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



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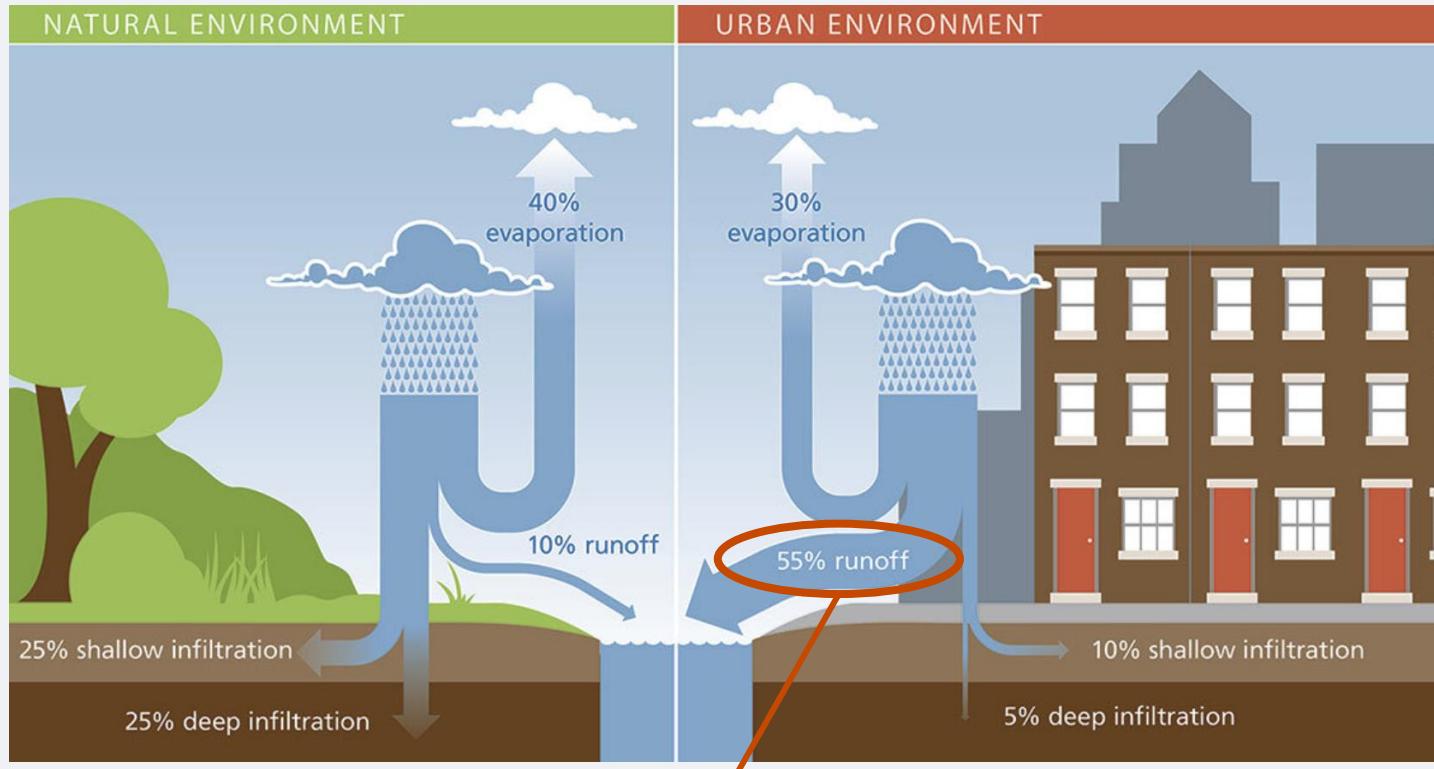
The City College
of New York



Background & Motivation

Urban Areas are Susceptible to Flash Flooding

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

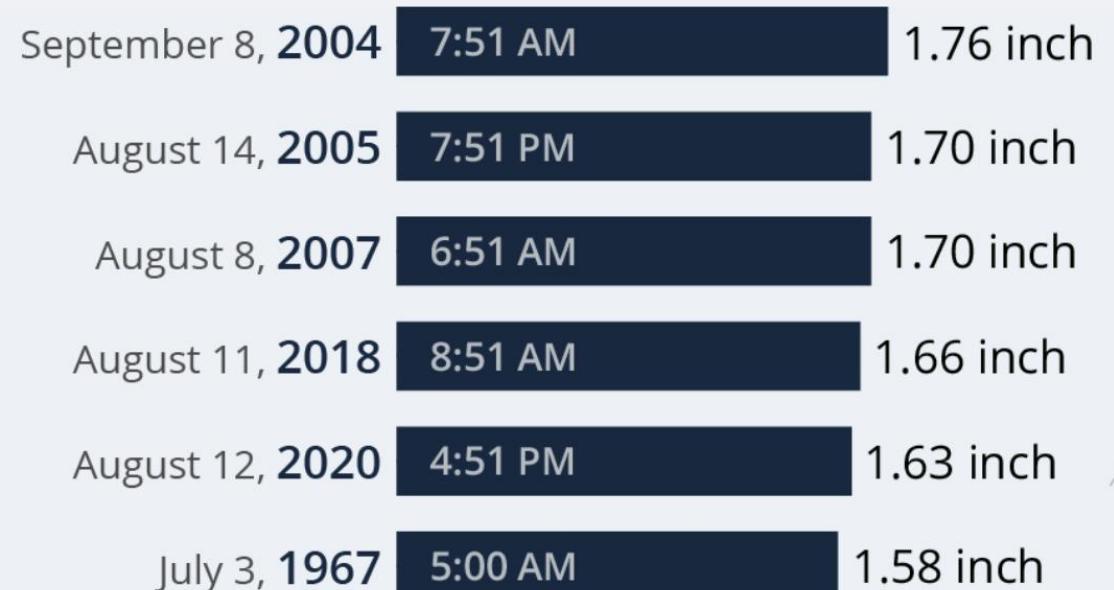


- Impervious concrete & asphalt
- Little vegetation
- **55% runoff on average**

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



Source: Iowa Environmental Mesonet

Statistica

Note: These values are from only one weather station and regular hourly METARs

2021 was already anomalously wet

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



Central Park ASOS Hourly Rainfall Amounts



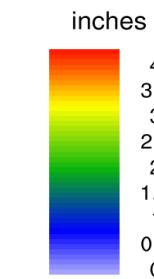
Source: Iowa Environmental Mesonet

Statistica

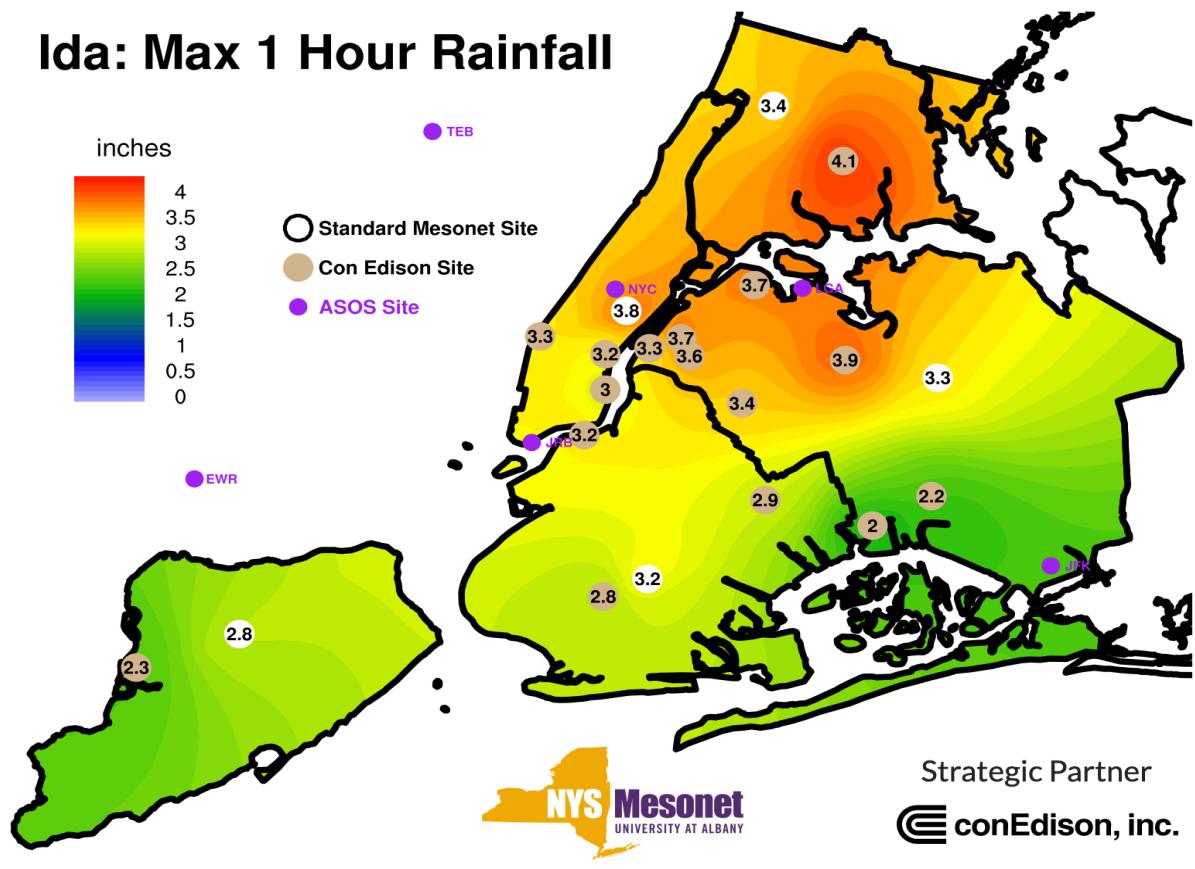
Ida shatters previous records

NYC Micronet Rainfall Measurements

Ida: Max 1 Hour Rainfall



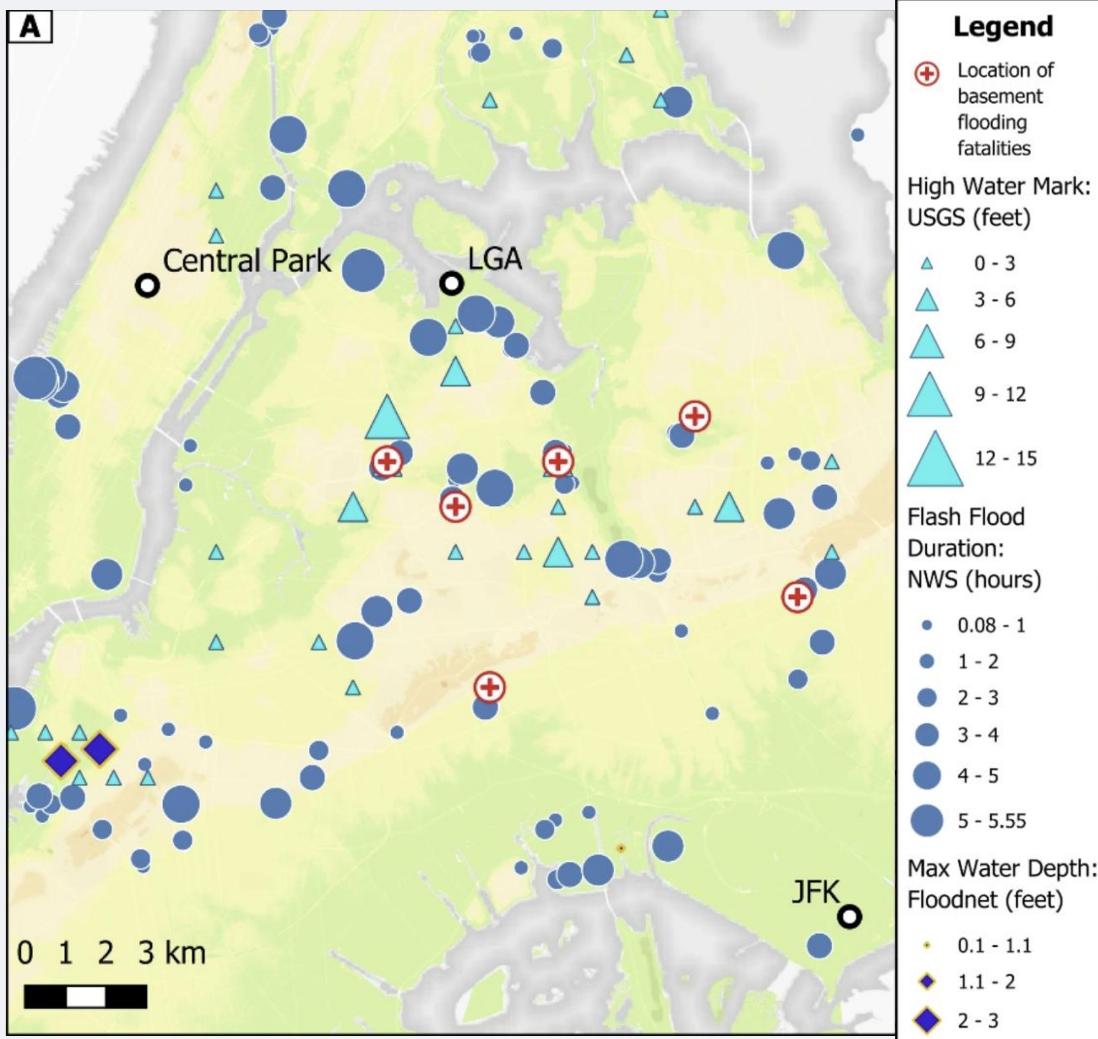
- Standard Mesonet Site
- Con Edison Site
- ASOS Site



Central Park ASOS Hourly Rainfall Amounts



Impact: Flash Flooding

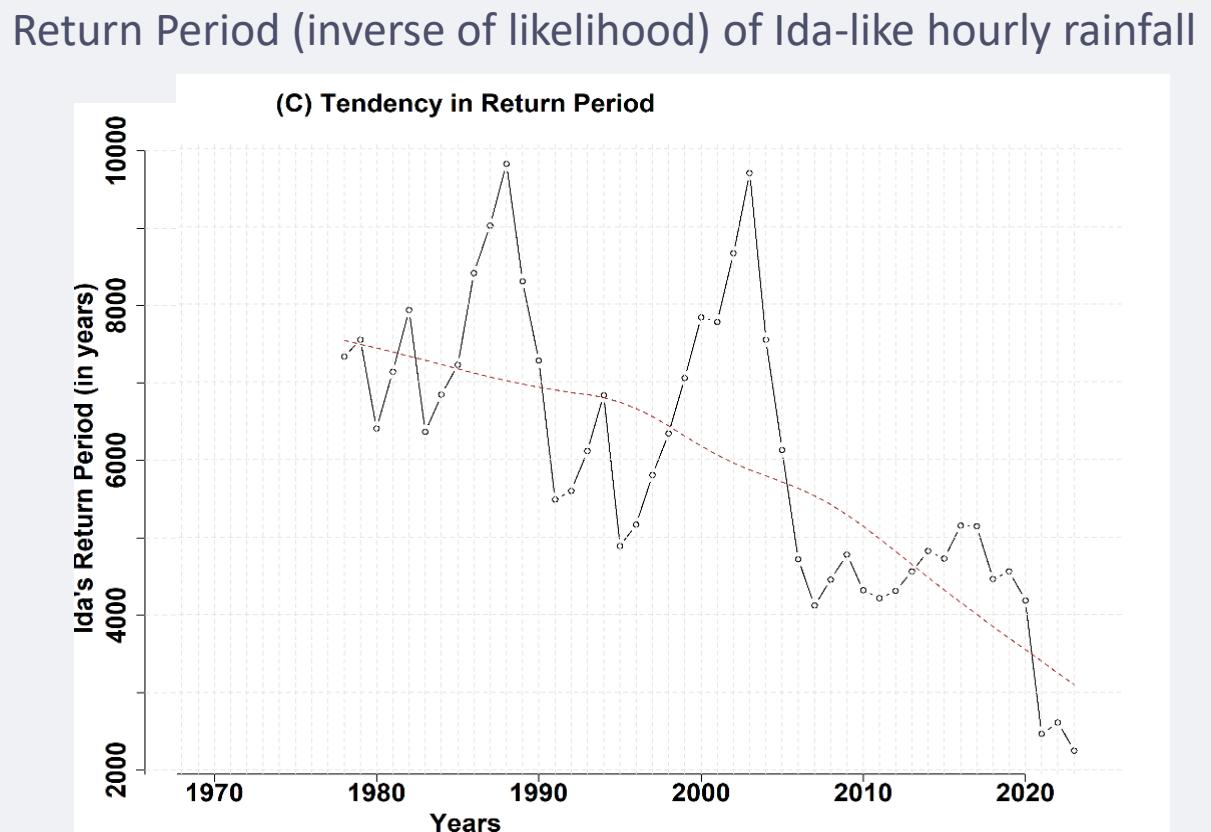


Adapted from Fig. 1 of Mossel et al. (2024)

- 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**



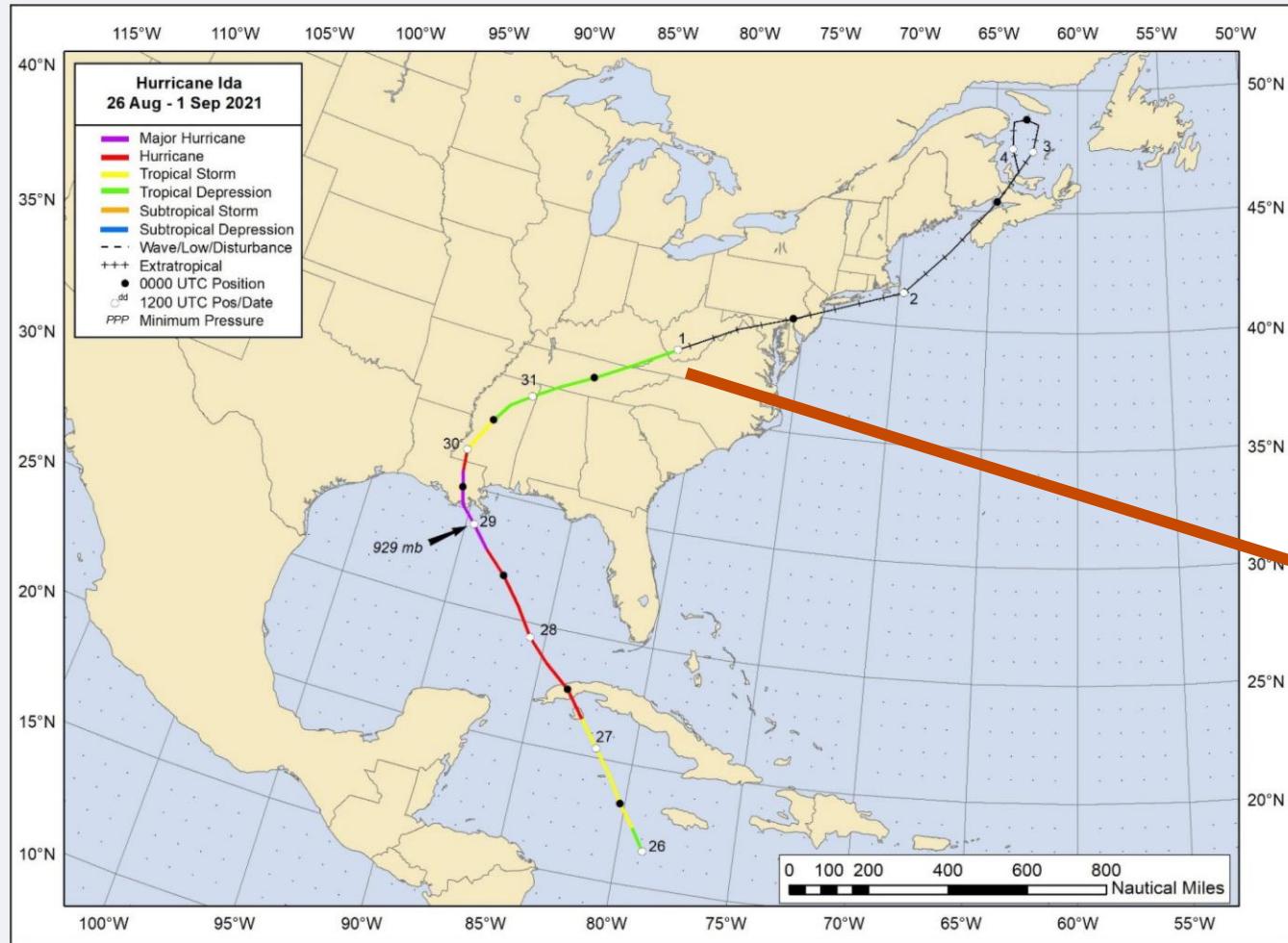
Adapted from Fig. 2 of Mossel et al. (2024)

Meteorological History

What exactly happened?

Hurricane Ida Track & Transition

Hurricane Ida Dated Track & Classifications

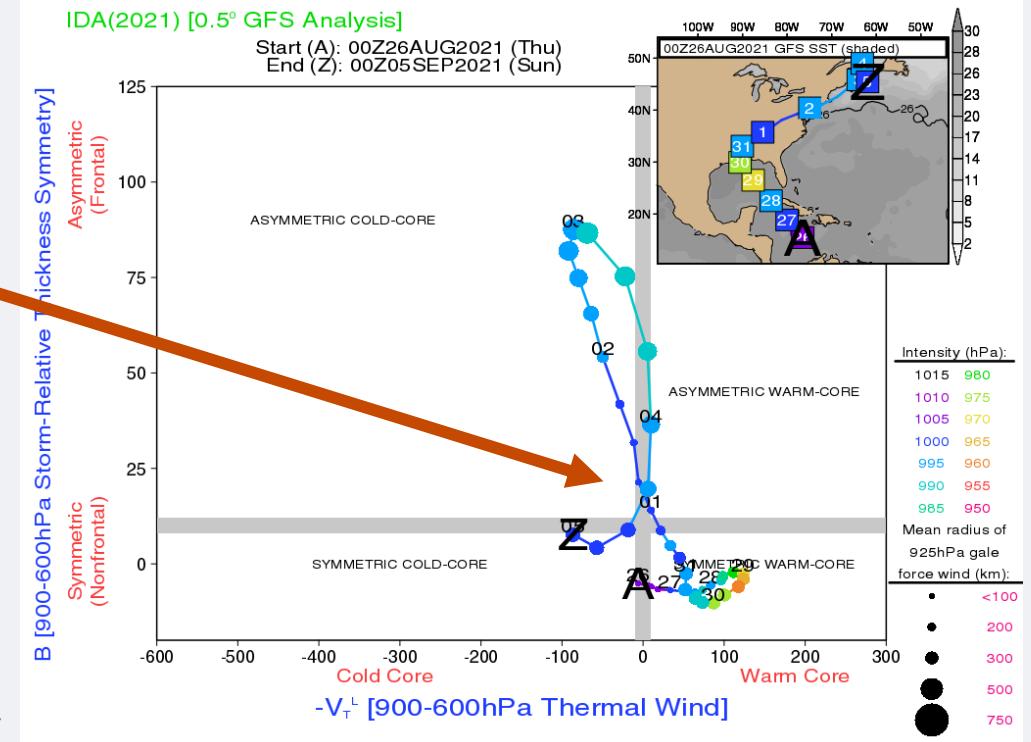


Formed: Aug 26, 2021

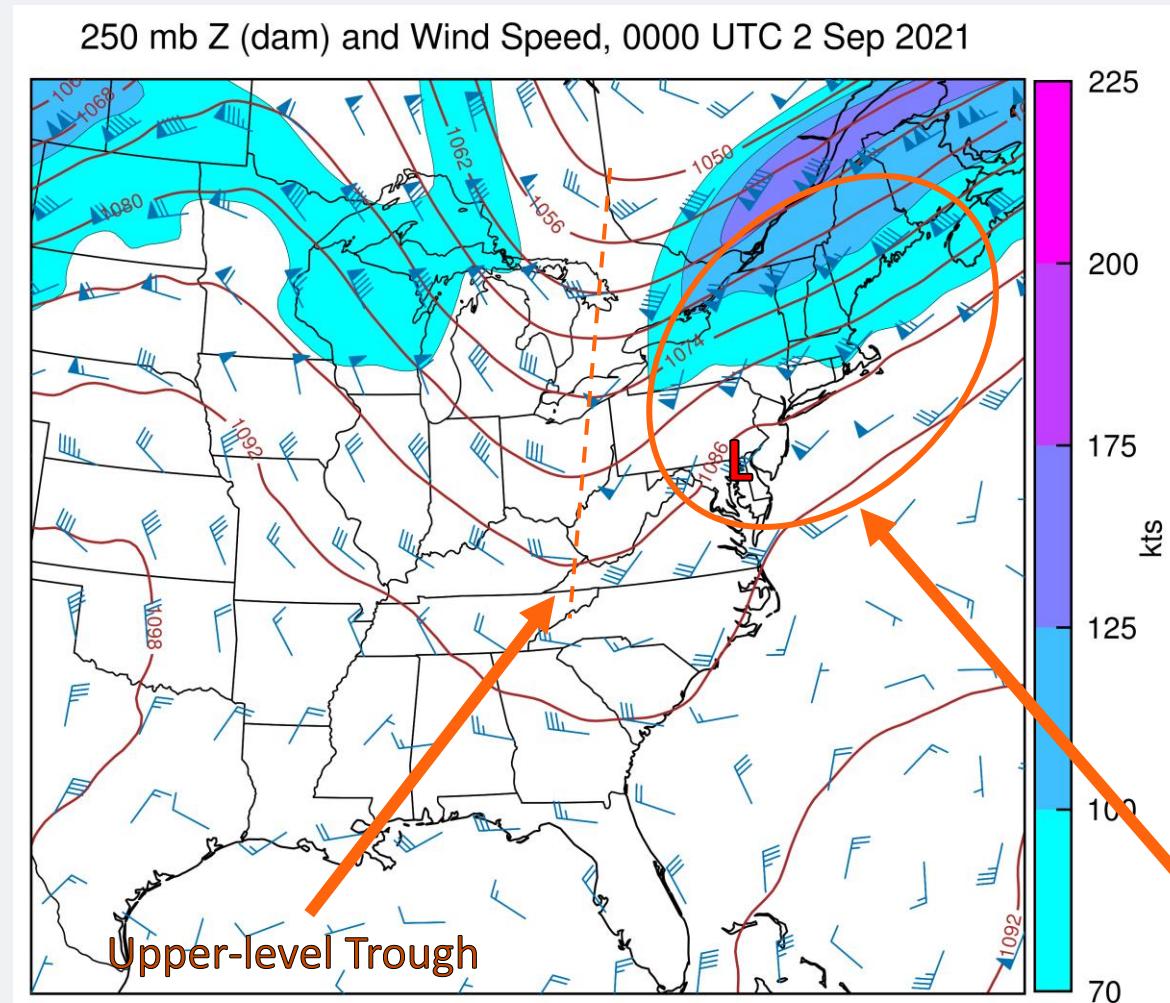
ET Transition: Sep 1, 2021

Dissipated: Sep 4, 2021

Hurricane Ida Phase Space Diagram



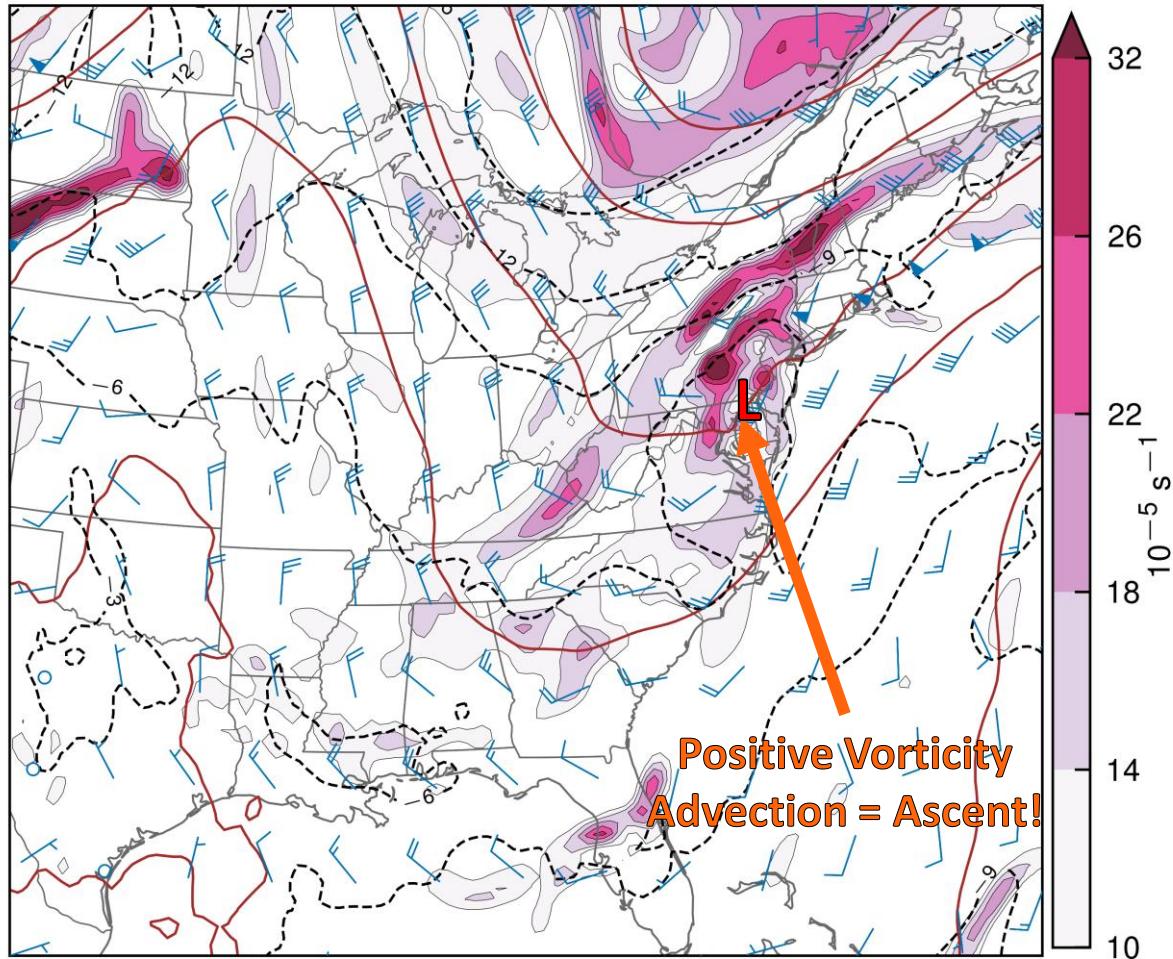
Upper-level support



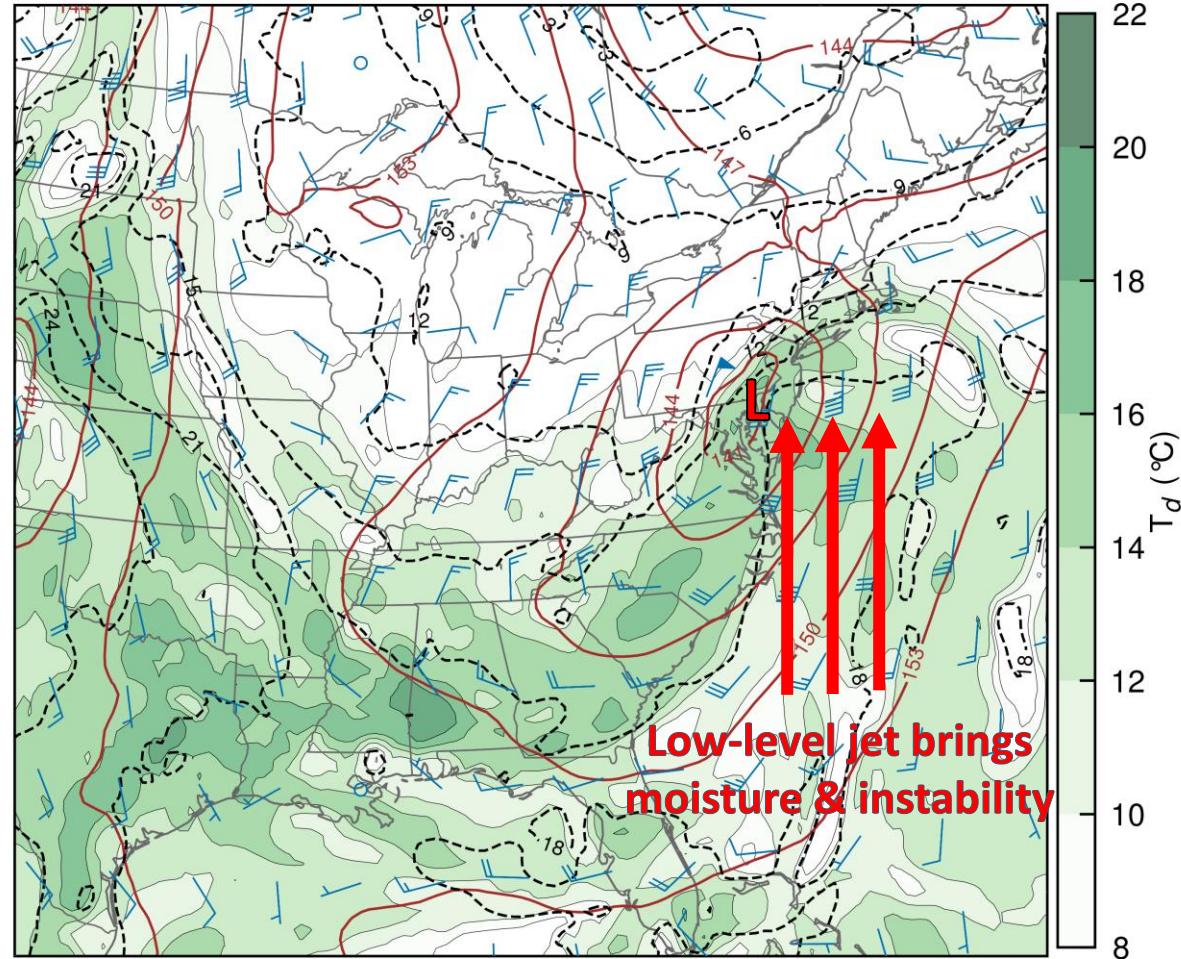
- Ohio Valley trough @ 250 mb
- Right-entrance region of jet streak = UL Divergence = Ascent = **Precipitation!**
- UL divergence also supports a **low-level jet** to bring energy and moisture

Mid-level Support

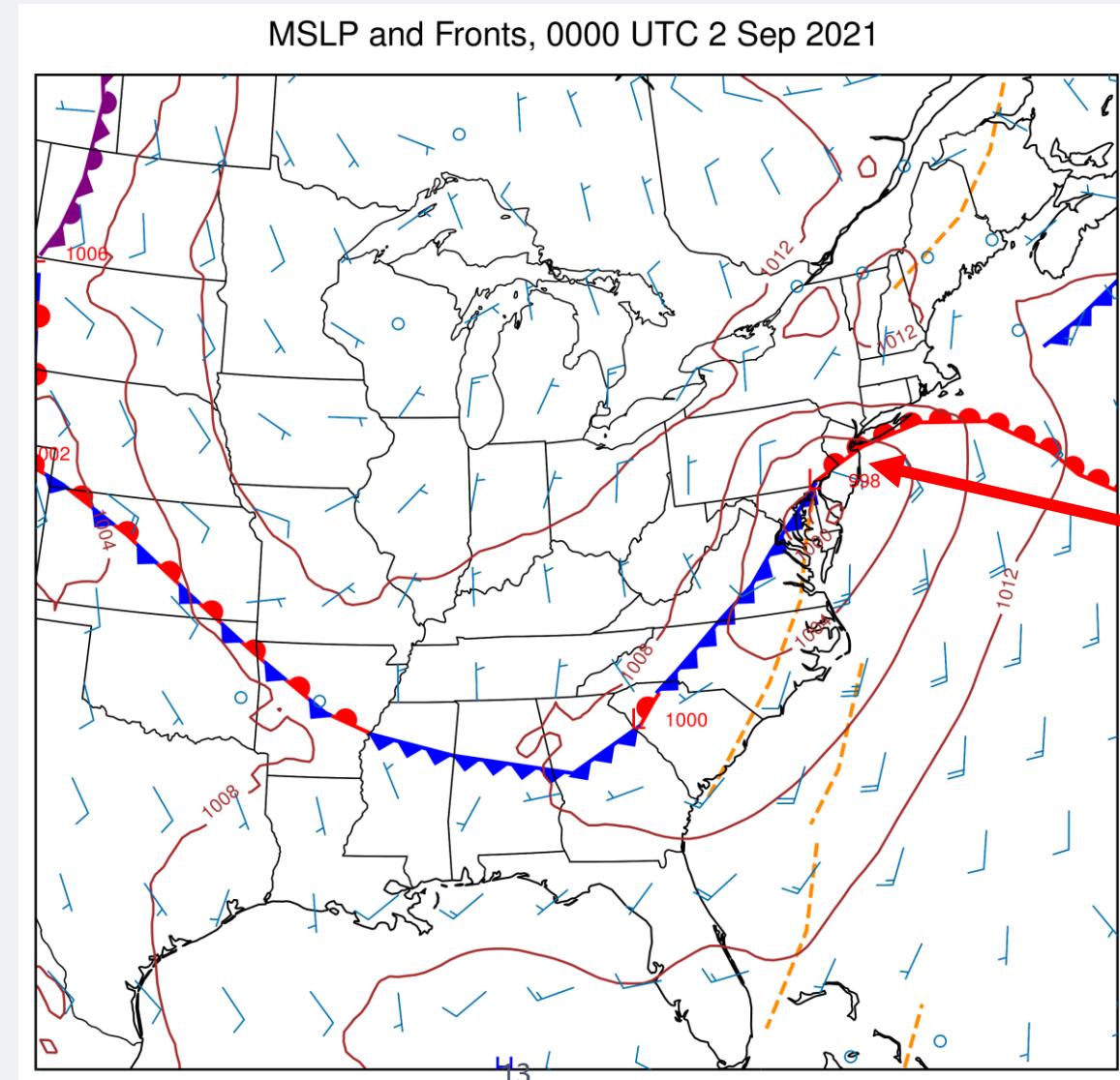
500 mb Z (dam) and Abs Vort, 0000 UTC 2 Sep 2021



850 mb Z (dam) and T ($^{\circ}$ C), 0000 UTC 2 Sep 2021



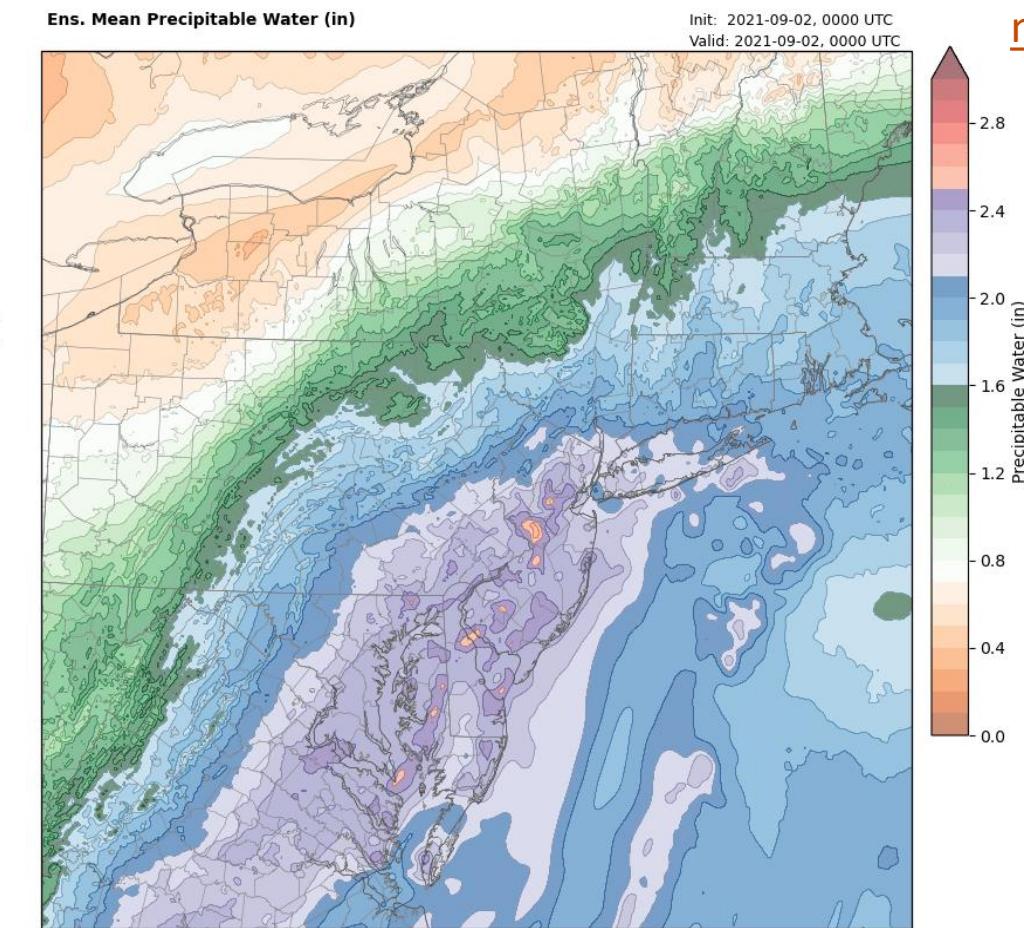
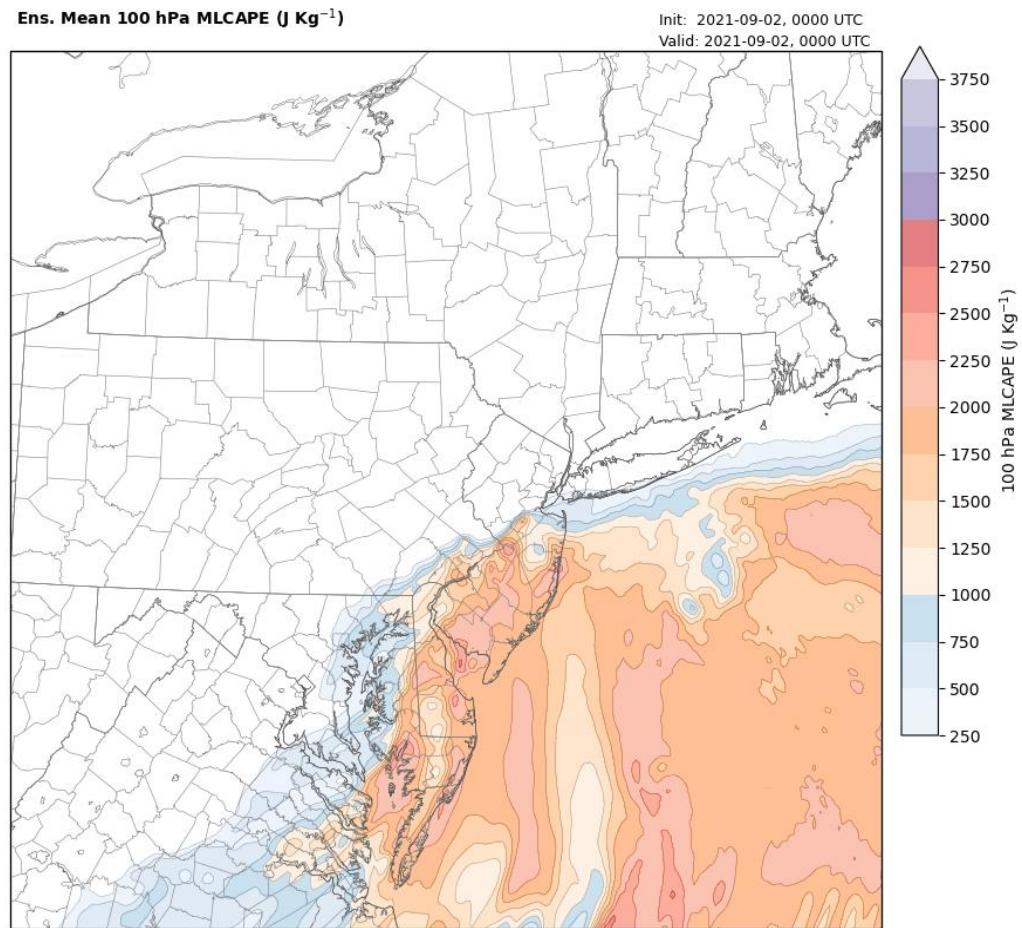
Surface Analysis



Mixed-Layer CAPE & Precipitable Water

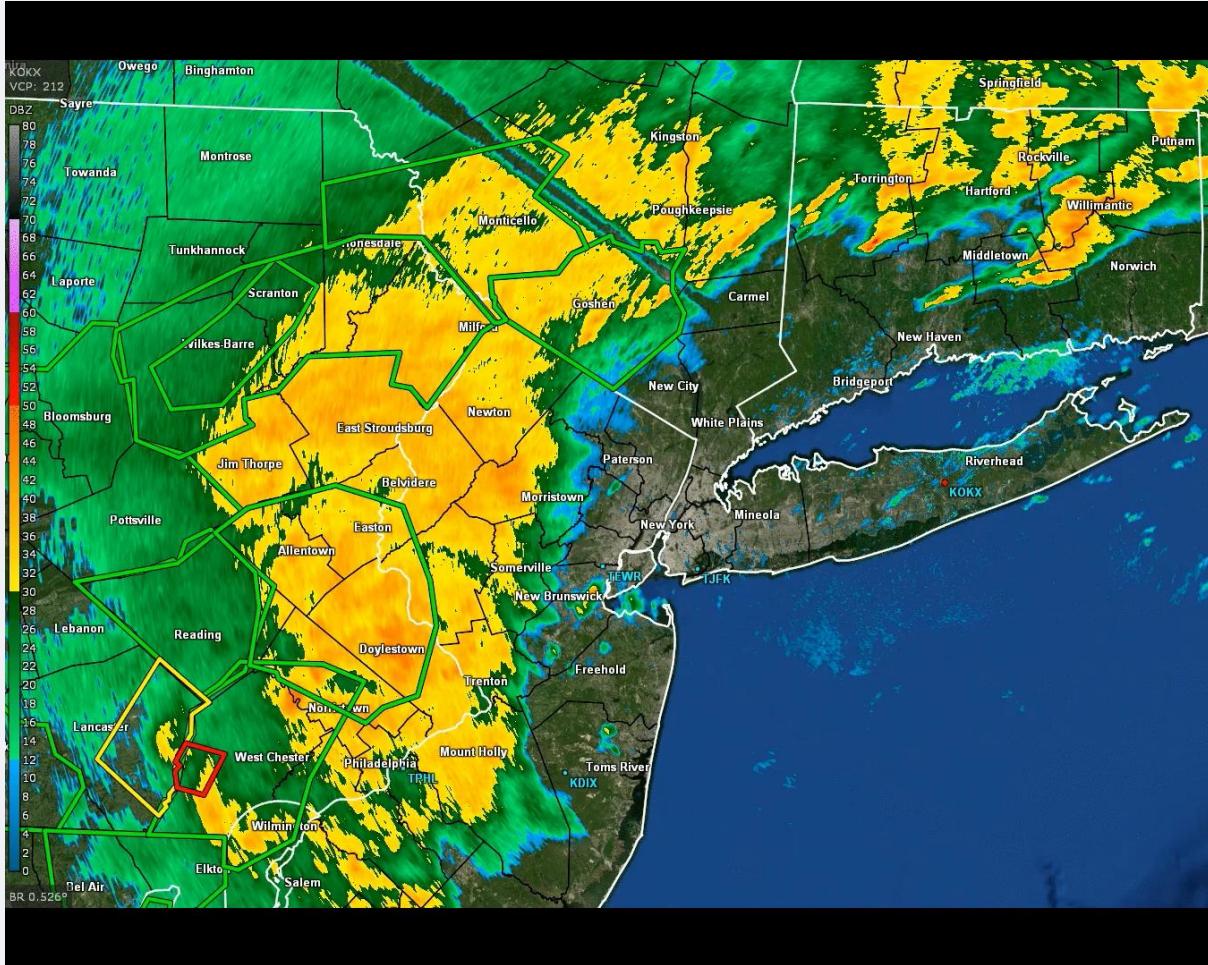
Precipitable water is a measure of moisture

Mixed-Layer CAPE is a measure of instability



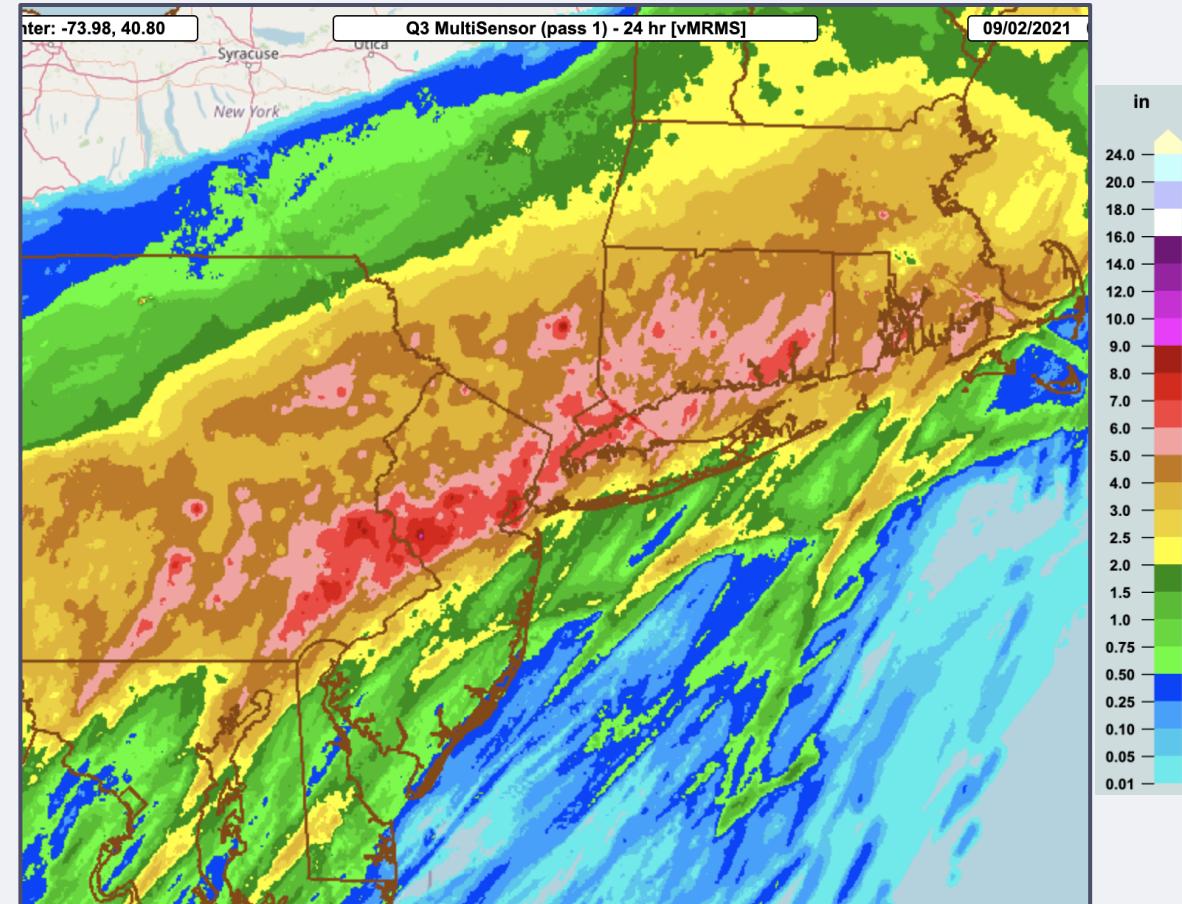
Radar Loop and 24 hr Rainfall

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

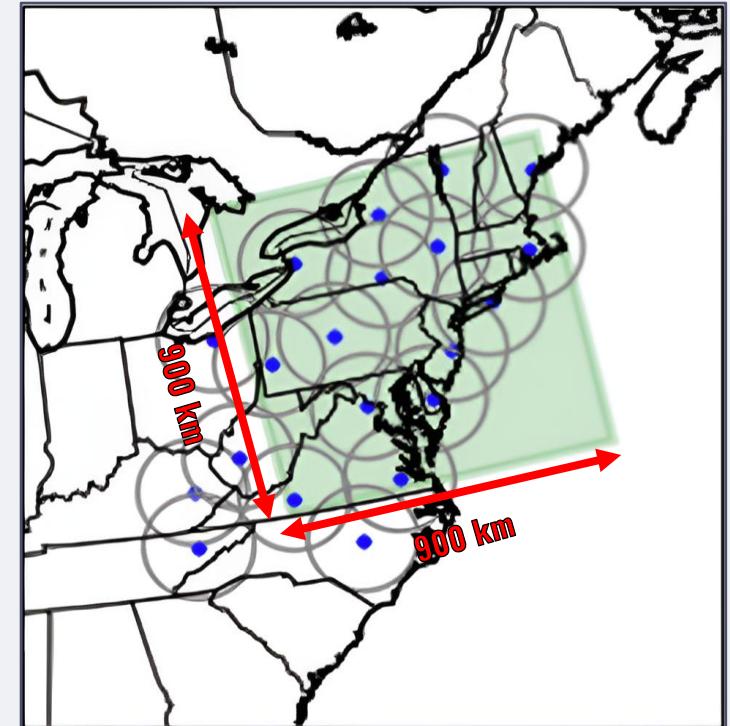
- The confluence of many factors across spatial scales made Ida so destructive
 - Trough and jet streak placement
 - Positive vorticity advection
 - Low-level jet
 - Slow-moving front
 - Ample moisture and instability
 - Training supercells
- **Which of these offers the most predictability for Ida and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

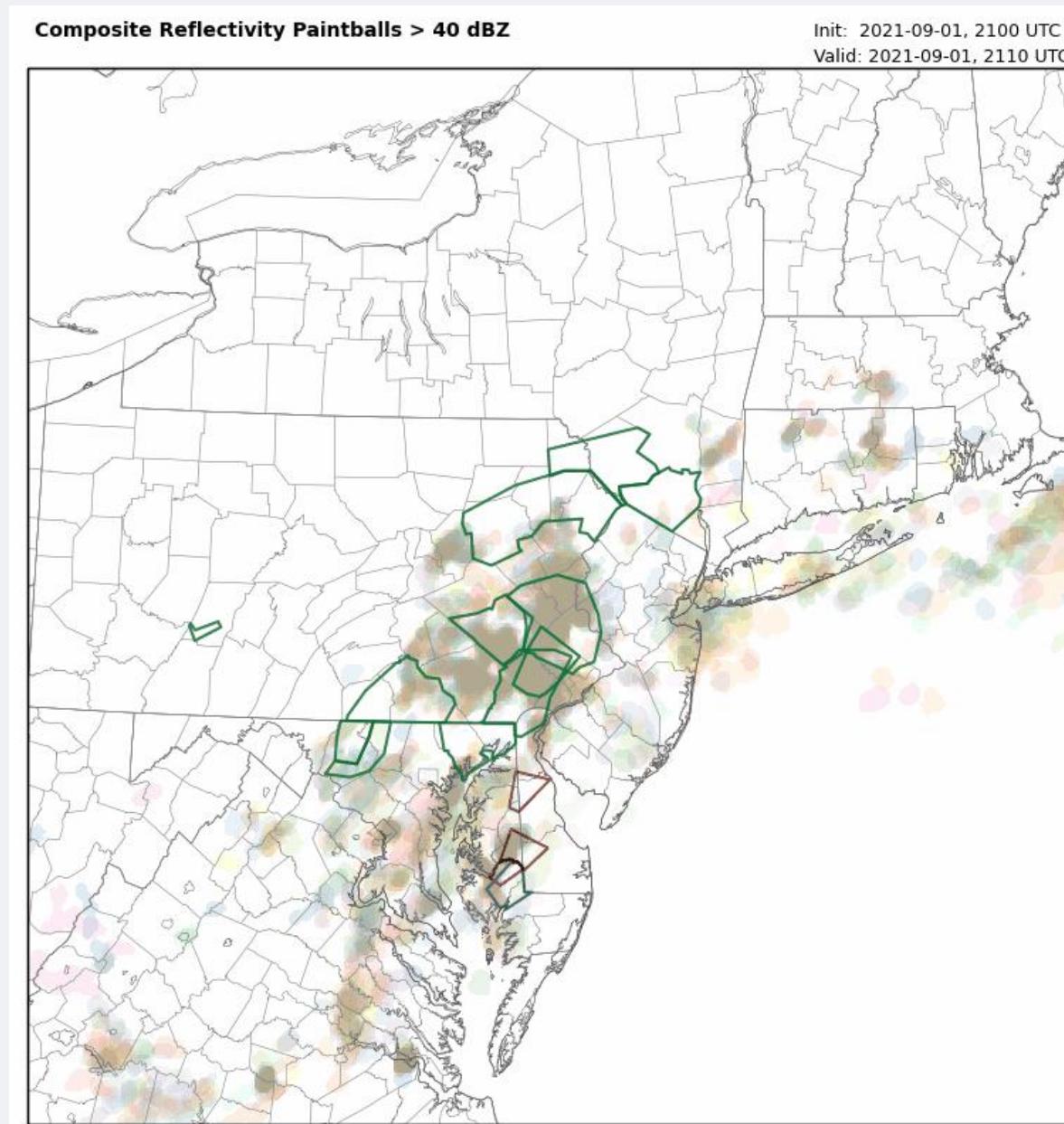
WoFS Grid on 1 Sep 2021



Radar locations (♦) with 150 km range rings

2100 Initialization of WoFS

Paintball plot
of reflectivity
values > 40
dBZ

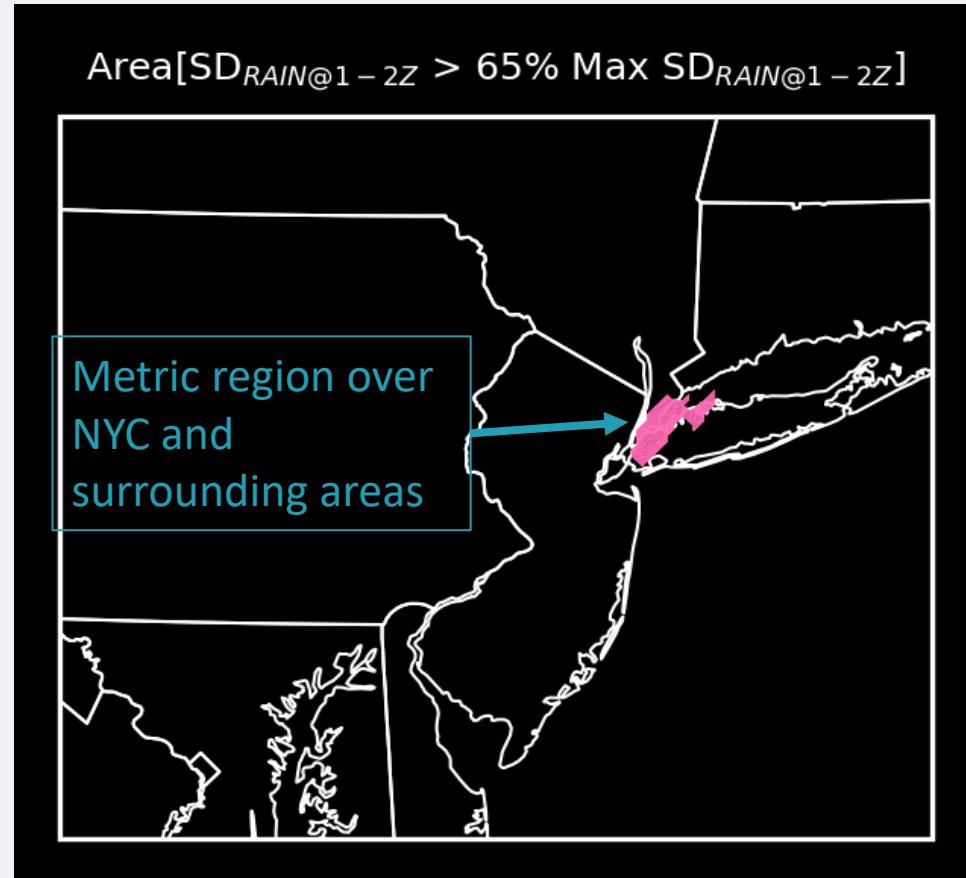


Green = flash
flood warning

Red = Tornado
warning

Blue = Severe
Thunderstorm
Warning

Region and rainfall metric



“NYC” = region where 72-member ensemble SD of hourly rainfall $\geq 65\%$ of domain-maximum SD

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

- 4 initializations \times 18 members = 72-member ensemble

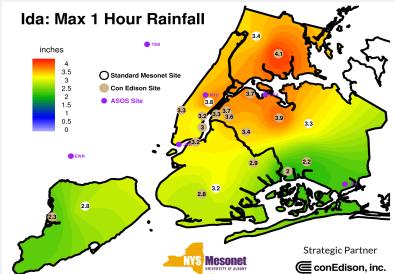
Rainfall metric: 0100–0200* UTC rainfall in NYC = **RAIN_{1-2, NYC}**

- Corresponds to observed maximum rainfall rates in Manhattan

*Results are relatively insensitive to hour chosen

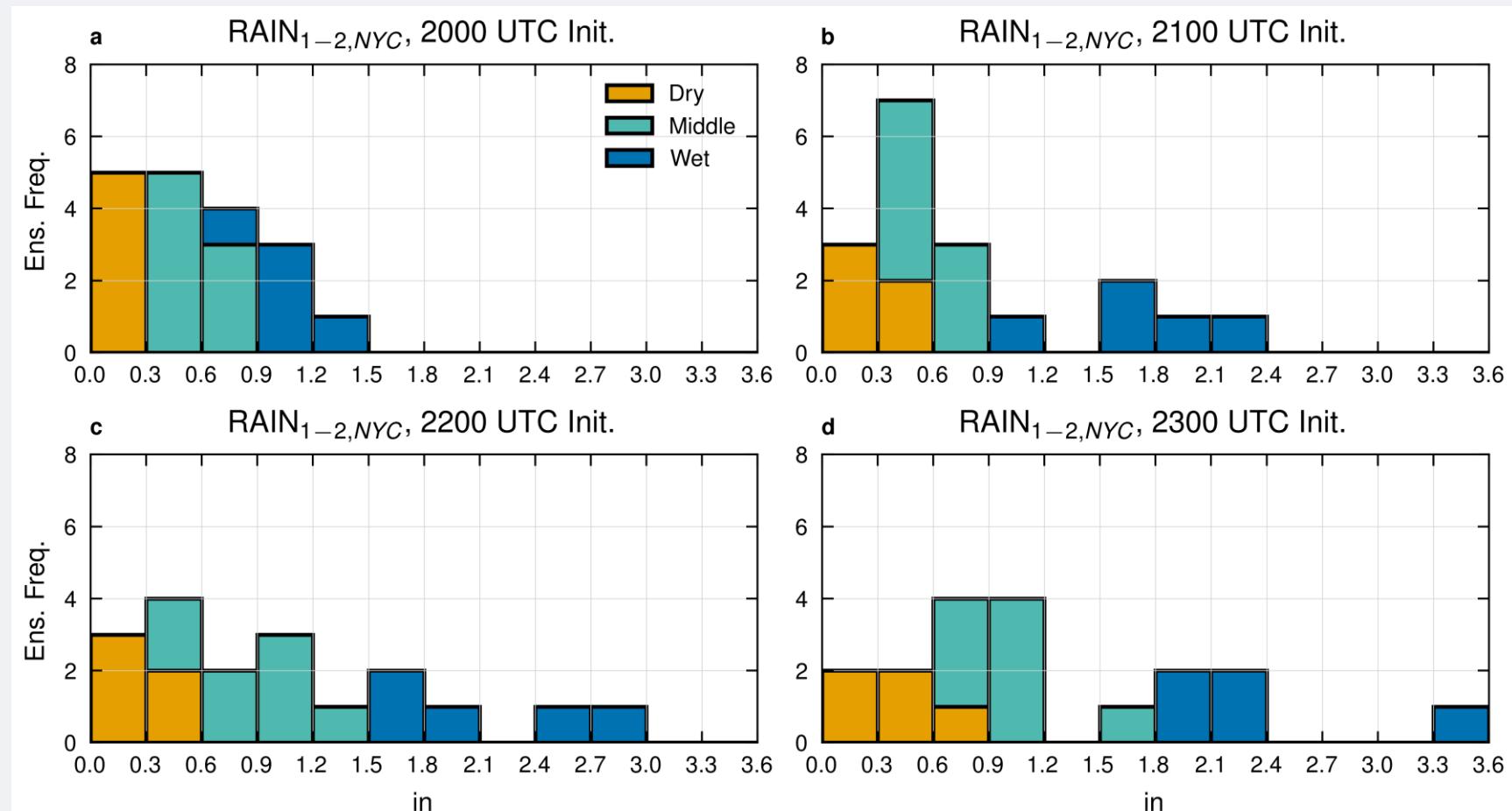
Huge ensemble spread in NYC rainfall!

Few ensemble members come close to matching observations!



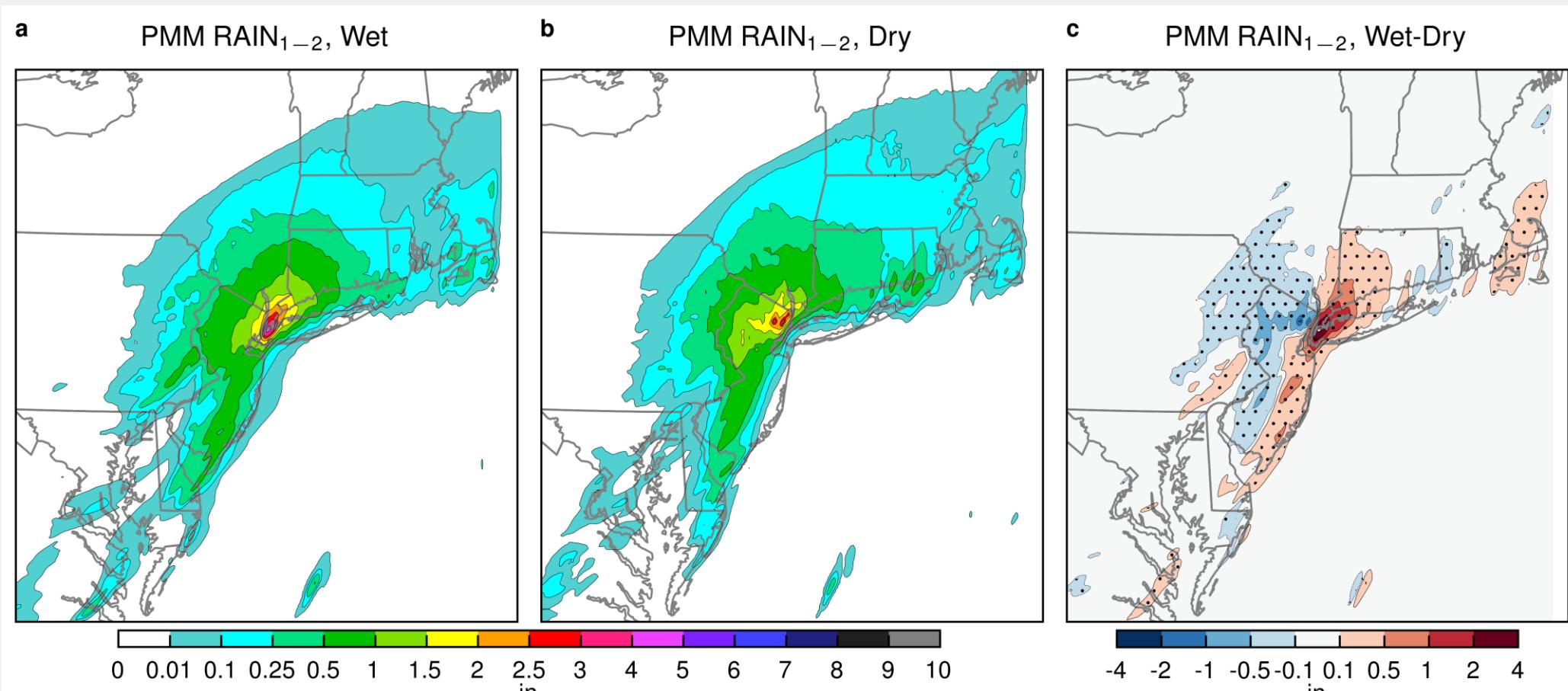
Approach #1: Compare the 5 wettest and 5 driest ensemble members from each initialization → Wet & Dry Subsets (n=20)

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

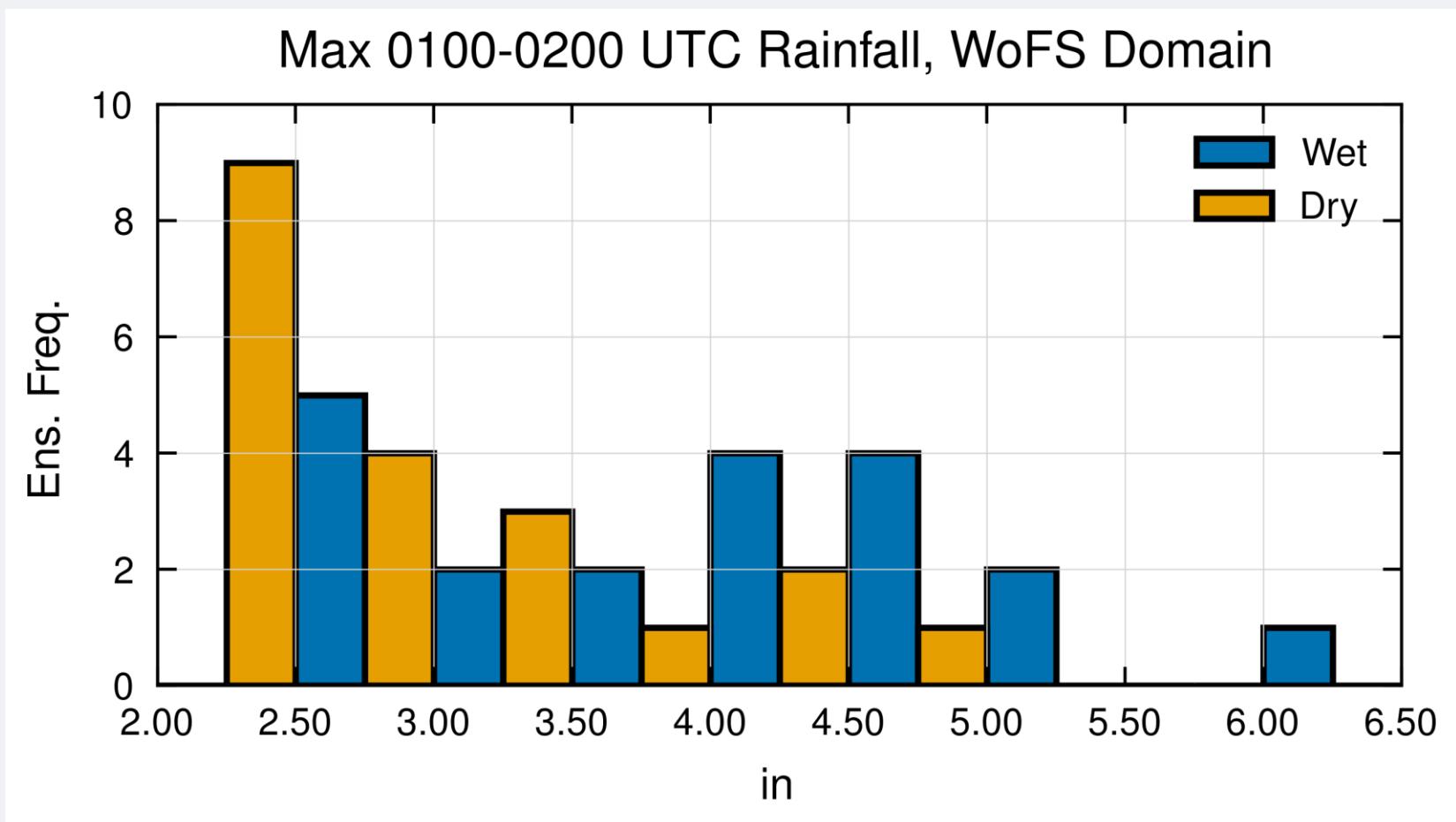


*Probability
matched
mean →
similar to
ensemble
mean, but
retains
extreme
values

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

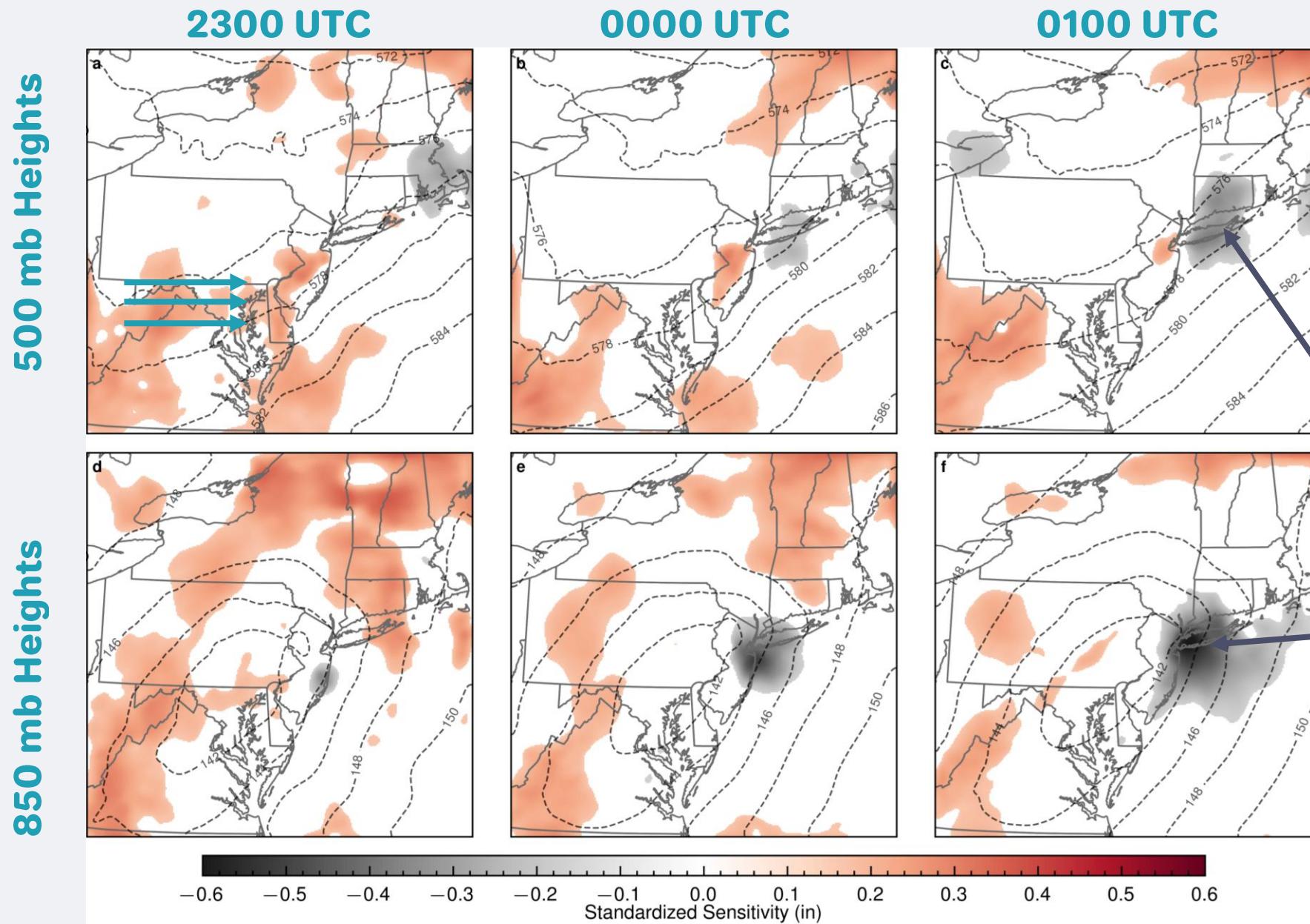
$$\frac{\partial \text{RAIN}_{1-2, \text{NYC}}}{\partial x} = \frac{\text{cov}(\partial \text{RAIN}_{1-2, \text{NYC}}, x)}{\text{var}(x)} \times \text{SD}(x)$$

↓ ↓ ↓
Sensitivity Slope of linear regression StDev of predictor

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

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

Sensitivity of RAIN_{1-2, NYC} to Geopotential 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_{1-2, NYC} to 850 mb Winds

2300 UTC

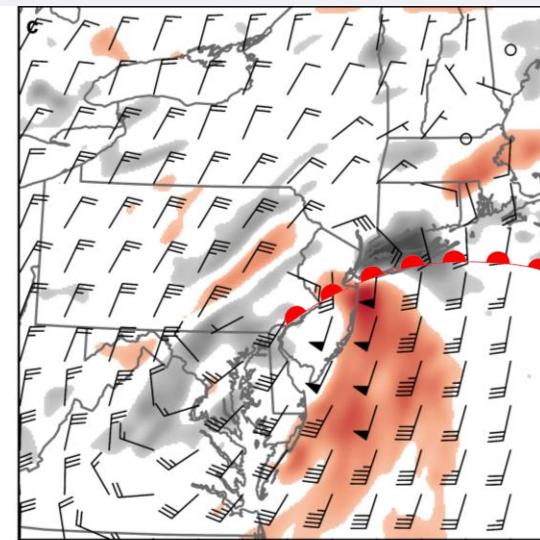
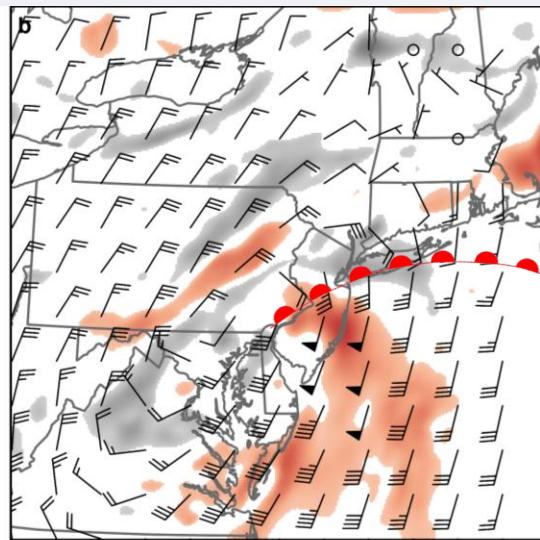
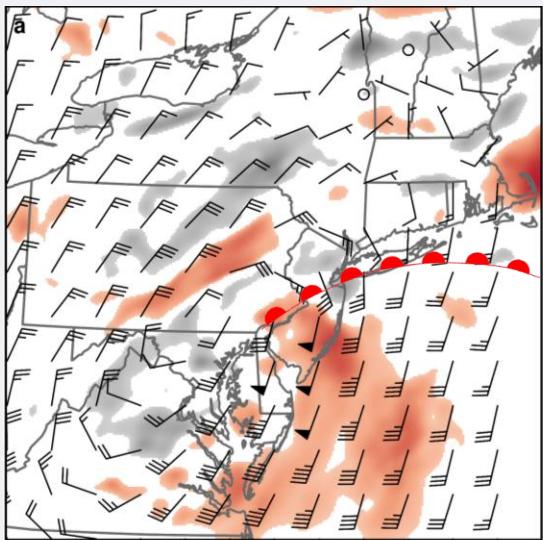
0000 UTC

0100 UTC

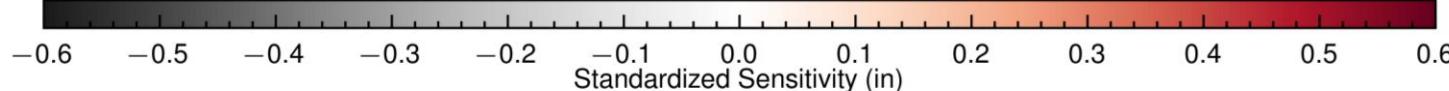
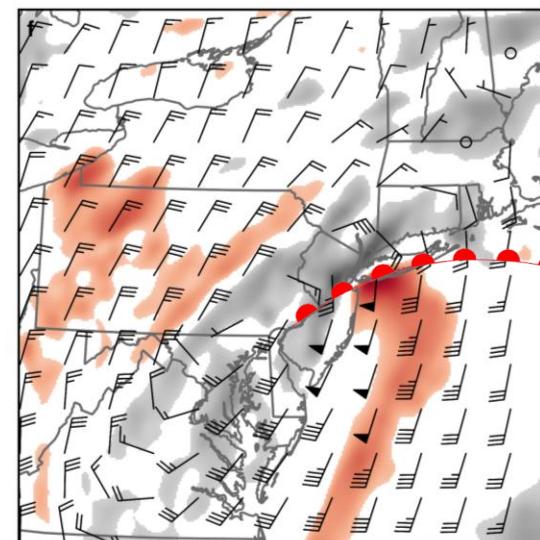
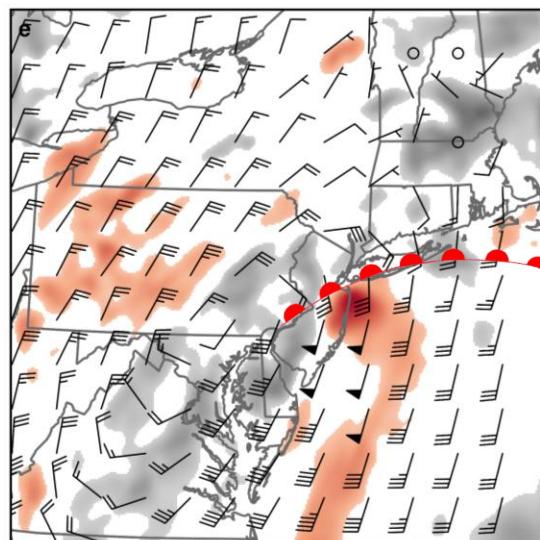
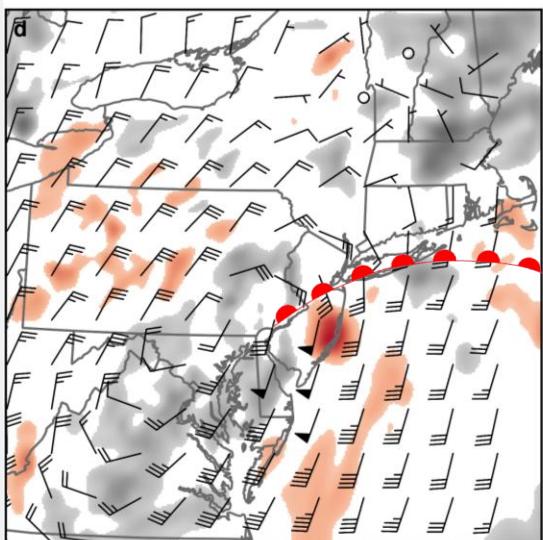
Cyclonic shear↑ =
frontogenesis↑ =
Ascent↑ = Rain↑

Stronger low-level
jet = more
moisture and
instability

850 mb Zonal Wind

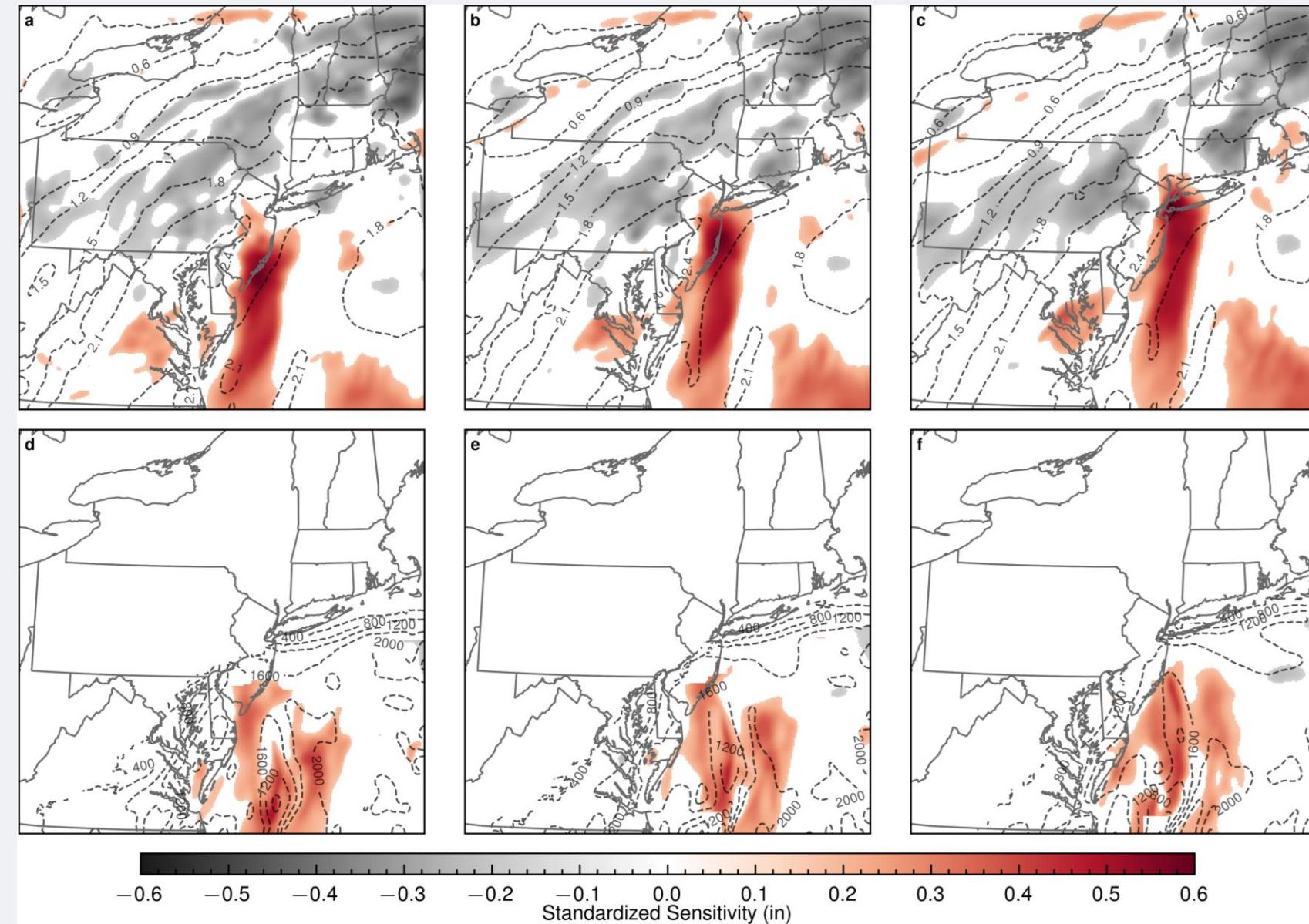


850 mb Meridional Wind



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

2300 UTC 0000 UTC 0100 UTC



Precipitable water
to the south \uparrow =
RAIN_{1-2, NYC} \uparrow

Mixed-Layer
CAPE \uparrow = More fuel
for convection

CAPE: Convective Available
Potential Energy (Instability)

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

Back to wet vs. dry!

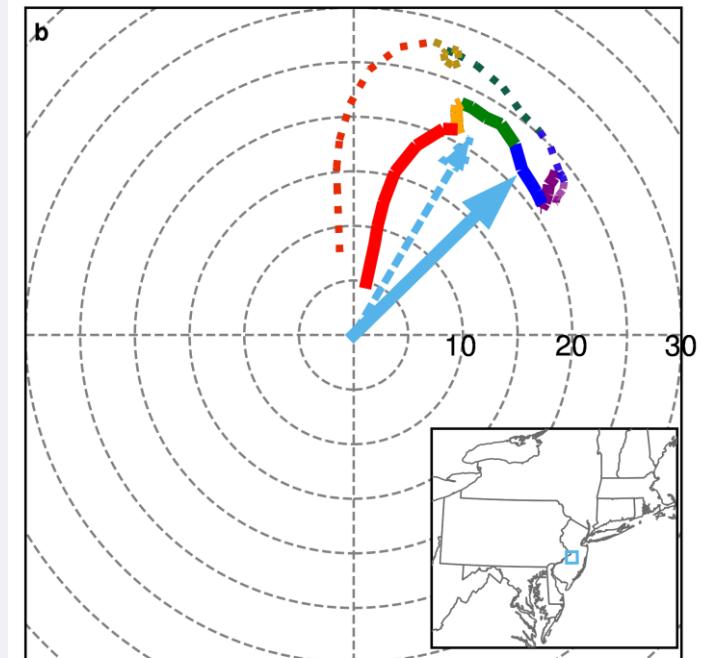
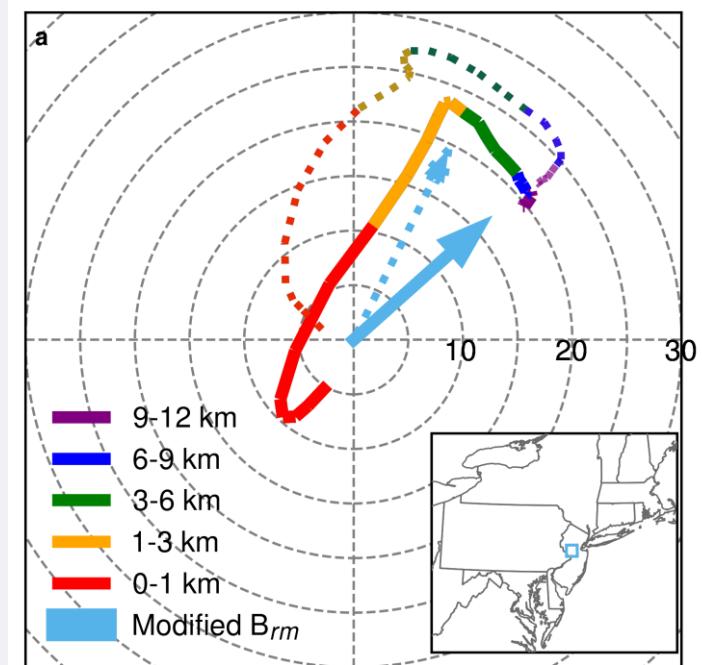
Hodographs

- 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



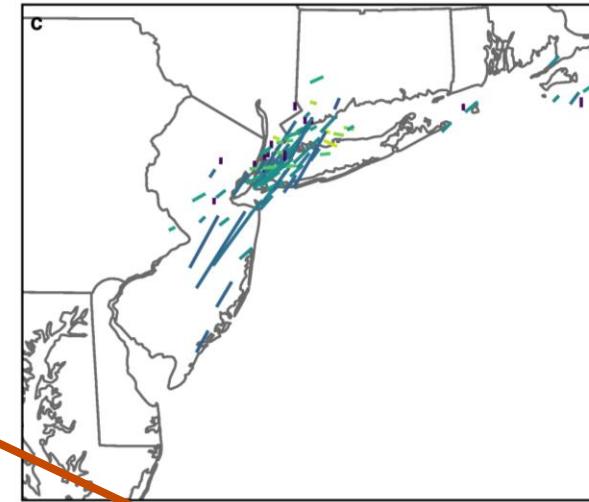
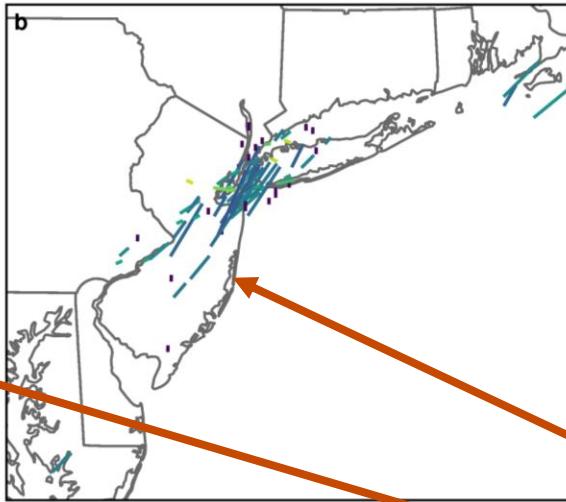
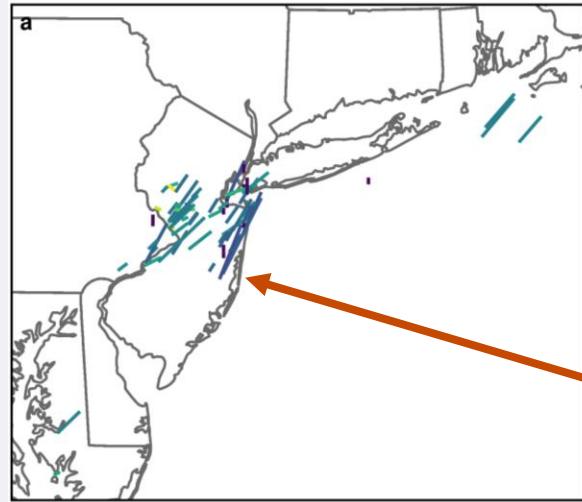
Wet & Dry UH > 20m²s⁻² with Trajectory Angles

2300 UTC

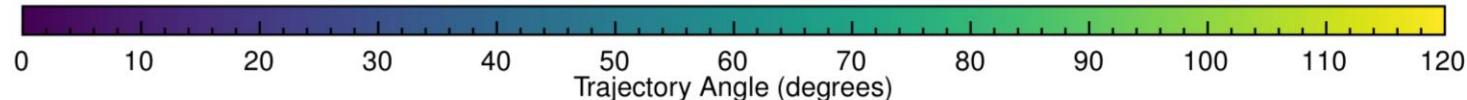
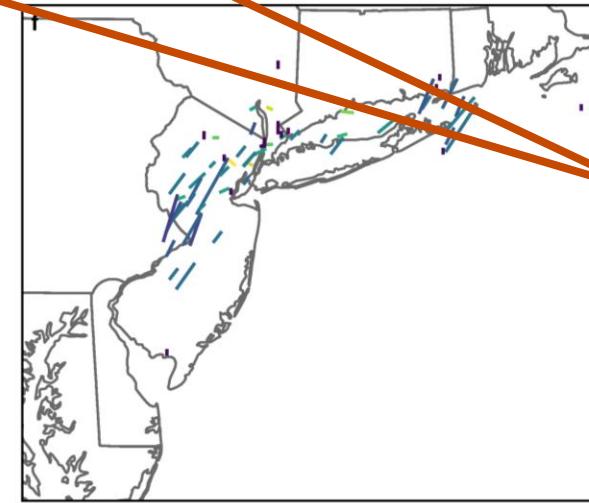
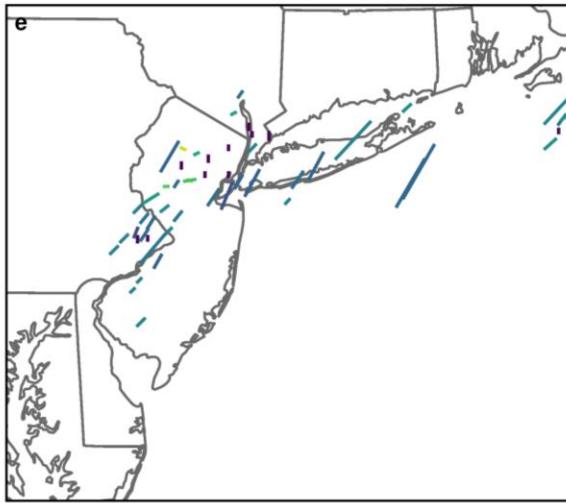
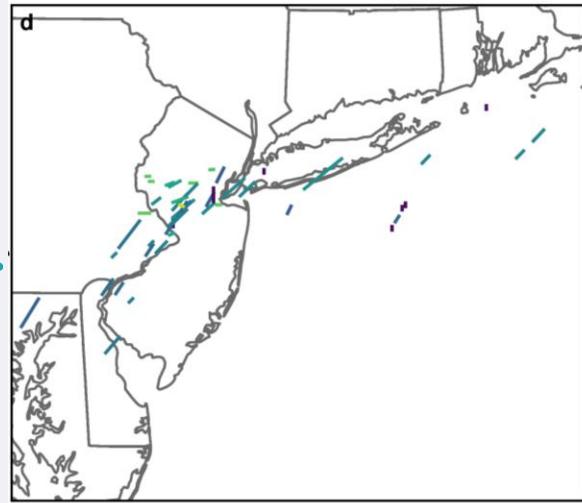
0000 UTC

0100 UTC

Wet



Dry



- 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)

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

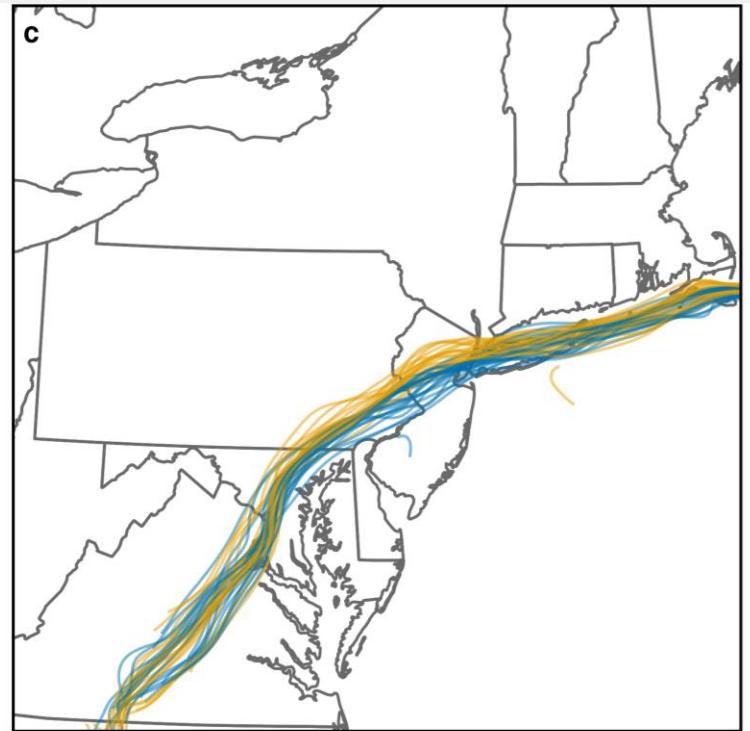
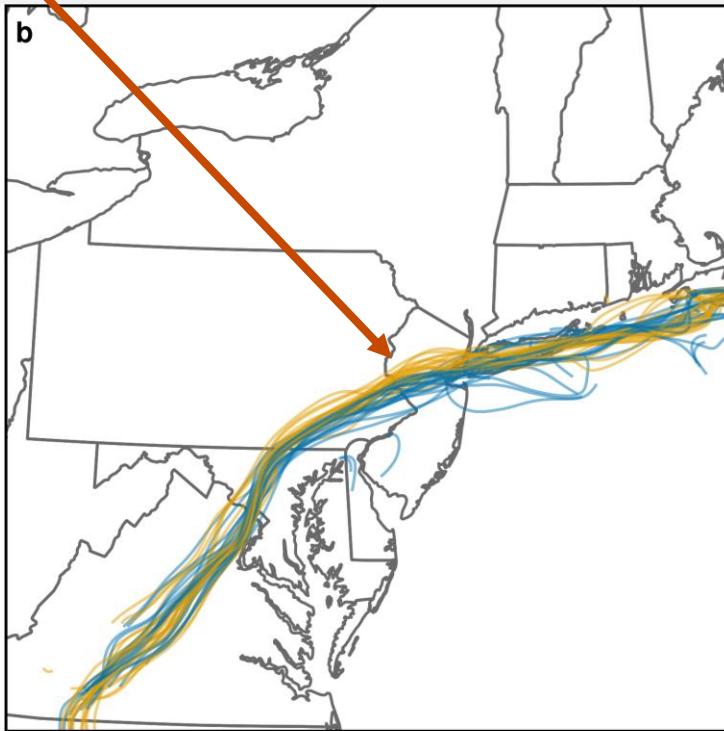
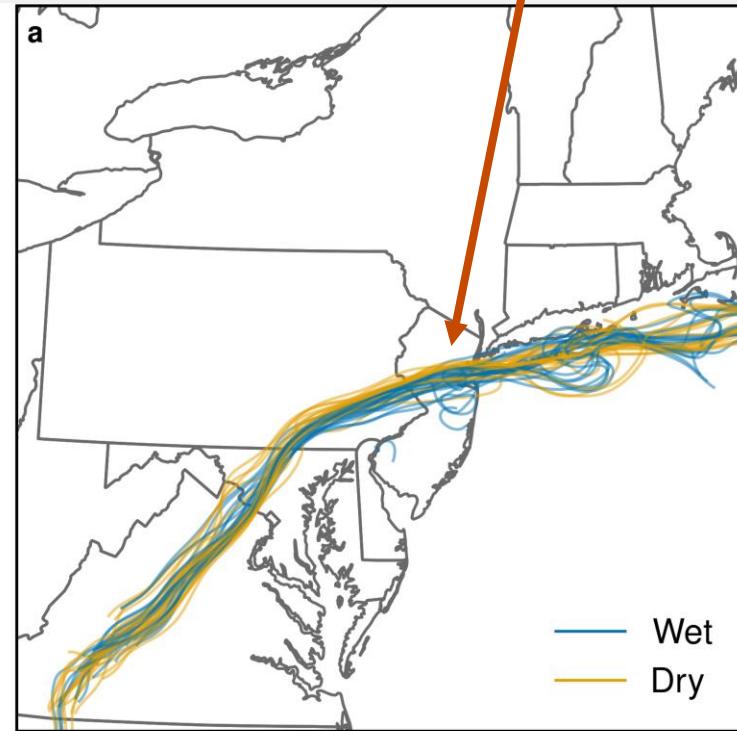
where $\theta_{e,850}$ is the equivalent potential temperature at 850 hPa

- 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!

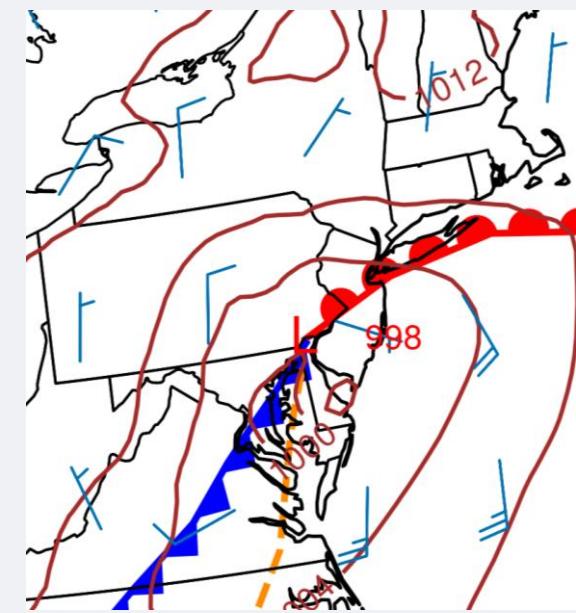
Warm front in wet subset located
farther south than in dry subset!

2300 UTC

WoFS Front Locations 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 may be important for increasing the predictability of future extreme rainfall events!

Contact Info

- Email: tjanoski@ccny.cuny.eu
- GitHub: github.com/tyfolino/ida-precip
- We have a forecasting discussion every Friday 1:30–2:00, we'd love to have you join!

References

- Mossel, C., Hill, S. A., Samal, N. R., Booth, J. F., & Deveneni, 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>