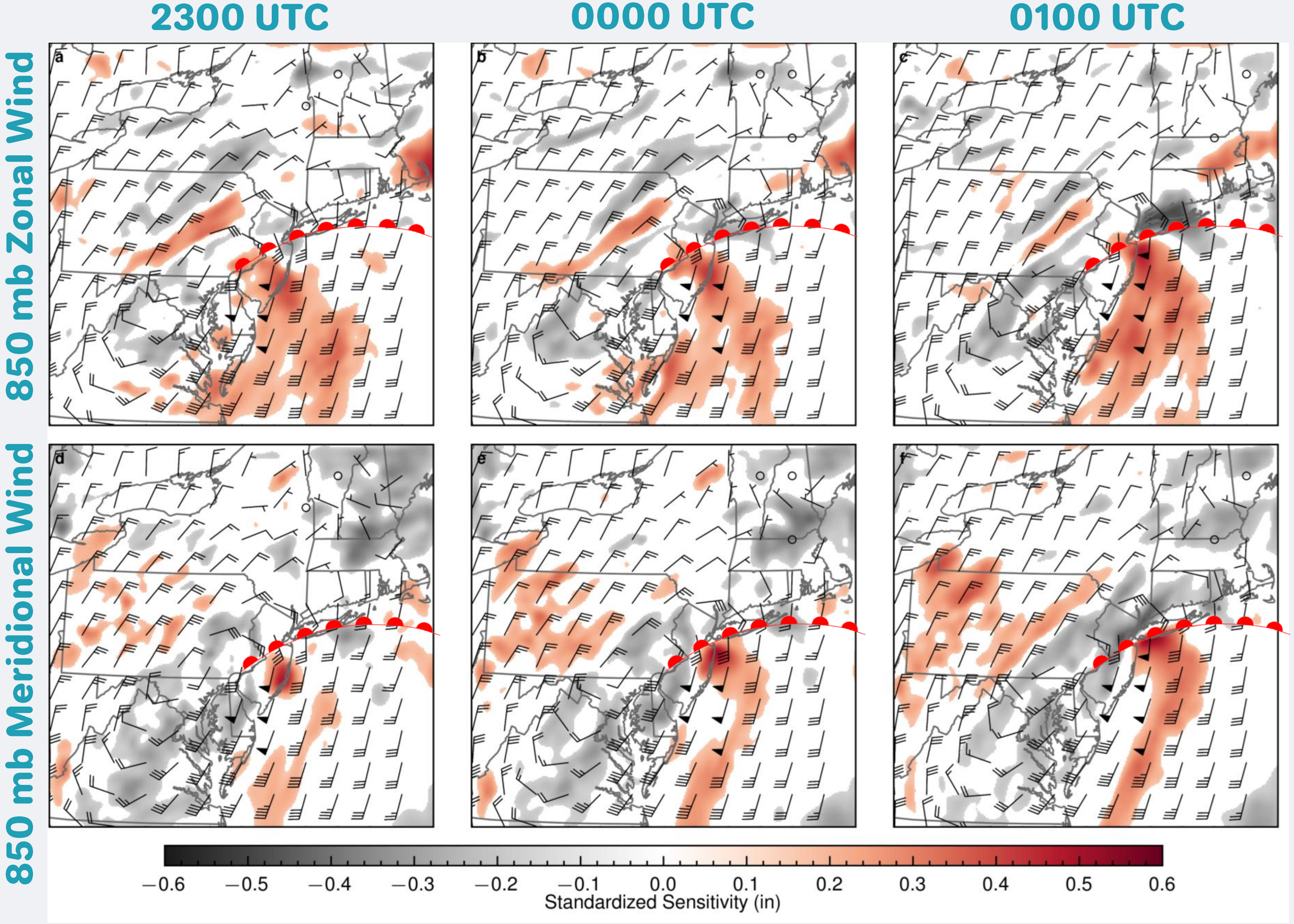
Likely a sign of **existing convection,** not synoptic scale circulation differences!

I only show values that are statistically significantly different from 0!

Sensitivity of $RAIN_{1\text{-}2,NYC}$ to 850 mb Winds

Cyclonic shear↑ = frontogenesis↑ = Ascent↑ = Rain↑

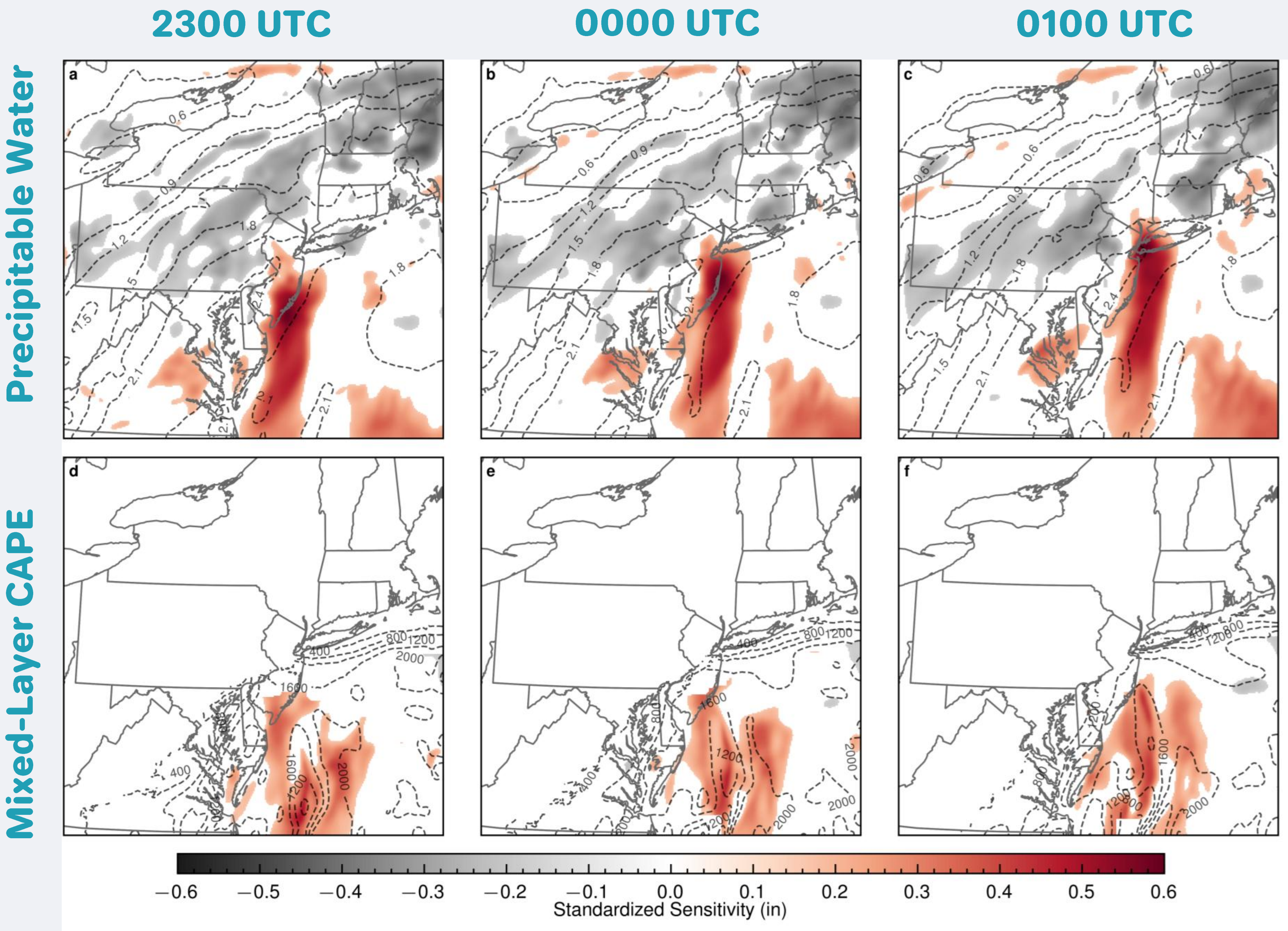
Stronger low-level jet = more moisture and instability



Sensitivity of $RAIN_{1-2,NYC}$ to PW and CAPE

Precipitable water to the south↑ = $RAIN_{1-2,NYC}$↑

Mixed-Layer CAPE↑ = More fuel for convection



CAPE: Convective Available Potential Energy (Instability)

Let’s look at smaller (meso, frontal) scale features

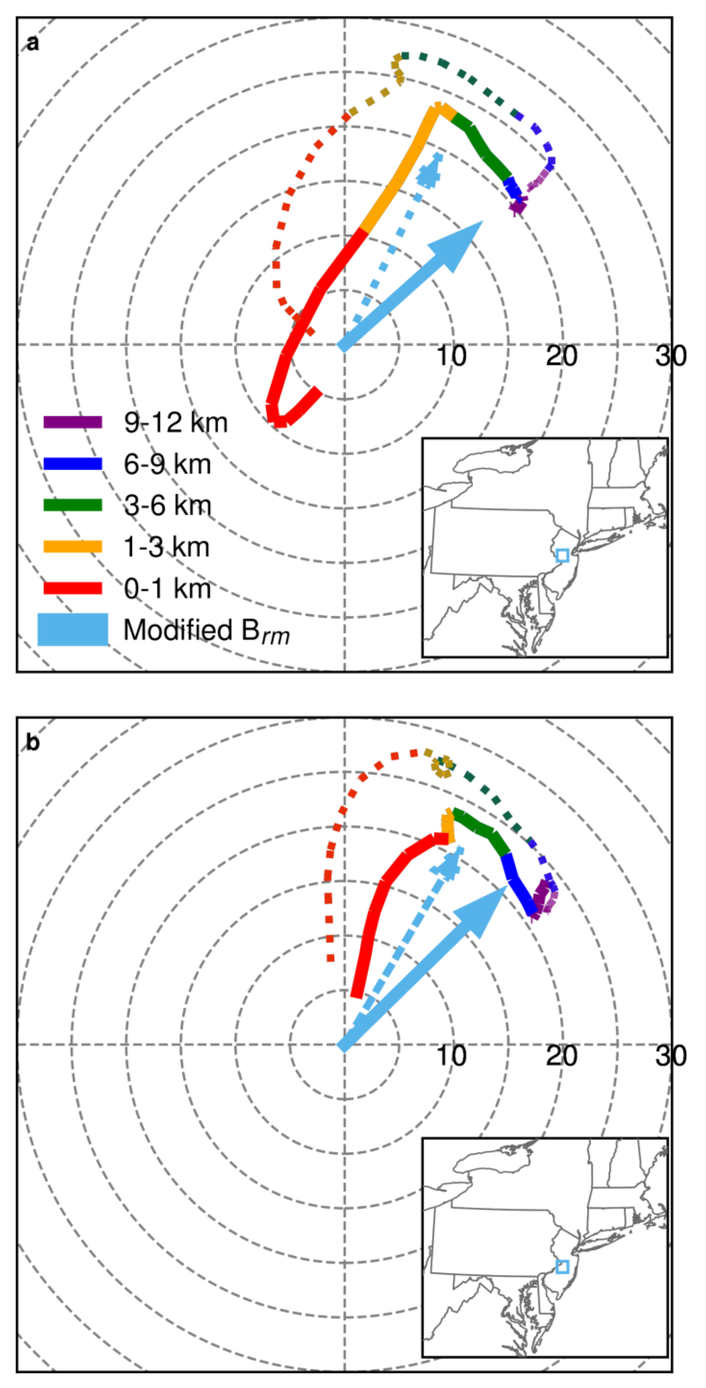
Back to wet vs. dry!

Hodographs

- Hodographs show how **wind** changes with **height**
- Wet subset has **slower, more eastward moving supercells**
- Our first clue that the **front location** is different in wet vs. dry!

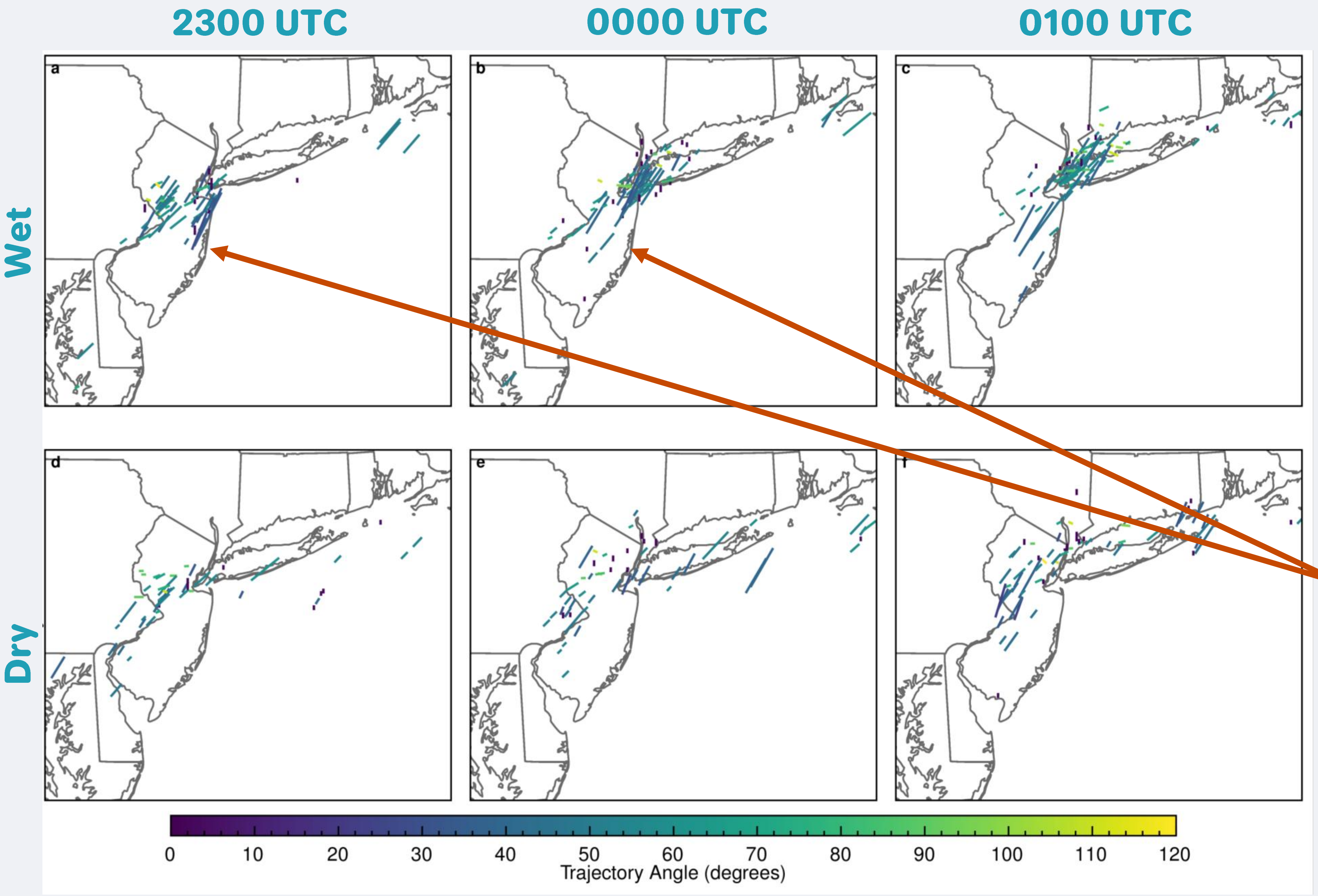
Polar coordinates:
θ = Wind direction
r = Wind Speed

Blue arrows are an estimate of storm motion



Dashed = Dry Subset Mean
Solid = Wet Subset Mean

Wet & Dry UH > $20 m^2 s^{-2}$ with Trajectory Angles



- Wet subset has greater number and trajectory angle of supercells
- Dry subset missing Jersey Shore storms

UH = Updraft helicity, a measure of “spininess” to track supercells!

Front Finding Algorithm

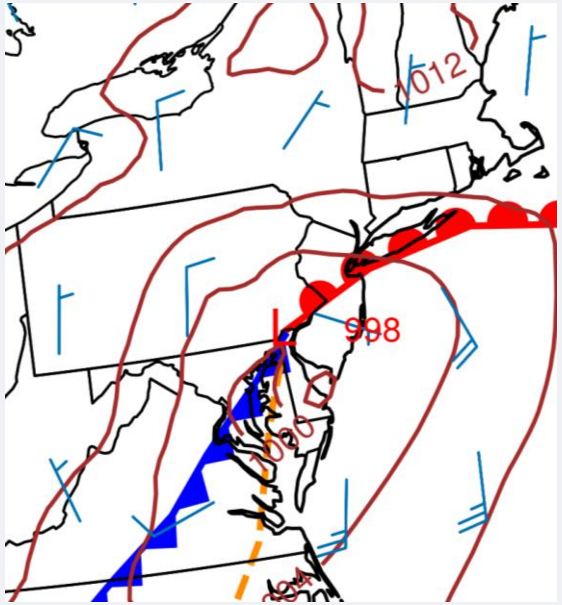
- Created a new front-finding algorithm for WoFS using the **thermal front parameter (TFP)** (Schemm et al. 2015)

$$TFP = -\nabla|\nabla\theta_{e,850}| \cdot \frac{\nabla\theta_{e,850}}{|\nabla\theta_{e,850}|}$$

where $\theta_{e,850}$ is the equivalent potential temperature at 850 hPa

- Fronts occur where TFP = 0 and $|\nabla\theta_{e,850}|$ is above a certain threshold
- Use **connected component labeling** to find the largest feature, which is the front!

Warm front in wet subset located **farther south** than in dry subset!

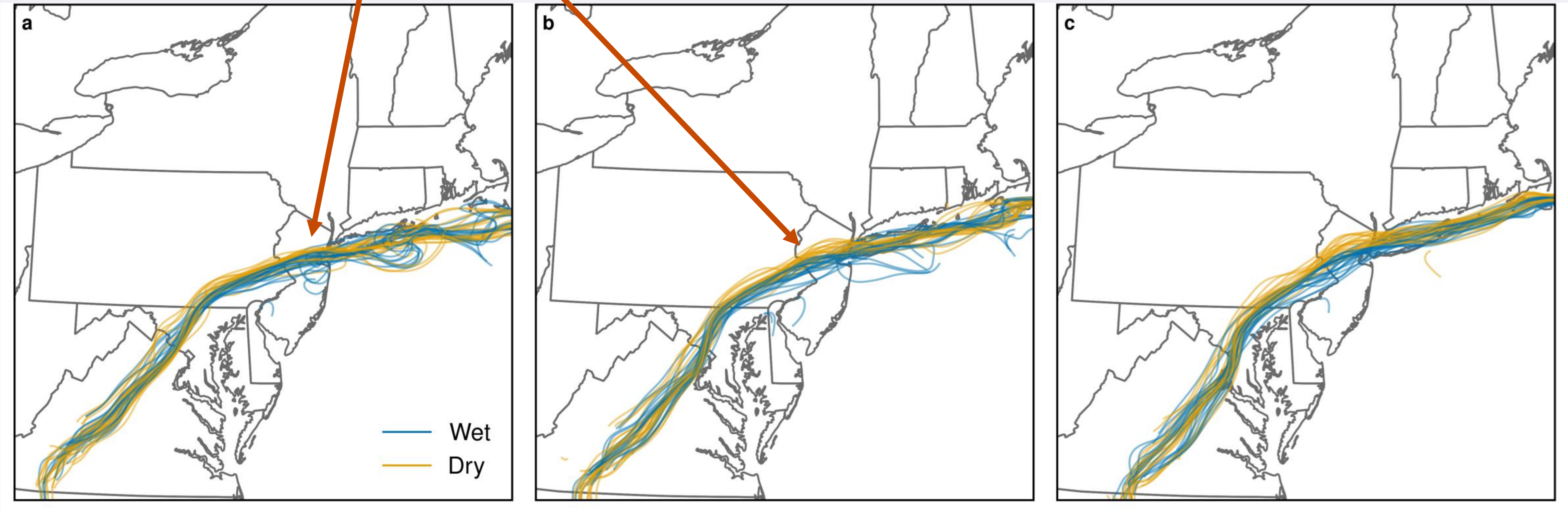


WoFS Front Locations

2300 UTC

0000 UTC

0100 UTC



Take-home Messages

- Hurricane Ida flooding in NYC resulted from a confluence of factors to produce record-breaking hourly rainfall
- It was a **tough forecast**, with huge spread among WoFS members
- The WoFS members that produced the most rain in NYC have:
  - A synoptic setup that favors **slower, more eastward moving supercells**
  - A **stronger low-level jet** to bring moisture and instability
  - A **stronger warm front located farther south** in NJ
- These factors should be considered

References

Mossel, C., Hill, S. A., Samal, N. R., Booth, J. F., & Devineni, N. (2024). Increasing extreme hourly precipitation risk for New York City after Hurricane Ida. *Scientific Reports*, *14*(1), 27947. https://doi.org/10.1038/s41598-024-78704-9

Schemm, S., Rudeva, I., & Simmonds, I. (2015). Extratropical fronts in the lower troposphere–global perspectives obtained from two automated methods. *Quarterly Journal of the Royal Meteorological Society*, *141*(690), 1686–1698. https://doi.org/10.1002/qj.2471