Observation System Simulation Experiments (OSSEs) Using Small UAVs for Short Term Numerical Weather Prediction of Thunderstorms

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Adapted from Presentation by Andrew Moore[1]
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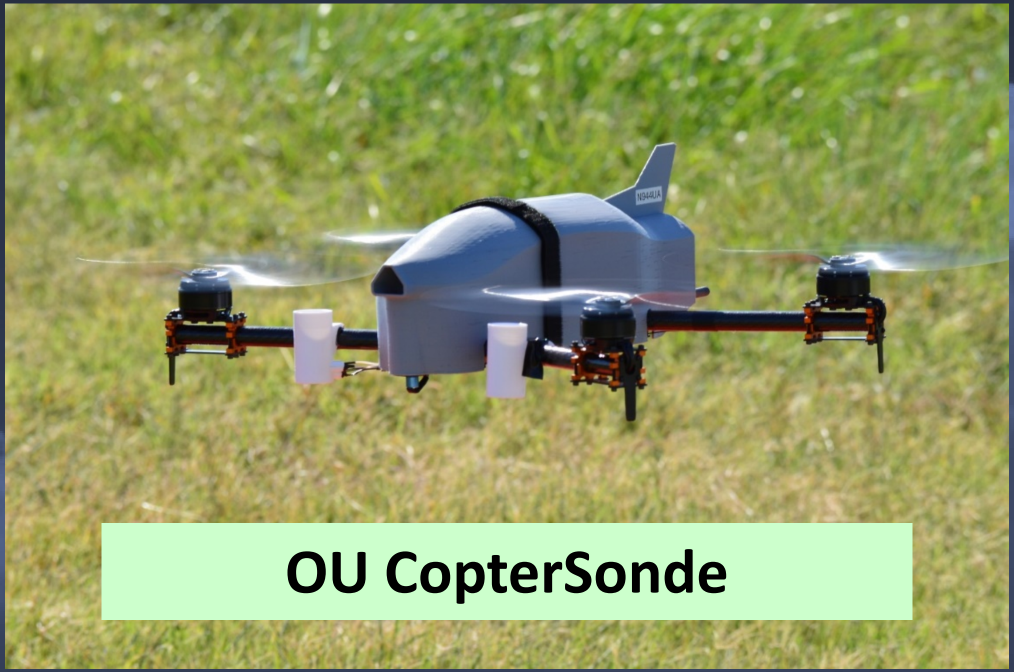
1 – University of Oklahoma
2 – OU Center for Analysis and Prediction of Storms
3 – OU Center for Autonomous Sensing and Sampling

Small Unmanned Aerial Vehicles (sUAV)



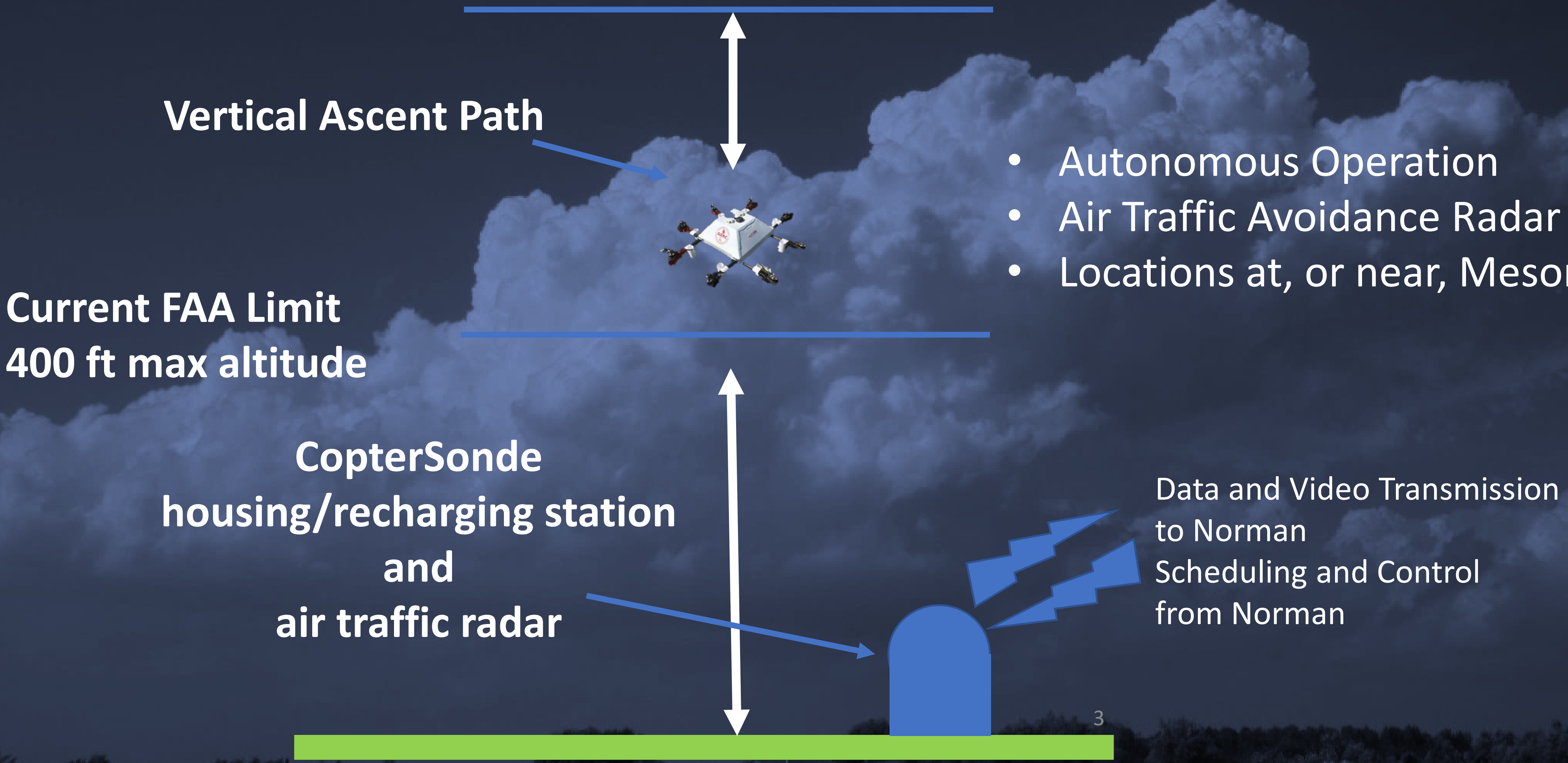
- Can make measurements in Planetary Boundary Layer
- PBL is key to many analysis/forecast problems
  - dispersion, severe weather, precipitation, etc
- Current radiosondes limited resolution
  - 12 h intervals
  - ~300-500 km spacing

<u>OU CopterSonde</u>

In-situ observations of
temperature, pressure, humidity, winds
Capable of expansion to other variables

The 3-D Mesonet Concept

- Autonomous Operation
- Air Traffic Avoidance Radar
- Locations at, or near, Mesonet Sites



Research Questions

Primary Question: Can observations from a network of small Unmanned Aerial Vehicles (sUAVs) improve PBL analyses and short-range convective forecasts?

Secondary Questions: If so, what is a sufficient network configuration?

- **Maximum Flight Altitude?**
- **Number of Stations/Horizontal Spacing?**

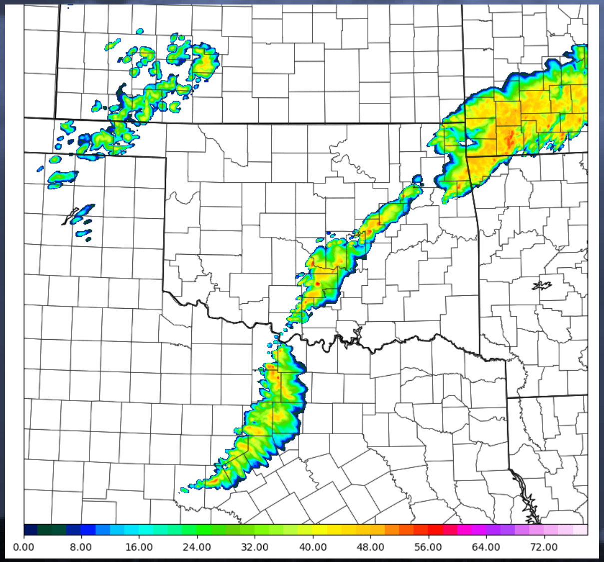
Observing System Simulation Experiment - OSSE

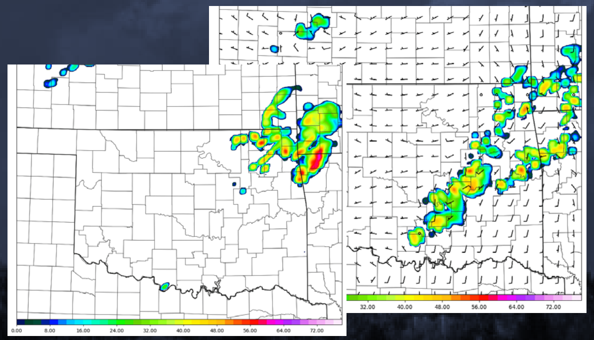
1) <u>Numerical Atmosphere</u>
   - Called the <u>Nature Run</u>
   - Accurate high-resolution numerical model
   - Needs to resemble the real atmosphere

2) <u>Simulated Observations</u>
   - Create simulated obs from the Nature Run for both current and proposed observing networks
   - Must mimic expected observational frequency and error

3) <u>Numerical Experiments</u>
   - Compares numerical forecast with/without proposed network to the Nature Run
   - Must use a different model than the Nature Run to avoid the "identical twin" problem.

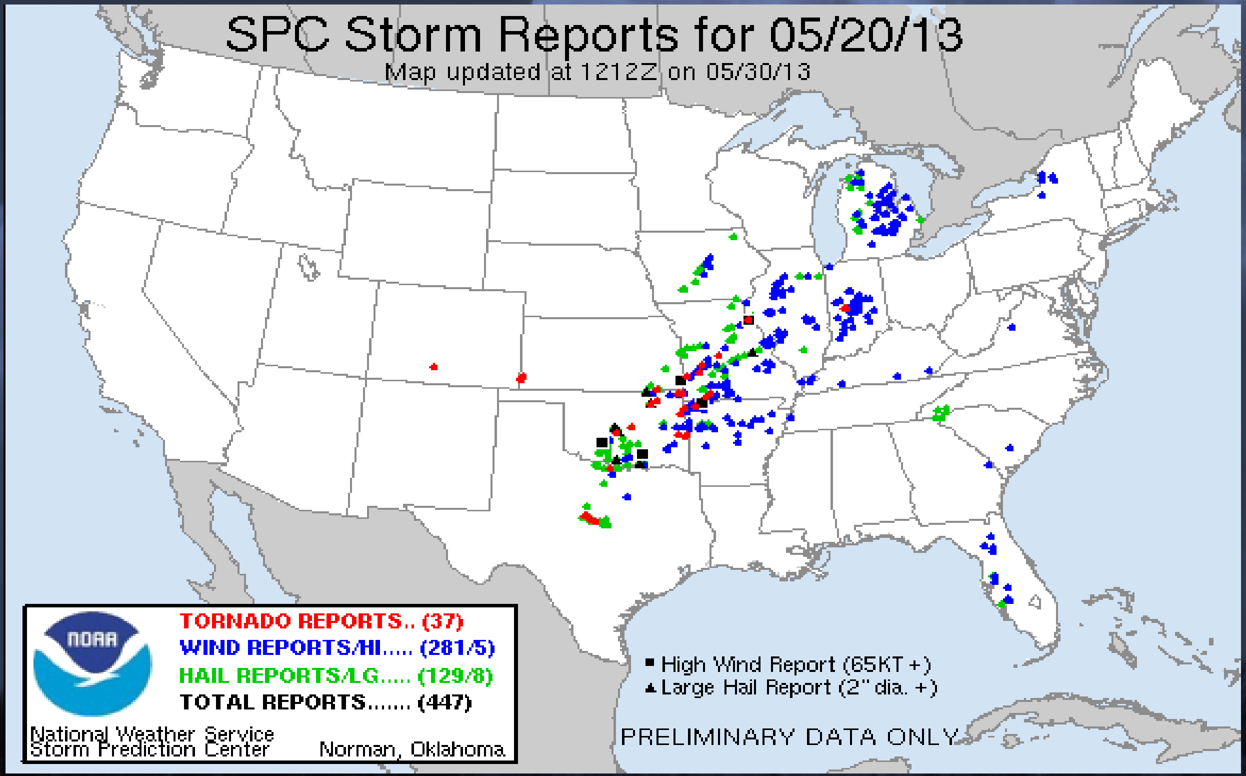
4) <u>Calibration OSE</u>
   - Complete an OSE using one of the current observing networks
   - Perform OSSE using simulated obs for existing network and compare to OSE results; should be similar.

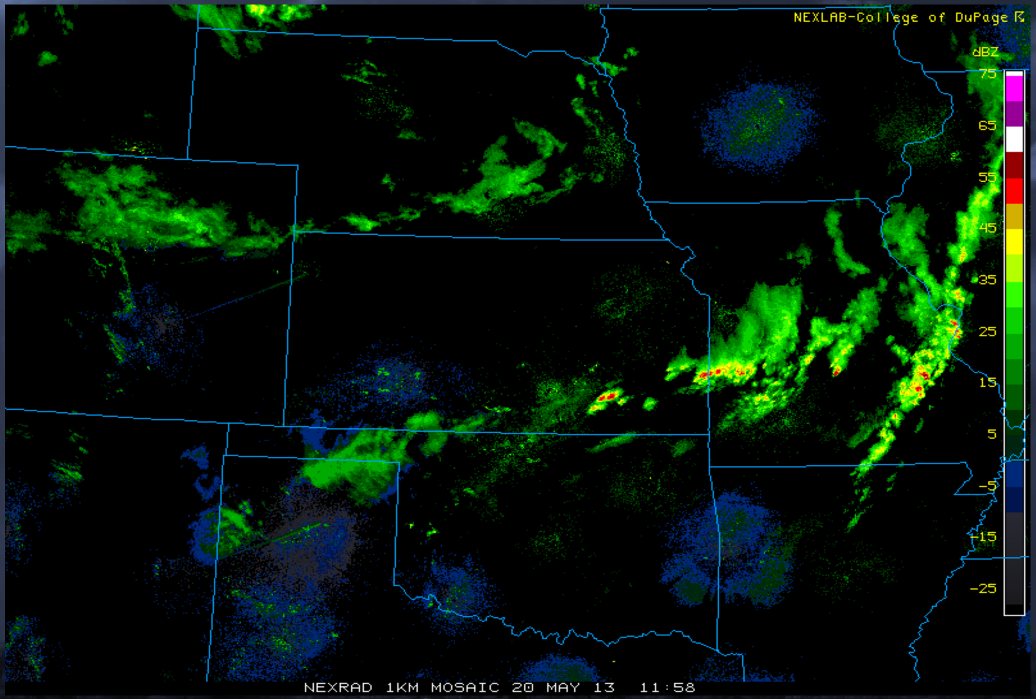




Numerical Atmosphere/Nature Run

- Study Event: May 20, 2013: Convective Initiation across Oklahoma
  - Advanced Regional Prediction System (ARPS) 1-km Model
  - Data Assimilation 06-12 UTC
  - Free forecast begins at 12 UTC
  - Forecast ends at 06 UTC on May 21, 2013





Observed Radar 20 May 12 UTC – 21 May 06 UTC

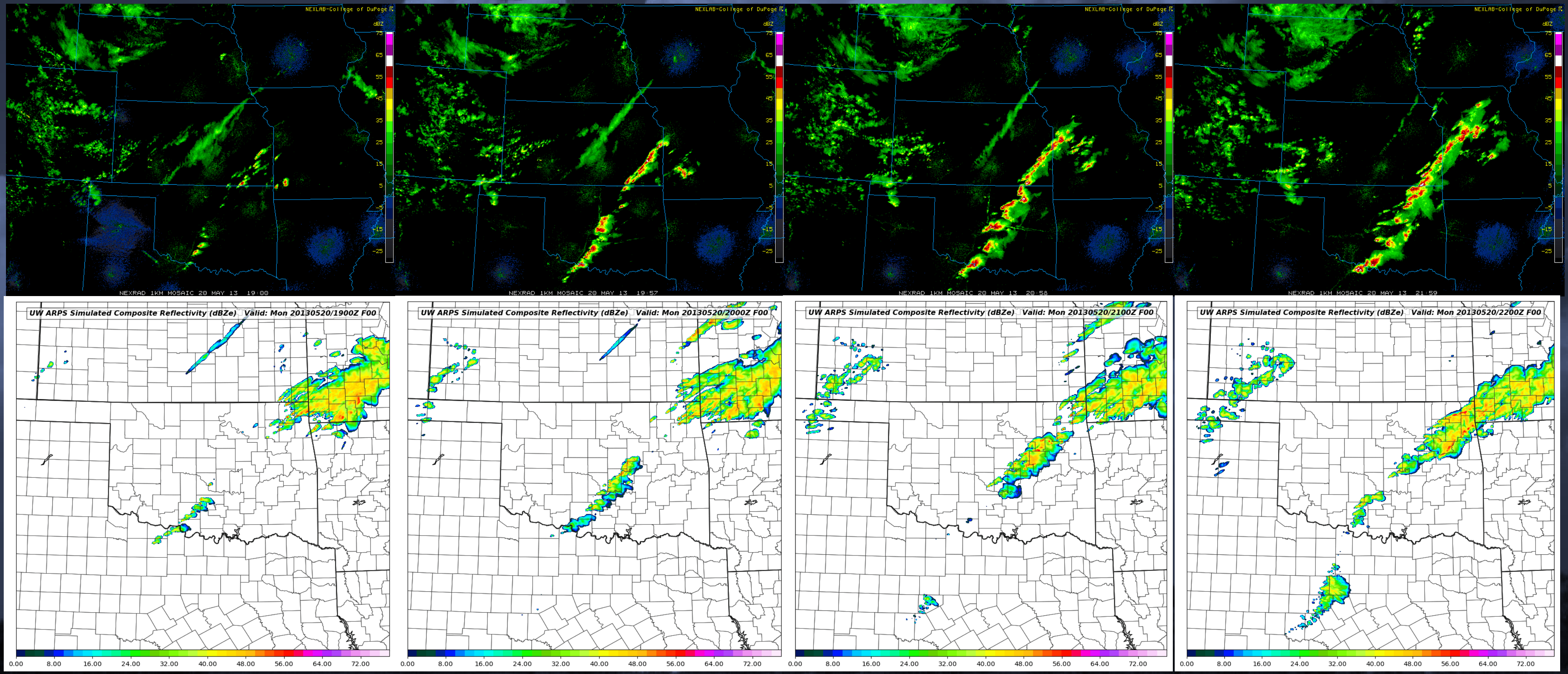
Nature Run vs. Reality

- For an OSSE, the Nature Run must resemble the real atmosphere
  - In this case, metrics are convective initiation, storm mode, and storm evolution

19 UTC | 20 UTC | 21 UTC | 22 UTC

Observed Radar

ARPS Nature Run



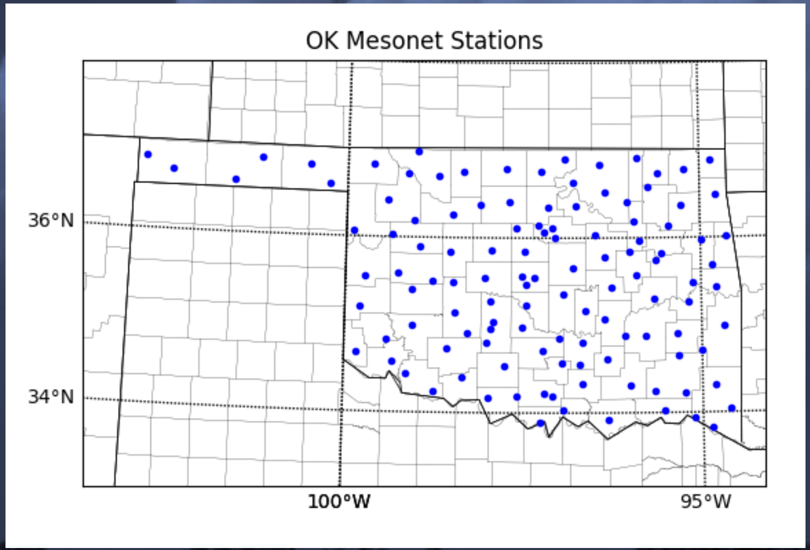
Simulated Observations

Three types of simulated observations:

1. Global Forecast System Final Analyses (GFS FNL) (1° lat-lon mesh -proxy for assimilated larger-scale data)
2. Oklahoma Mesonet
3. UAV (3-D Mesonet)

Simulated Observations
Simulated Mesonet

- Observations Simulated:
  - 1.5 meter Temperature
  - 9 meter Temperature
  - 2 meter wind speed
  - 10 meter wind speed/direction
  - 1.5 dewpoint Temperature



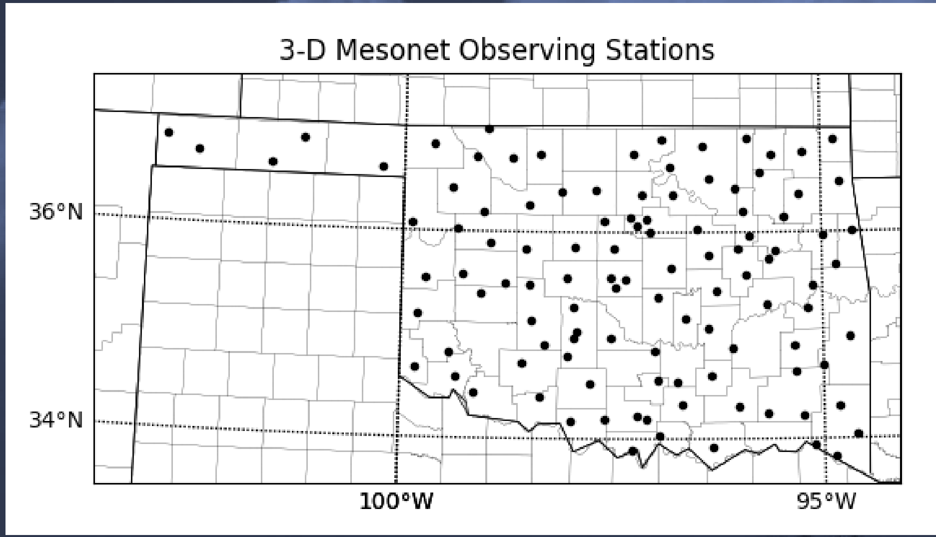
120 Mesonet Observation Points

- Observation Errors:
  - Created for each individual obs type.
  - Randomly sampled a non-biased Gaussian distribution
  - Instrument's reported accuracy used as the standard deviation.
  - Inter-variable dependencies incorporated into errors

- Assumes:
  - Gaussian dist. for errors
  - No instrument bias

Simulated UAV Observations

- Sampled from Nature Run:
  - Pressure
  - Temperature
  - Dewpoint
  - Wind Speed & Direction

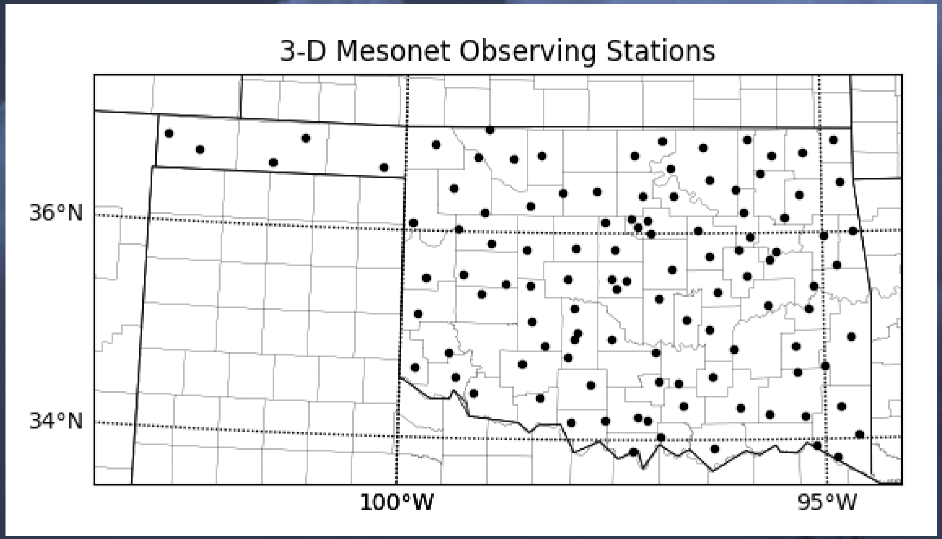


110 3-D Mesonet Observation Points

- Observations sampled at every 10 meters AGL.
- Assumes constant ascent velocity of 3 m/s
- Observations taken on ascent only – assumed a faster descent to conserve battery life.
- Flights limited to once per hour.

Simulated UAV Observations (cont.)

- Sampled from Nature Run:
  - Pressure
  - Temperature
  - Dewpoint
  - Wind Speed & Direction



110 3-D Mesonet Observation Points

- Time adaptive – Nature Run data are available every 5 minutes, so flights lasting longer than 5 minutes are updated with new Nature Run data.
  - Accounts for changing atmospheric conditions during flight.
  - Flights begin prior to the data's valid time (ex: data valid at 12 UTC would begin up to 15 minutes prior to 12 UTC). Does not account for time needed for transmission and quality control.
- Cloud Checking – FAA regulations restrict UAVs from flying beyond visual sight, including clouds.
  - Can use RH and Qi/Ql to stop flights in the presence of clouds

Simulated UAV Observations (cont.)

Observation Errors:

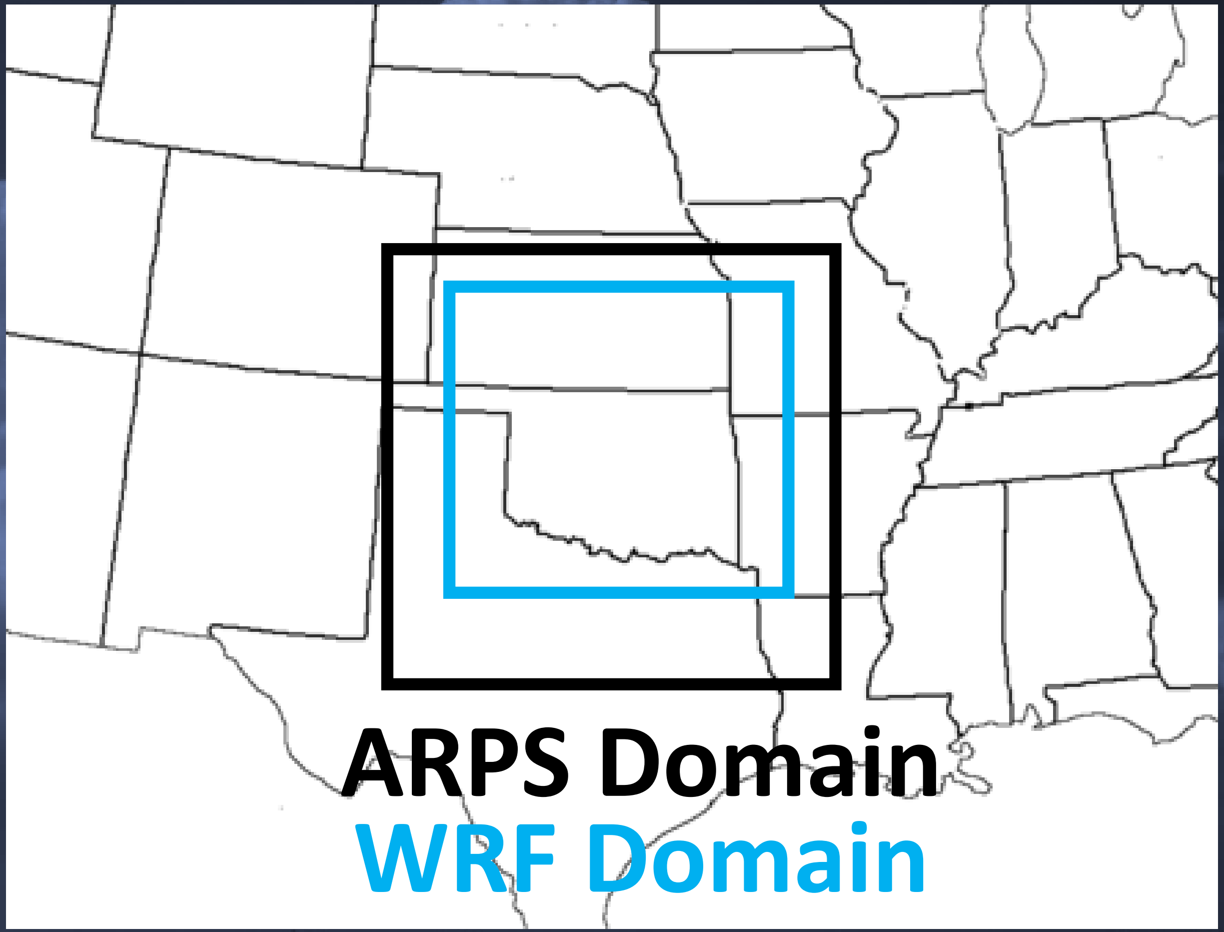
- **Instrument performance is based on CASS CopterSonde accuracy goals.**
- **Randomly samples non-biased Gaussian Distribution with standard deviations determined by instrument accuracy goals.**
- **Accounts for inter-variable dependencies (example: changing temp accuracy with height).**

UAV Observation Error Goals & Specifications		
Temp.	+/- 0.2 (C)	P > 100 hPa
	+/- 0.3 (C)	P <= 100 hPa
Rel. Humidity	+/- 5%	
Wind Speed	+/- 0.5 ms^{-1}	P > 100 hPa
	+/- 1.0 ms^{-1}	P <= 100 hPa
Wind Direction	+/- 5^0	
Pressure	+/- 1.0 hPa	

Numerical Experiments
WRF 3-km Forecast

WRF Set Up Specifications:

- Horizontal Grid: 237 x 201 single domain with 3 km resolution.
- Vertical Grid: 50 vertical layers
- Time Step: 9 sec
- Microphysics: Thompson MP
- PBL Physics: MYNN Scheme
- Cumulus: None
- Radiation: Dudhia (shortwave)
  RRTM (longwave)

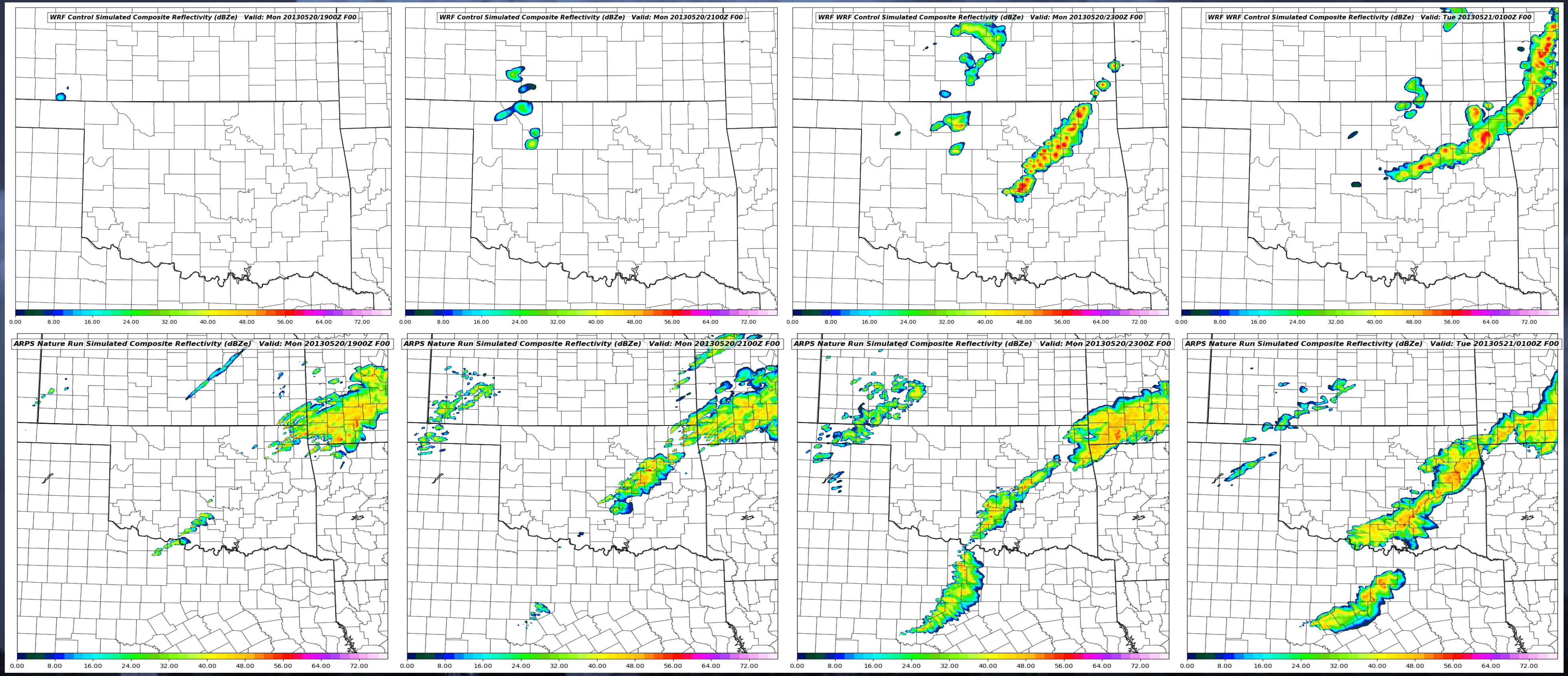


Numerical Experiments
WRF Control Run vs. Nature Run

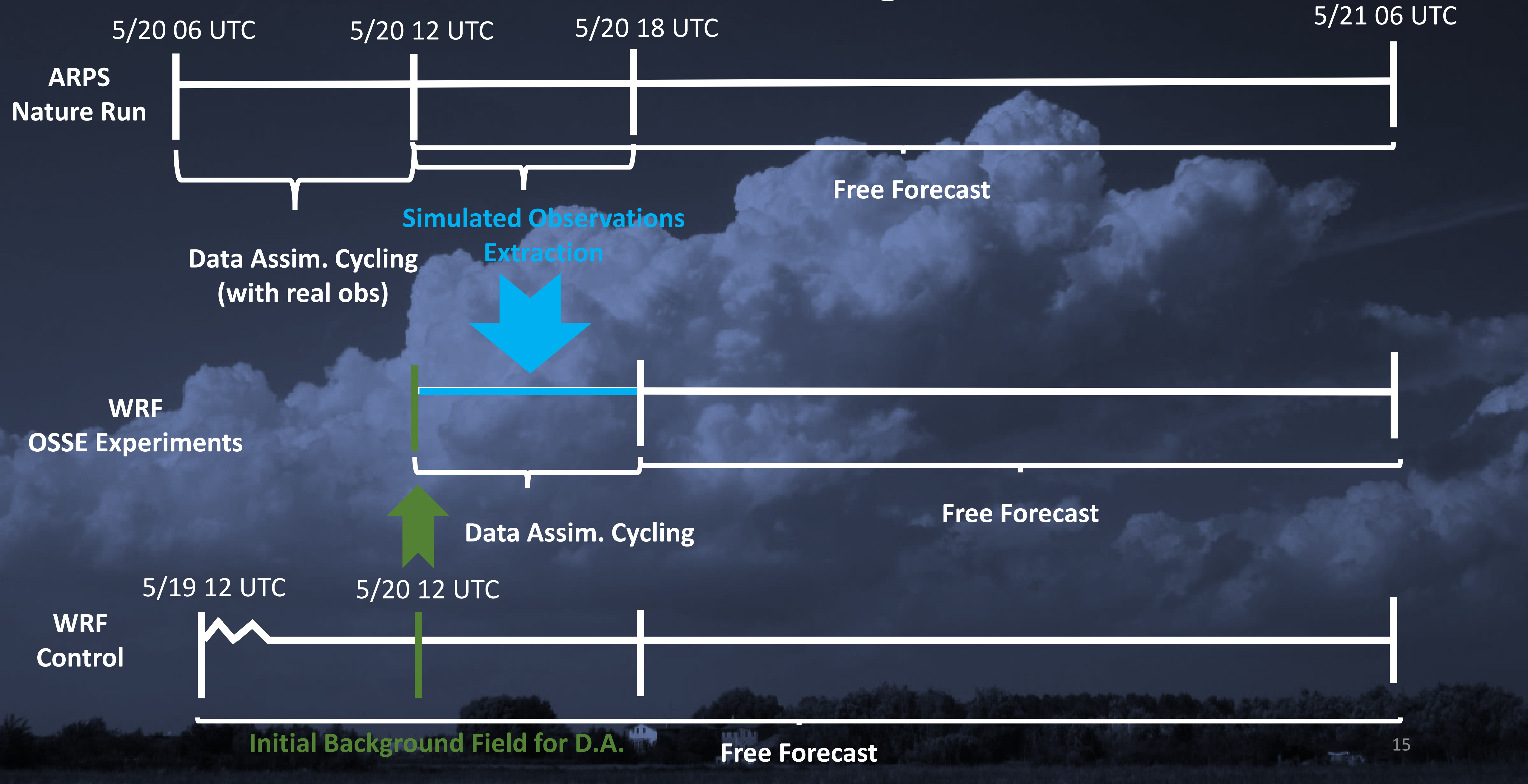
19 UTC | 21 UTC | 23 UTC | 01 UTC

WRF Control

ARPS Nature Run



OSSE Design



5/20 06 UTC
5/20 12 UTC
5/20 18 UTC
5/21 06 UTC
ARPS
Nature Run
Free Forecast
Simulated Observations
Extraction
Data Assim. Cycling
(with real obs)
WRF
OSSE Experiments
Free Forecast
Data Assim. Cycling
5/19 12 UTC
5/20 12 UTC
WRF
Control
Initial Background Field for D.A.
Free Forecast

Numerical Experiments
Data Assimilation

- Data analysis performed with the ARPS Data Assimilation System (ADAS)
  - Follows a process similar to Watson (2010) and Case et al. (2006)

- Data analysis cycling begins at 12 UTC on May 20, and is cycled hourly until 18 UTC.
  - Free forecast for OSSE experiments begins at 18 UTC.

- Observations are assimilated at different intervals based on type.

DA Cycling and Data Input

Time (UTC)	12	13	14	15	16	17	18
UAV	X	X	X	X	X	X	X
Mesonet	X	X	X	X	X	X	X
FNL	X			X			X

Numerical Experiment #1: Maximum Flight Altitude (MFA)

Current FAA restrictions only allow for a UAV to fly to 400 ft AGL, but is this enough to make an impact on the analysis and forecast?

Which level makes the optimal positive impact to PBL analyses and forecasts?

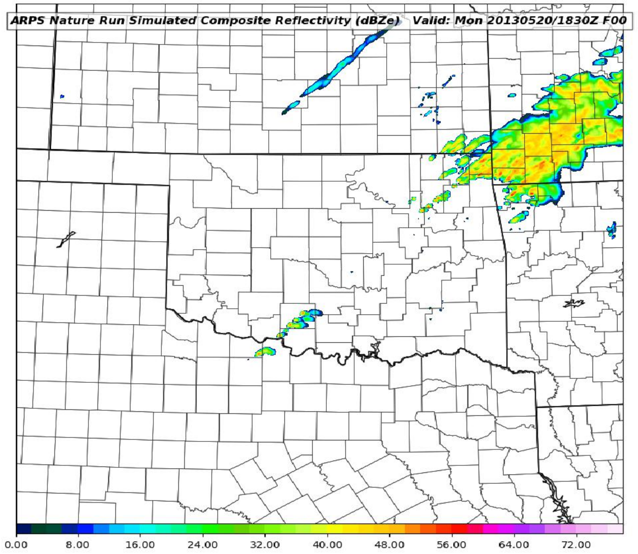
First OSSE Experiment: Create forecasts using UAV data collected through a depth of:

- 400 ft AGL
- 1 km AGL
- 2 km AGL
- 3 km AGL
- One test performed using no UAV data ("No UAV" test)

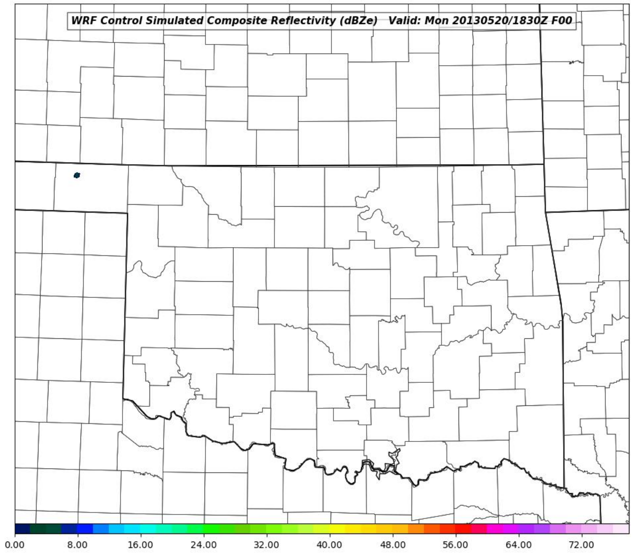
MFA Results: Composite Reflectivity

MFA Results: Comp. Reflectivity 1830 UTC

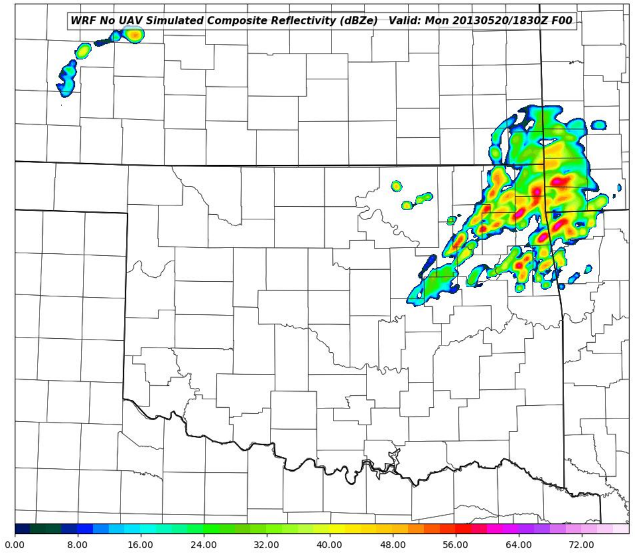
Nature Run



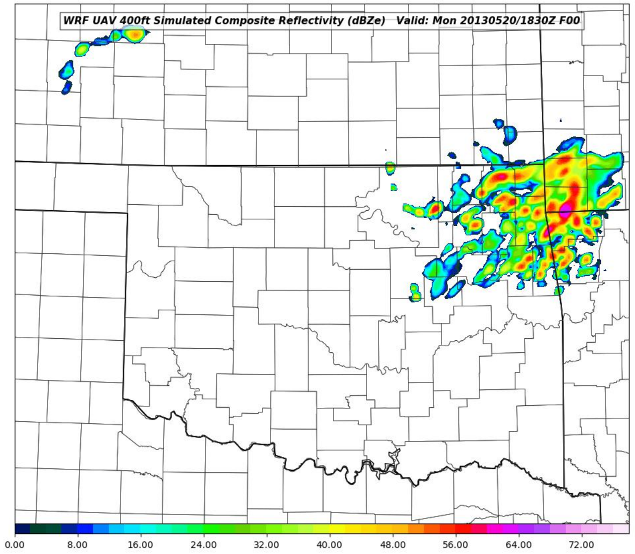
WRF Control

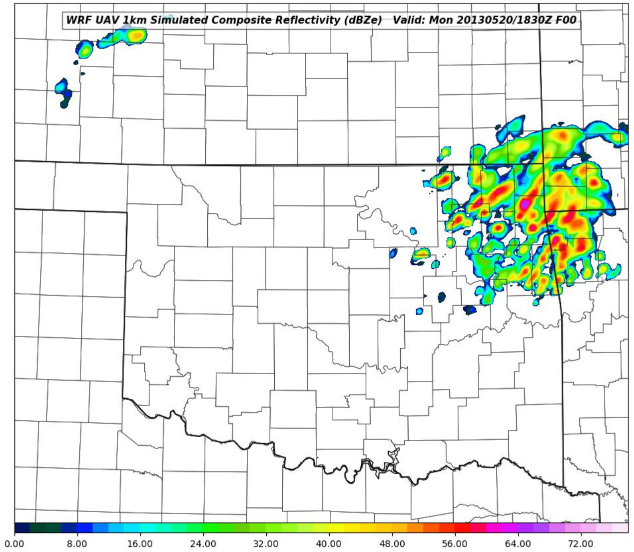


No UAV

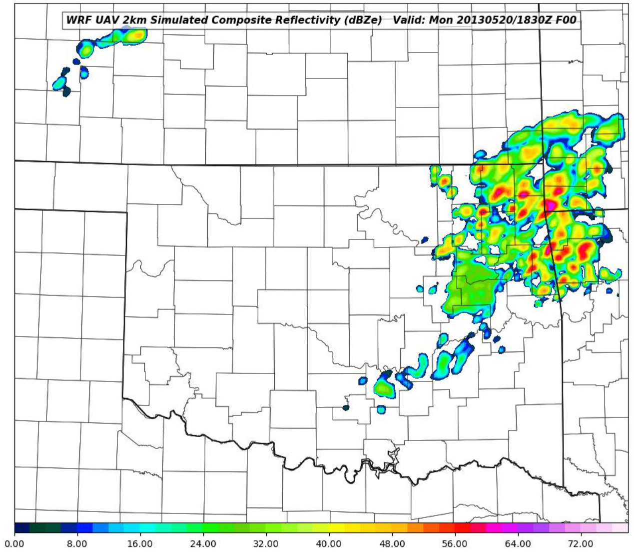


UAV 400 ft

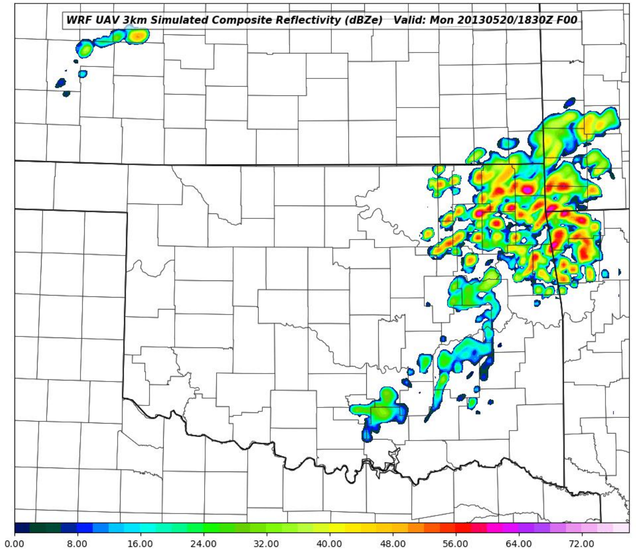




UAV 1km



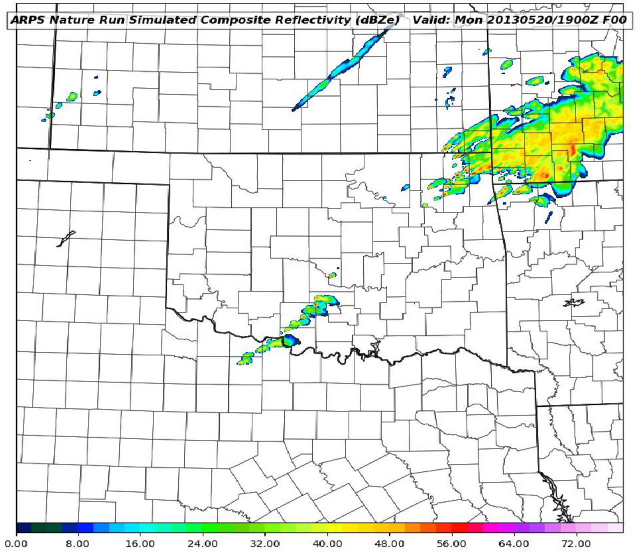
UAV 2km



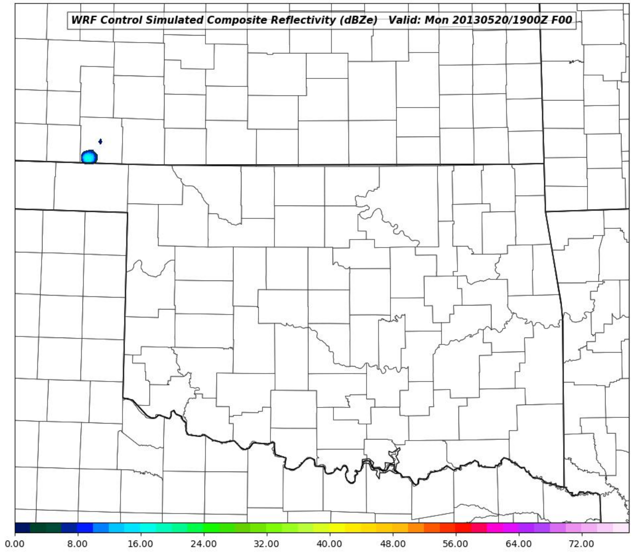
UAV 3km

MFA Results: Comp. Reflectivity 1900 UTC

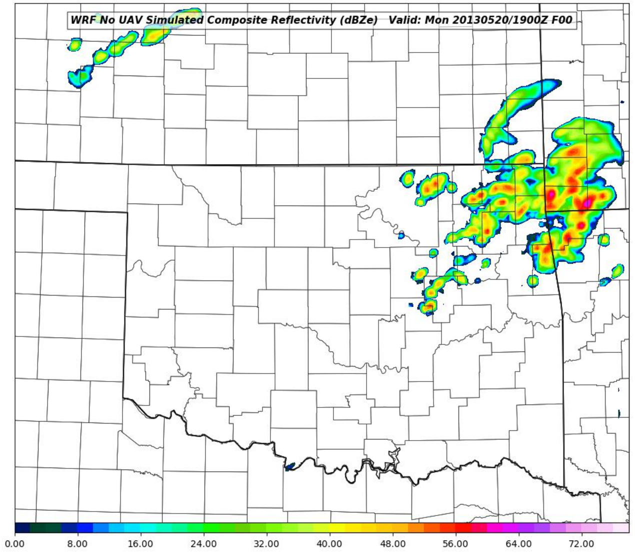
Nature Run



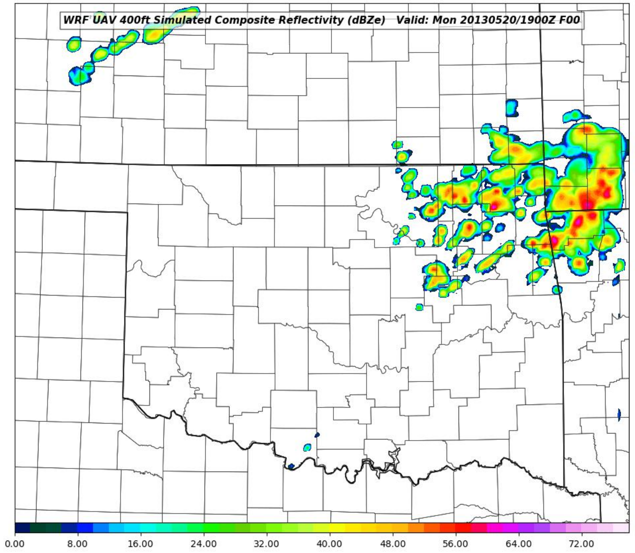
WRF Control

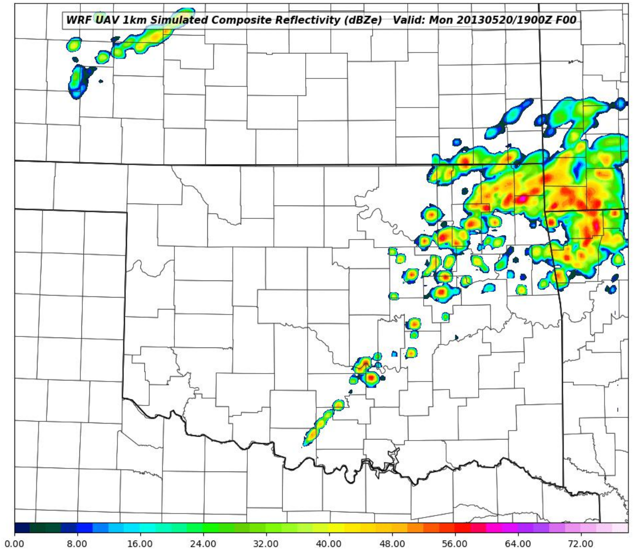


No UAV

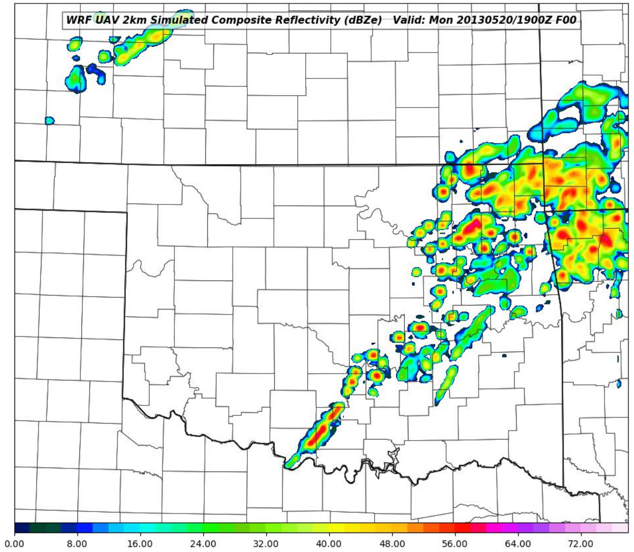


UAV 400 ft

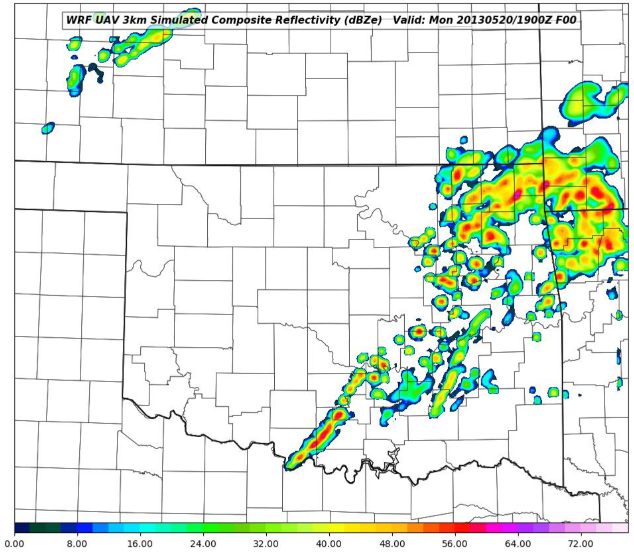




UAV 1km



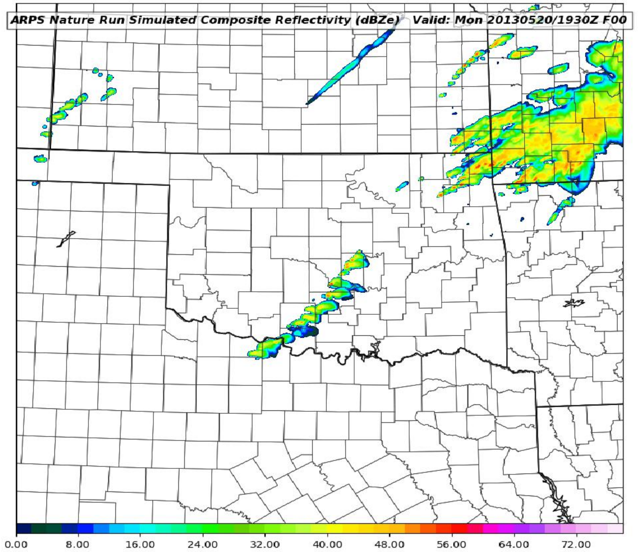
UAV 2km



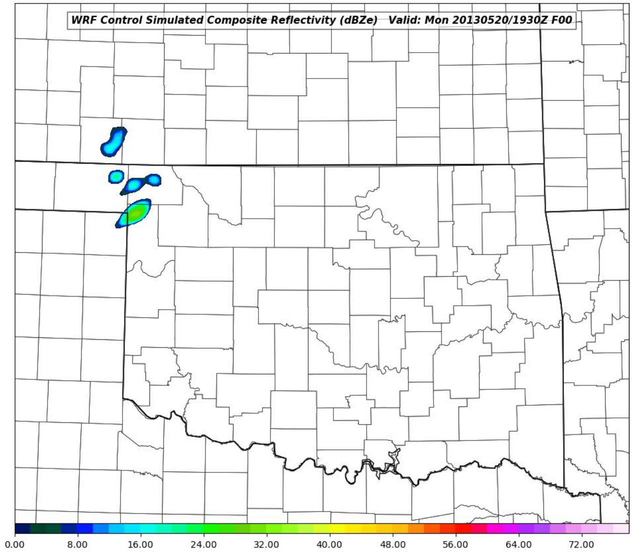
UAV 3km

MFA Results: Comp. Reflectivity 1930 UTC

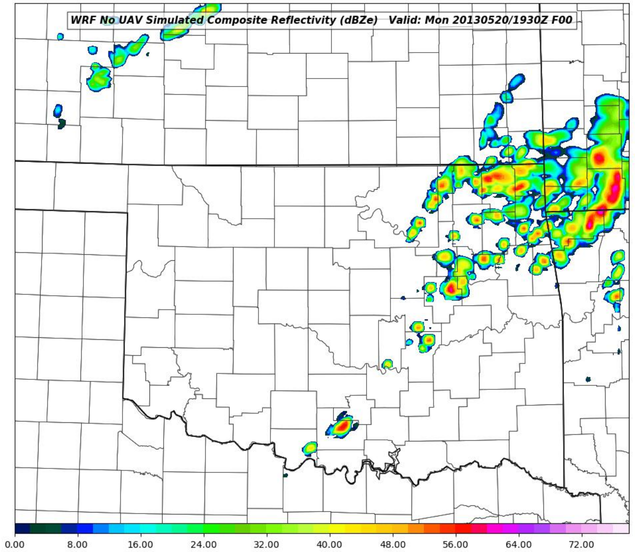
Nature Run



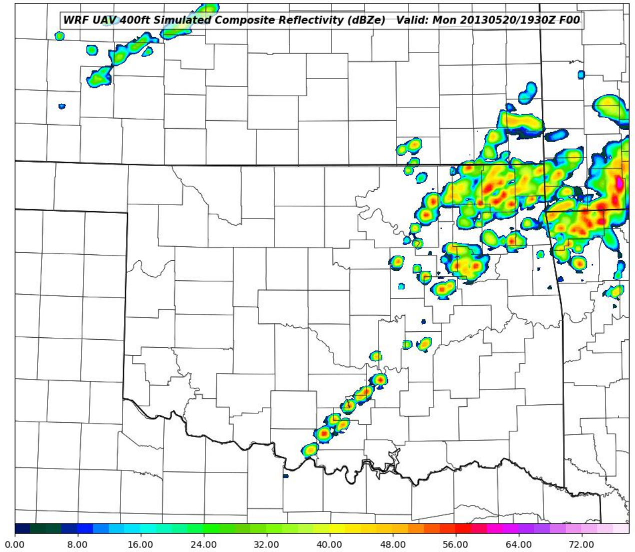
WRF Control

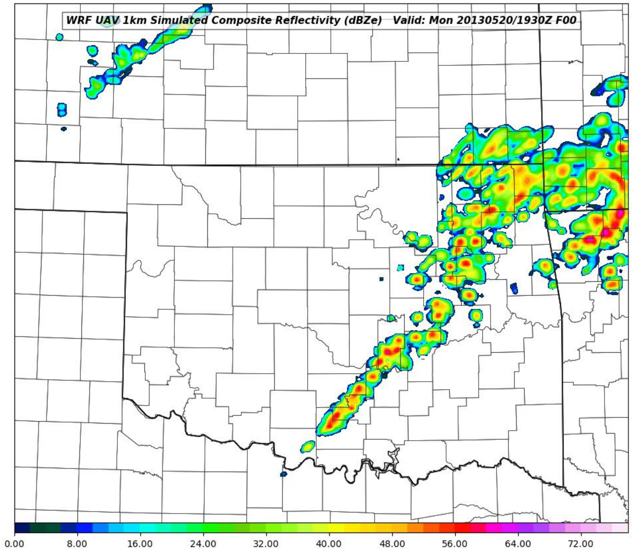


No UAV

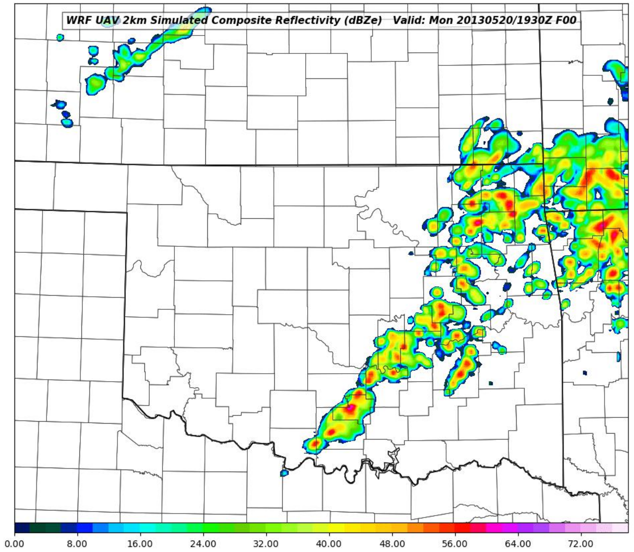


UAV 400 ft

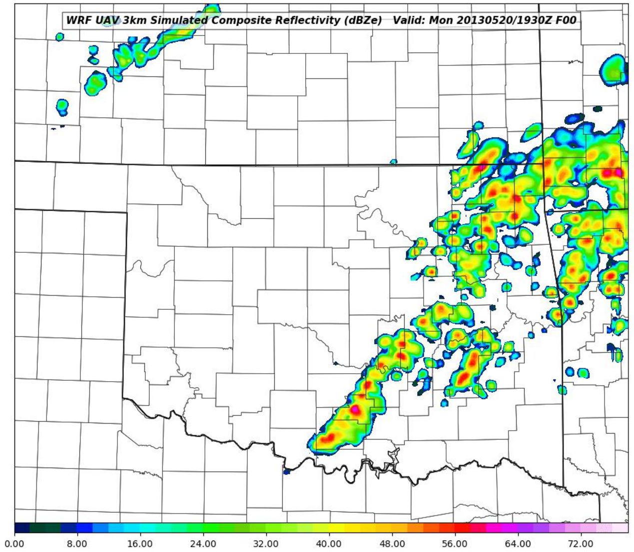




UAV 1km



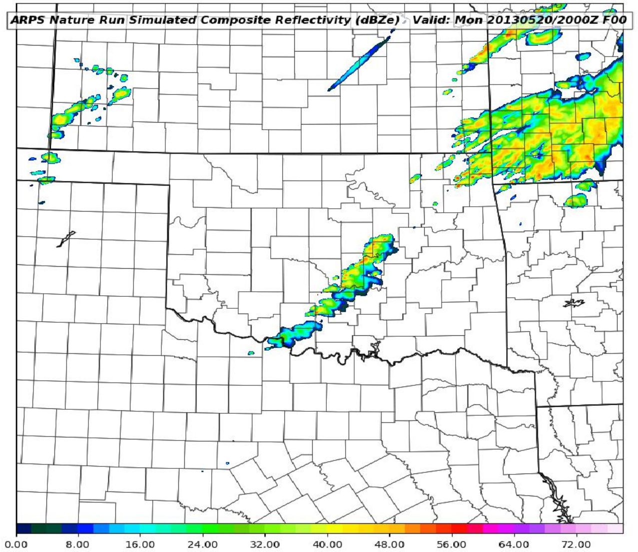
UAV 2km



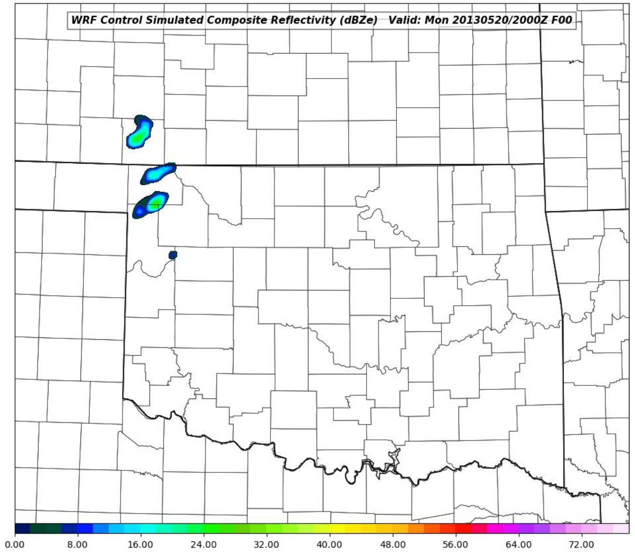
UAV 3km

MFA Results: Comp. Reflectivity 2000 UTC

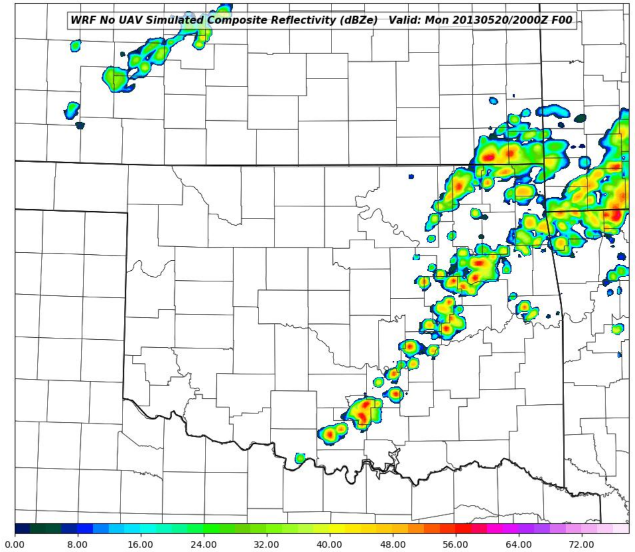
Nature Run



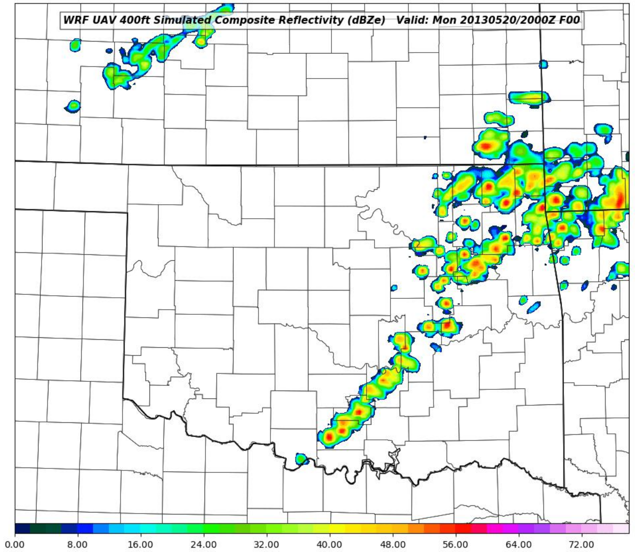
WRF Control

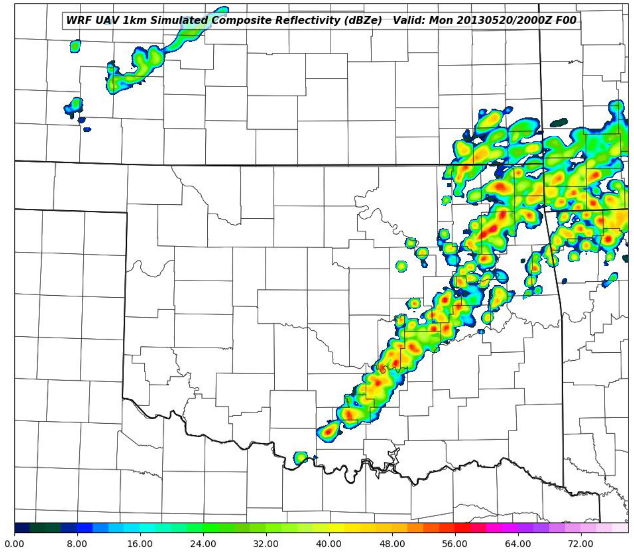


No UAV

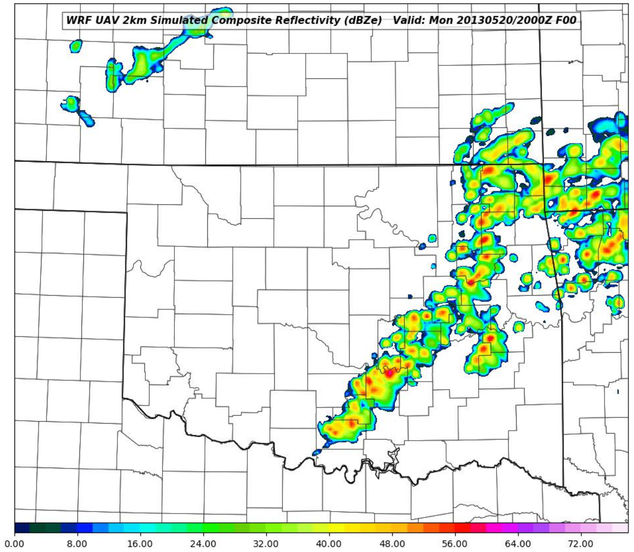


UAV 400 ft

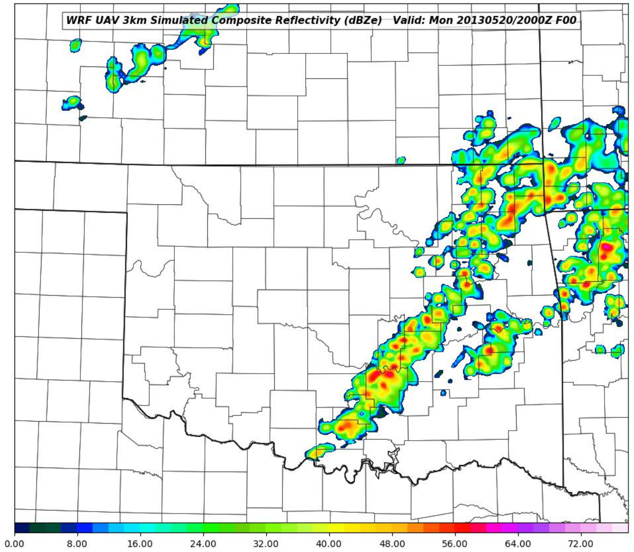




UAV 1km

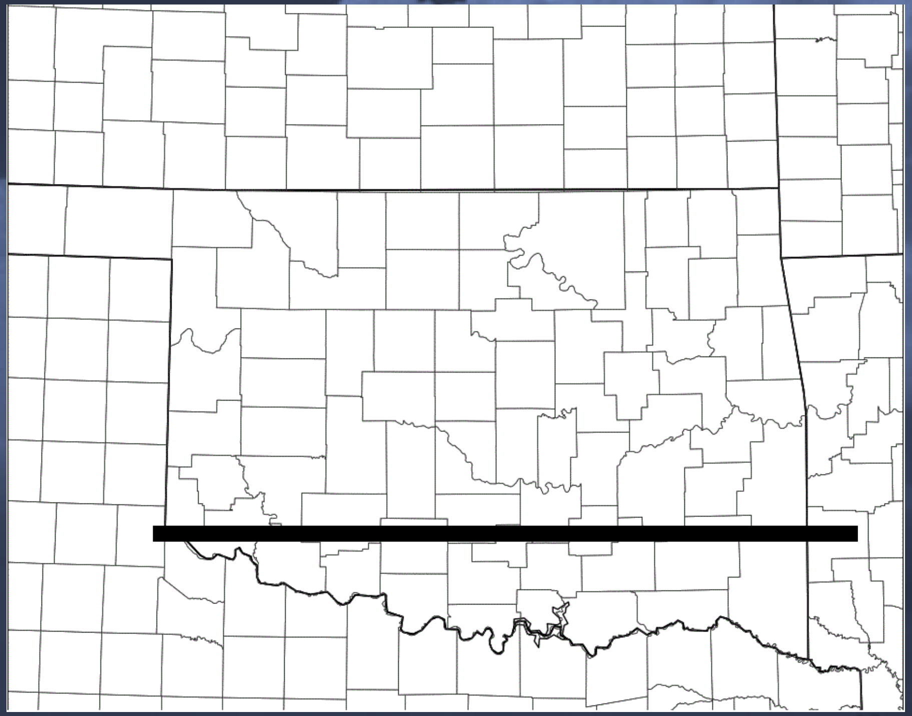


UAV 2km



UAV 3km

MFA Results: Mixing Ratio Cross Sections

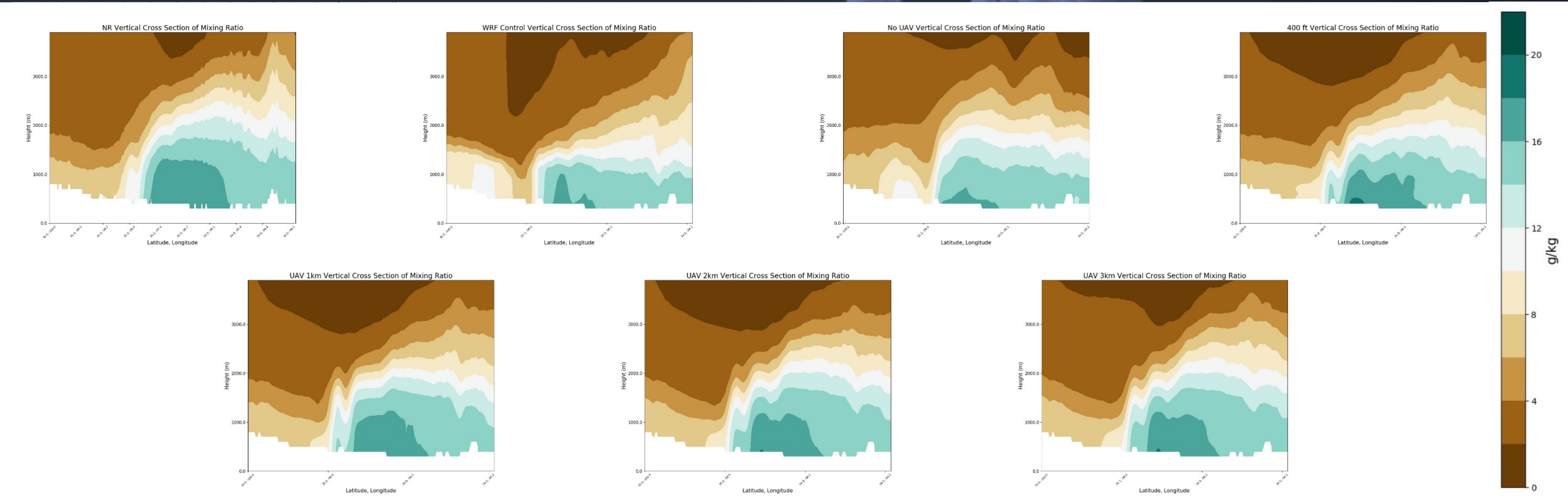


Cross Section Sample Line

Gives view of warm sector PBL and dryline structure

MFA Results: Vertical Cross Sections 18 UTC

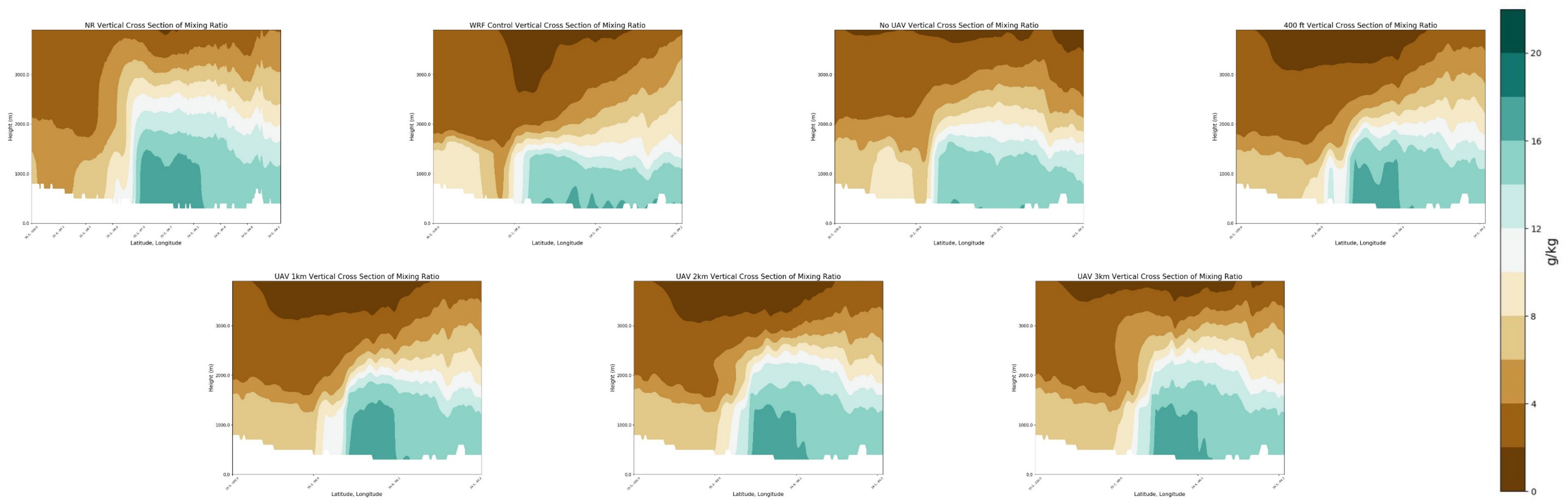
Nature Run | WRF Control | No UAV | UAV 400 ft



UAV 1km | UAV 2km | UAV 3km

MFA Results: Vertical Cross Sections 19 UTC

Nature Run | **WRF Control** | **No UAV** | **UAV 400 ft**



UAV 1km | **UAV 2km** | **UAV 3km**

Numerical Experiment #2: Network Density

In an effort to reduce the cost of a 3-D Mesonet, it is valuable to identify the lowest number of stations that will still provide an improved forecast.

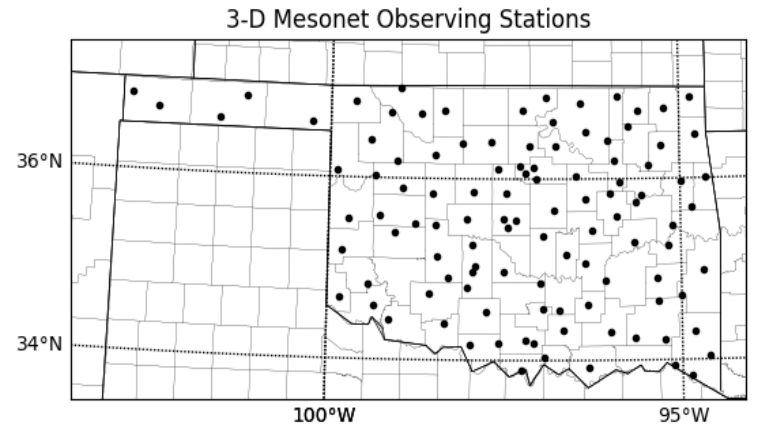
Currently, there are 110 possible 3-D Mesonet locations, but do we need that many?

Second OSSE Experiment: Create forecasts using UAV data collected from 1 km AGL from:

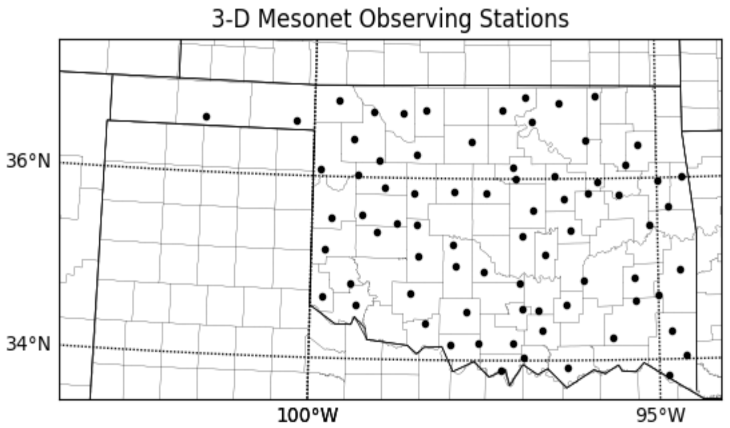
- **110 stations**
- **75 stations**
- **50 stations**
- **25 stations**
- **10 stations**

Numerical Experiment #2: Network Density

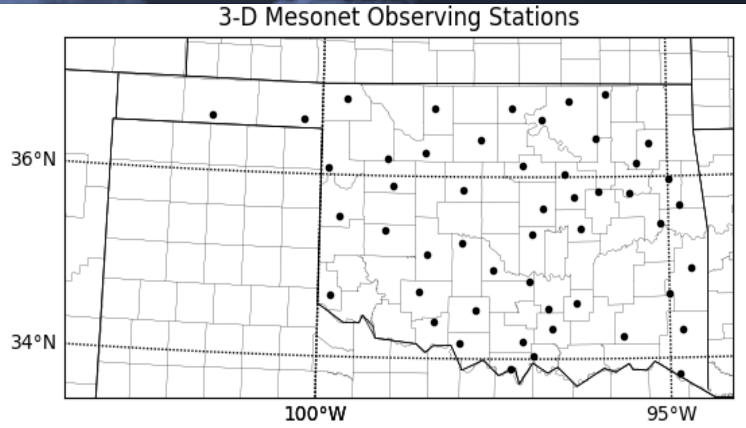
110 Stations

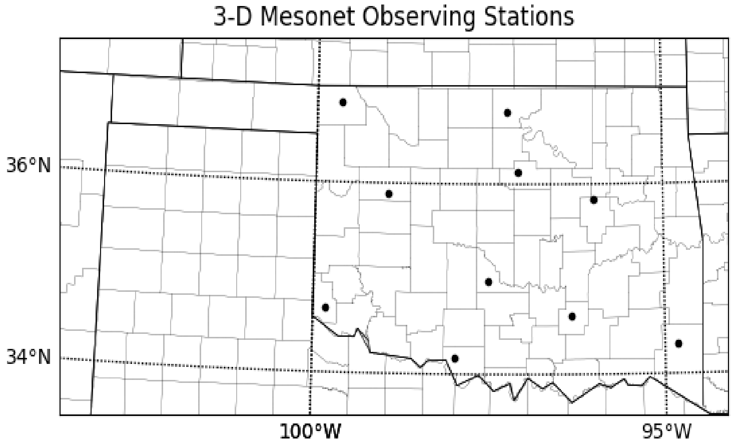


75 Stations

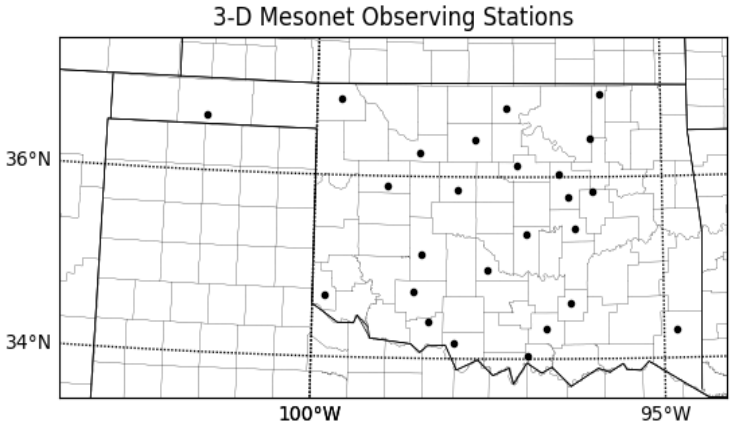


50 Stations





25 Stations

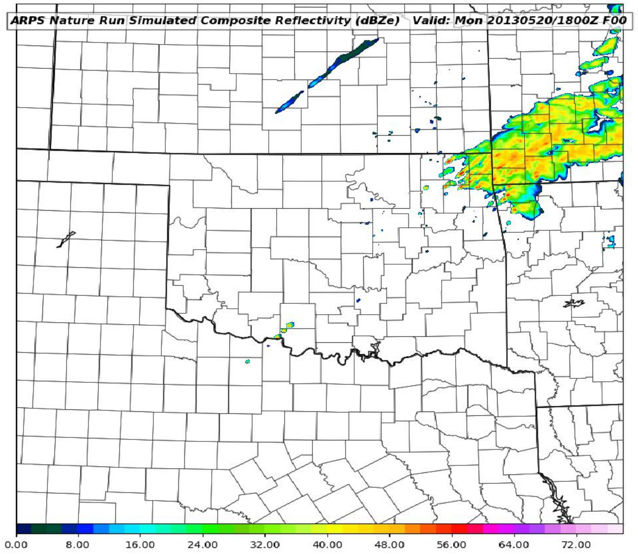


10 Stations

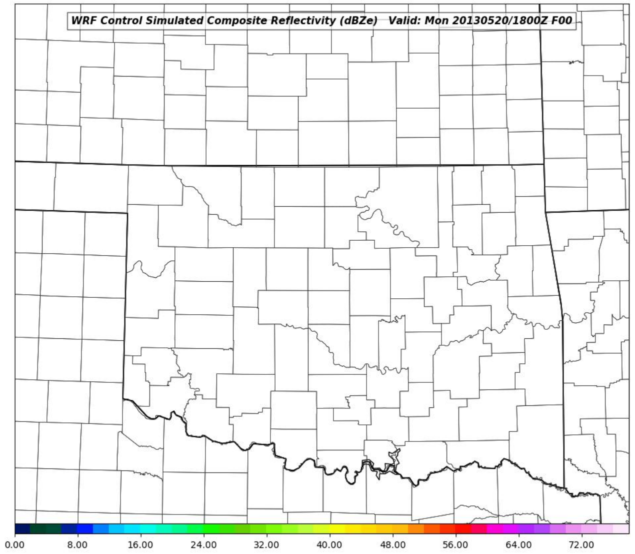
Network Density Results: Composite Reflectivity

Net. Density Results: Comp. Reflectivity 1800 UTC

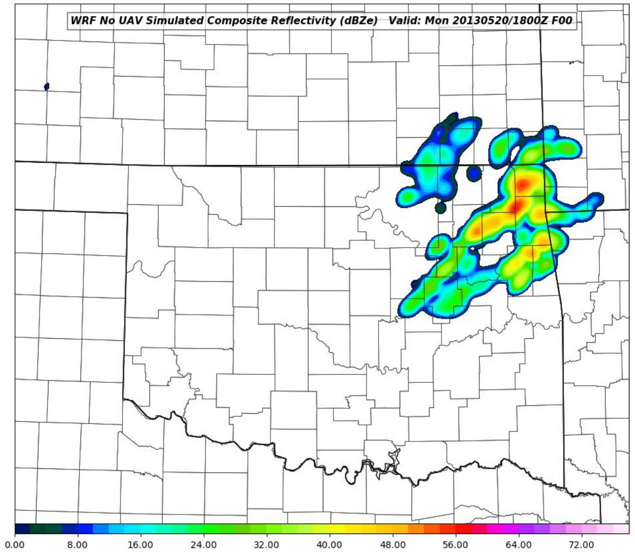
Nature Run



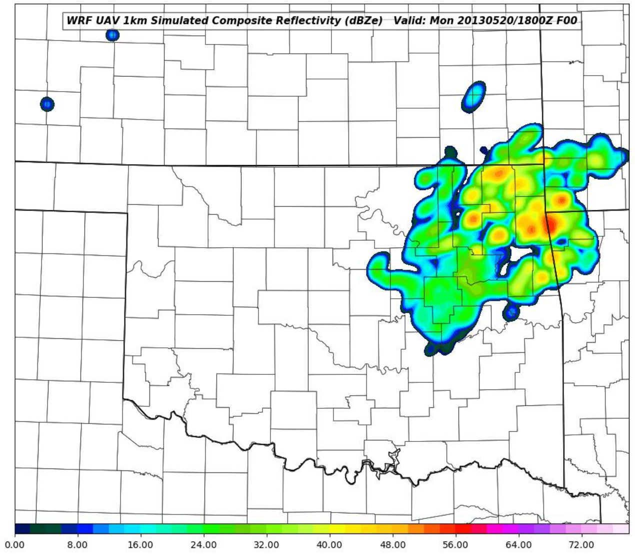
WRF Control

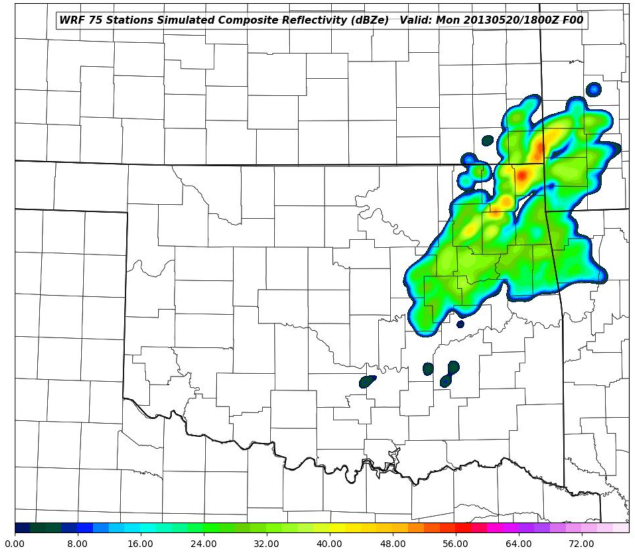


No UAV

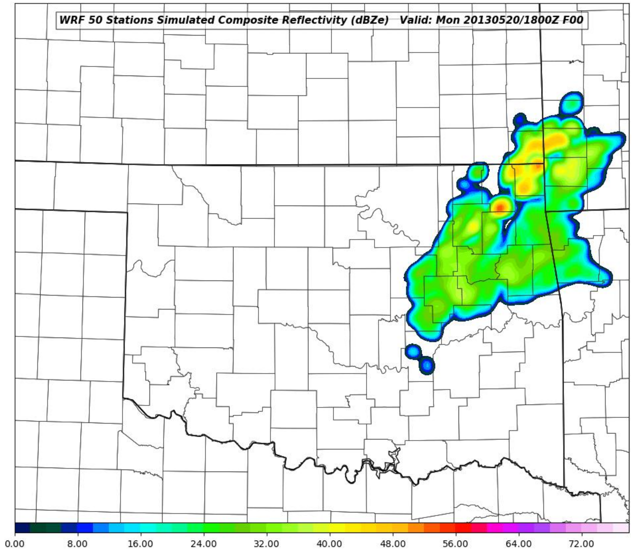


110 Stations

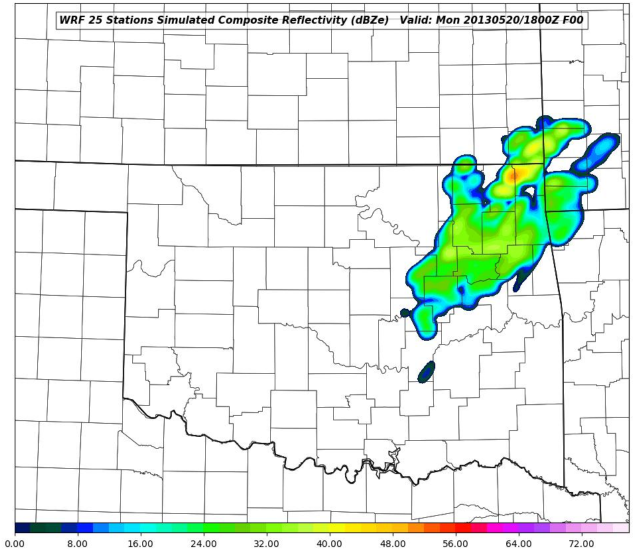




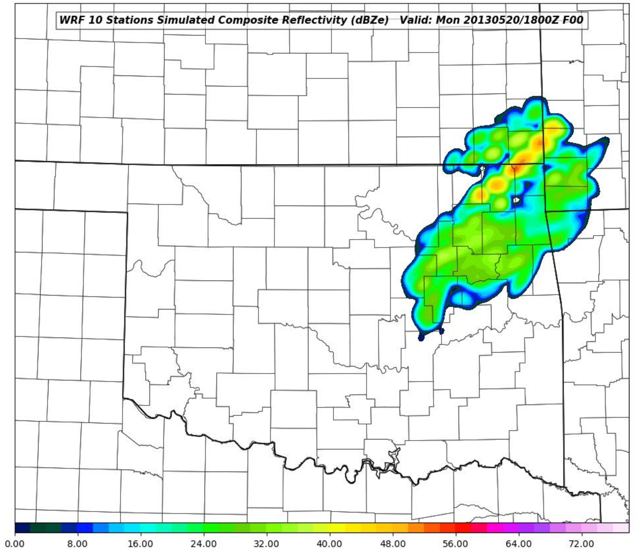
75 Stations



50 Stations



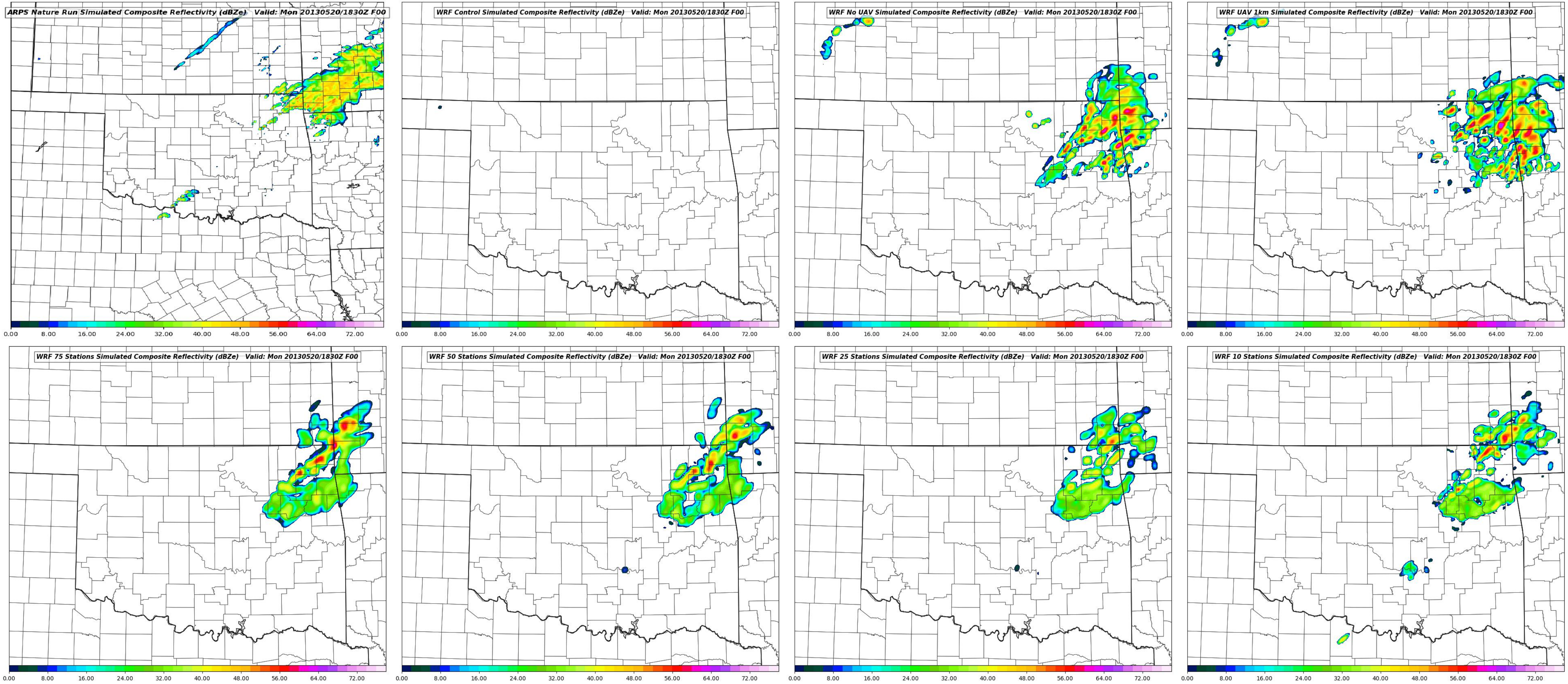
25 Stations



10 Stations

Net. Density Results: Comp. Reflectivity 1830 UTC

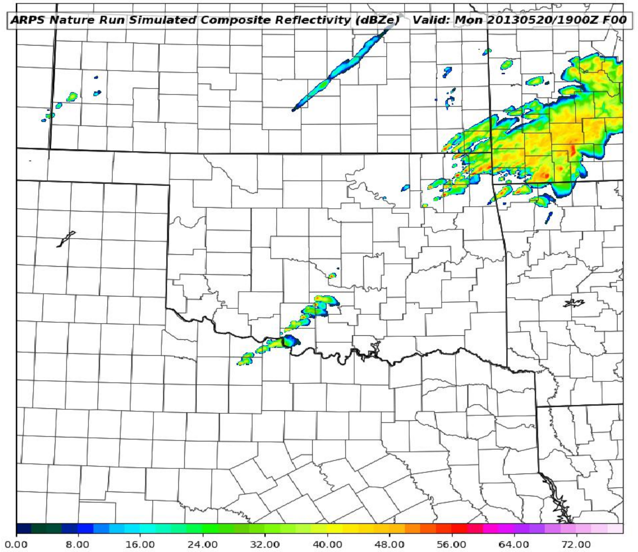
Nature Run | WRF Control | No UAV | 110 Stations

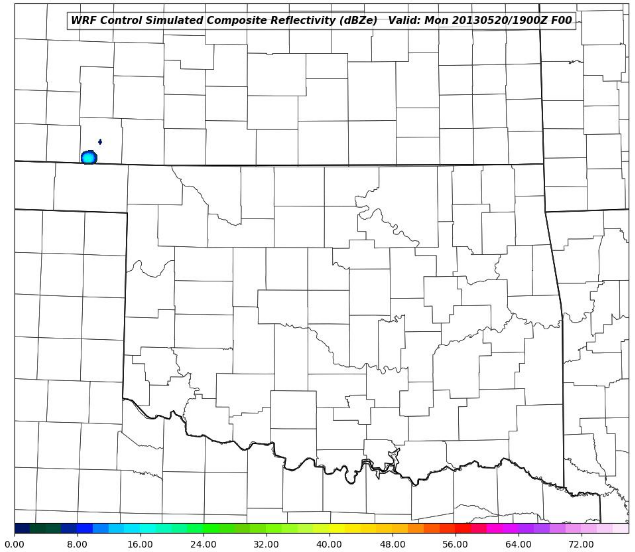


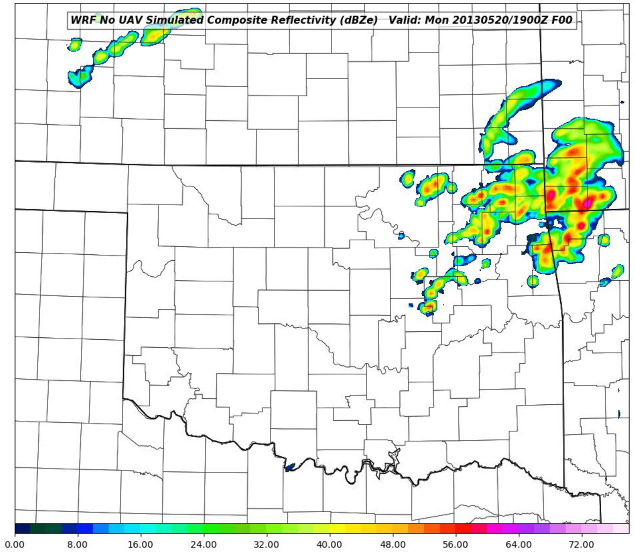
75 Stations | 50 Stations | 25 Stations | 10 Stations

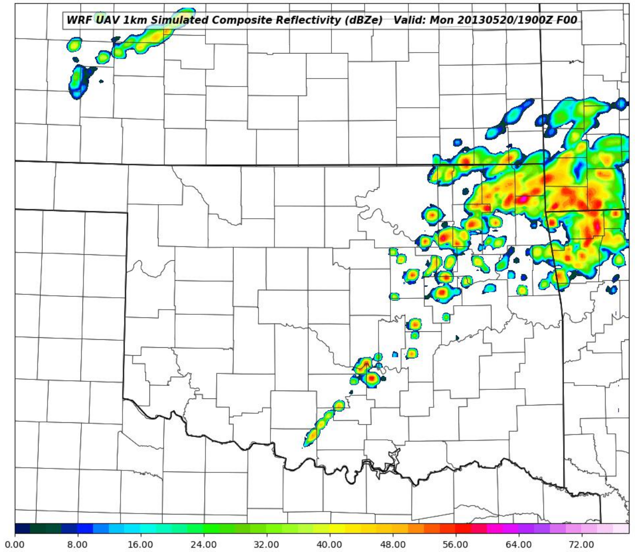
Net. Density Results: Comp. Reflectivity 1900 UTC

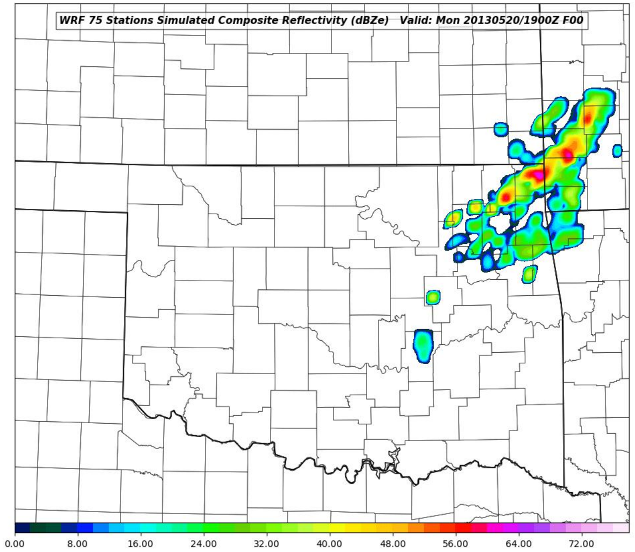
Nature Run | **WRF Control** | **No UAV** | **110 Stations**

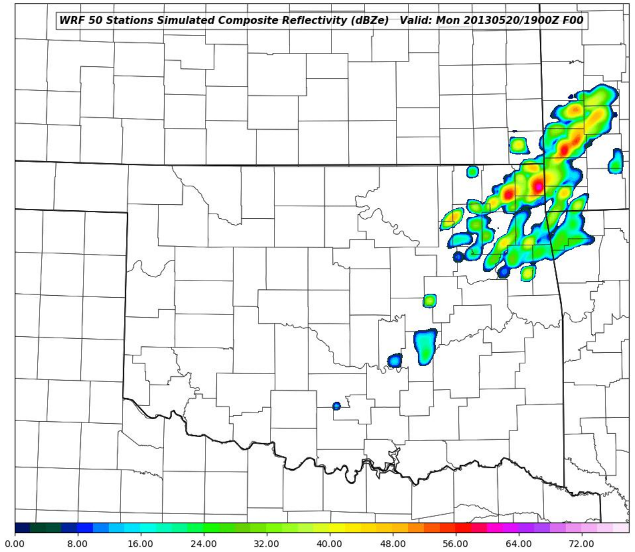


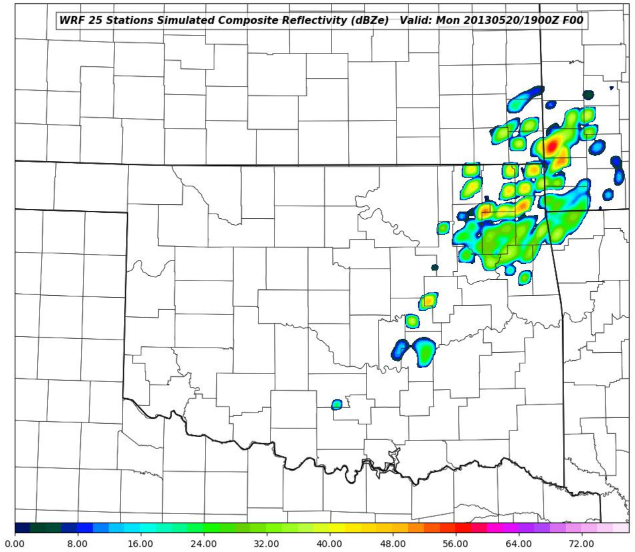


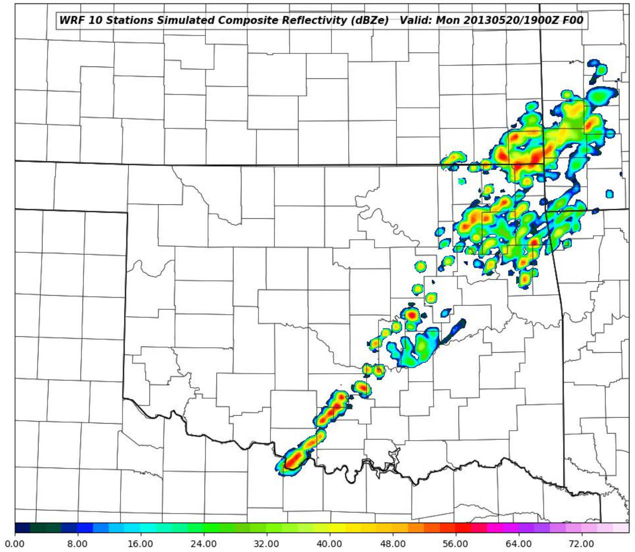








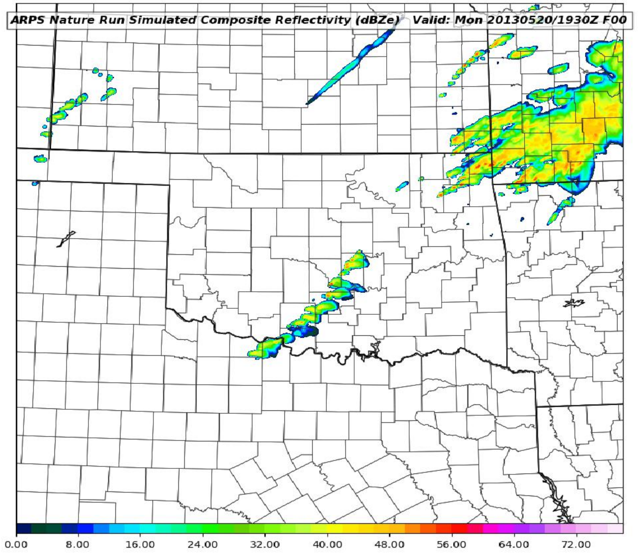


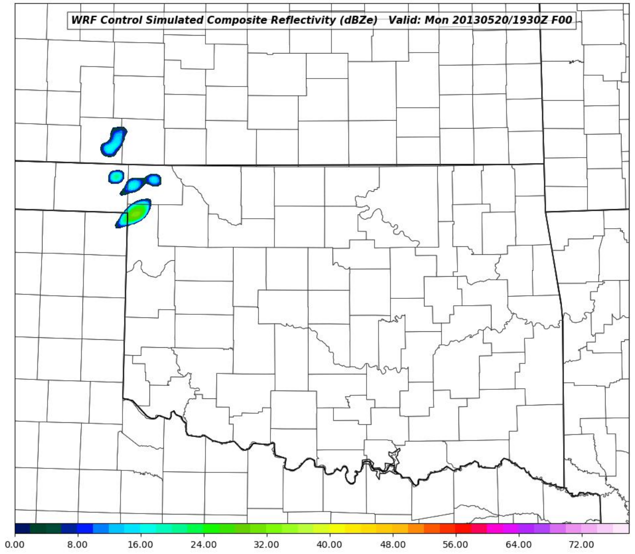


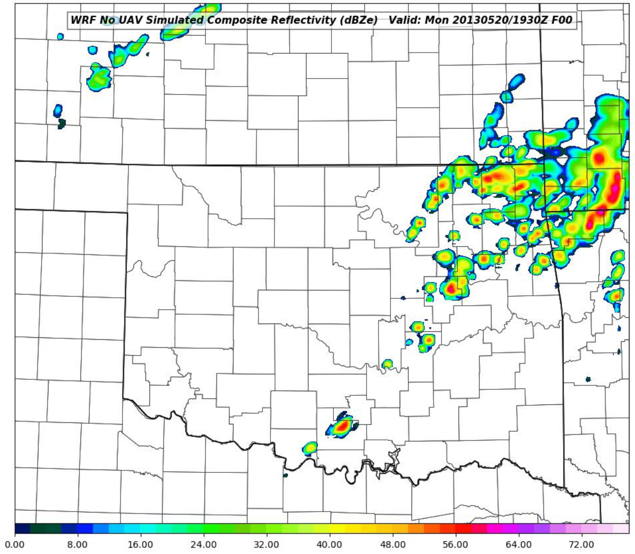
75 Stations | **50 Stations** | **25 Stations** | **10 Stations**

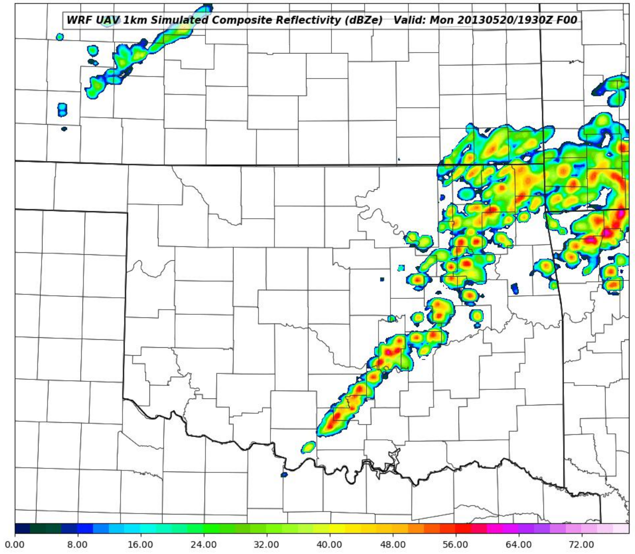
Net Density Results: Comp. Reflectivity 1930 UTC

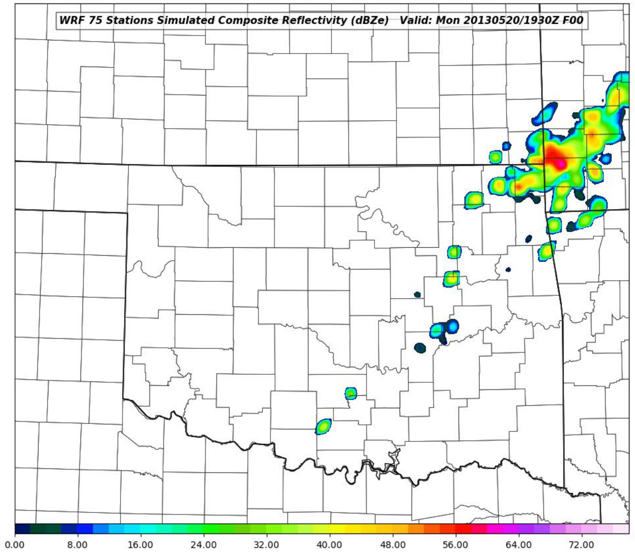
Nature Run | **WRF Control** | **No UAV** | **110 Stations**

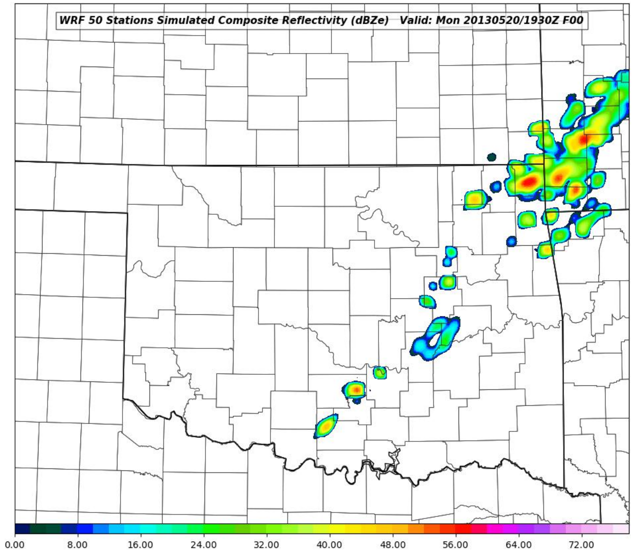


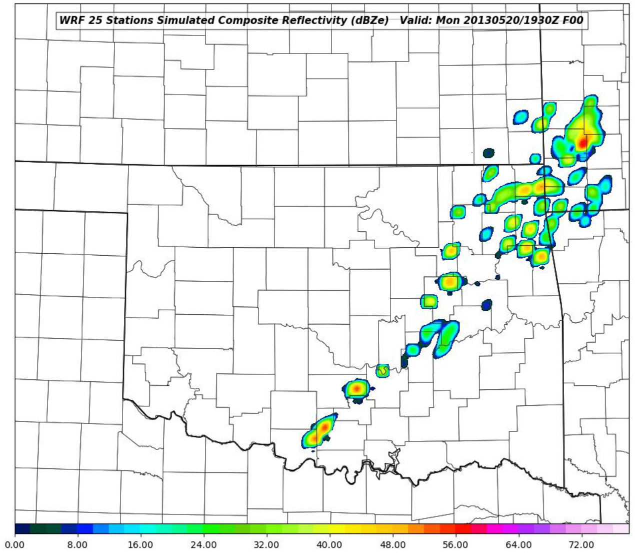


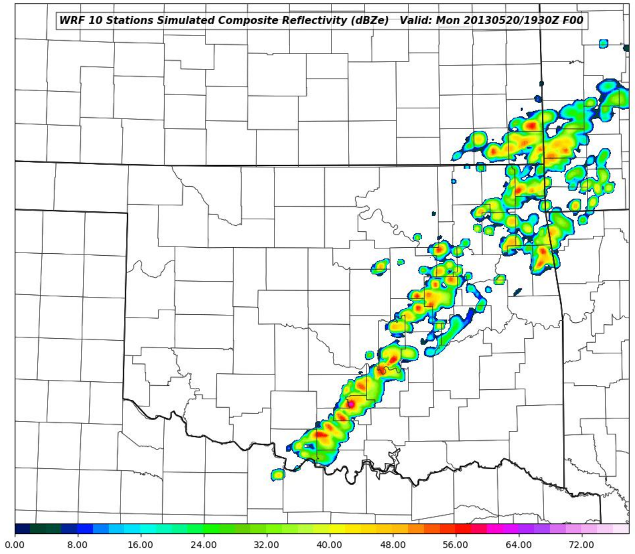








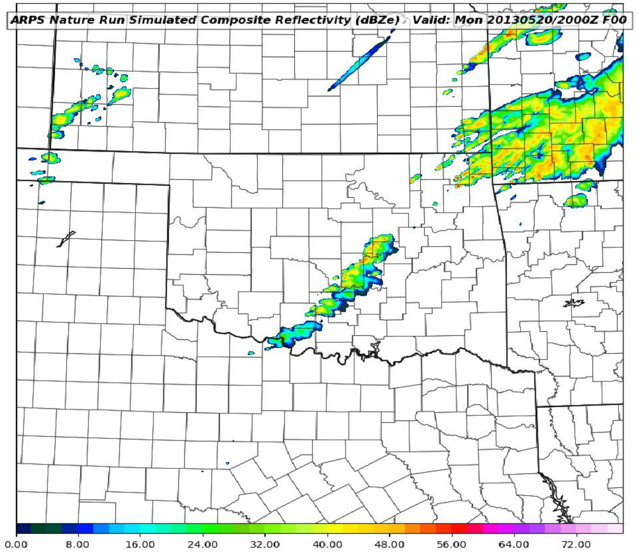




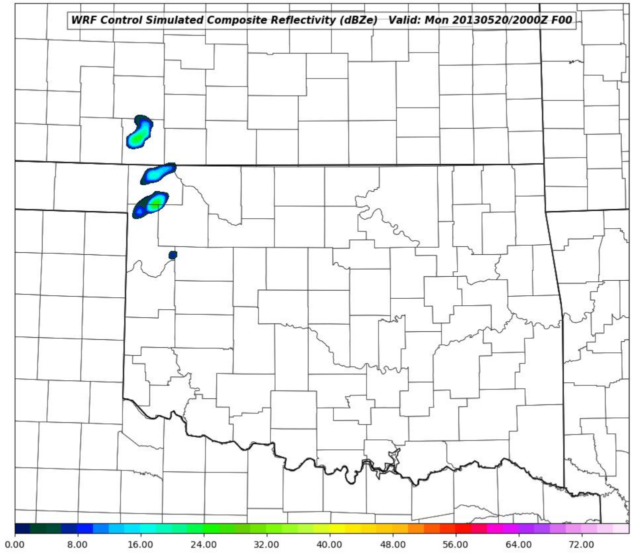
75 Stations | **50 Stations** | **25 Stations** | **10 Stations**

Net. Density Results: Comp. Reflectivity 2000 UTC

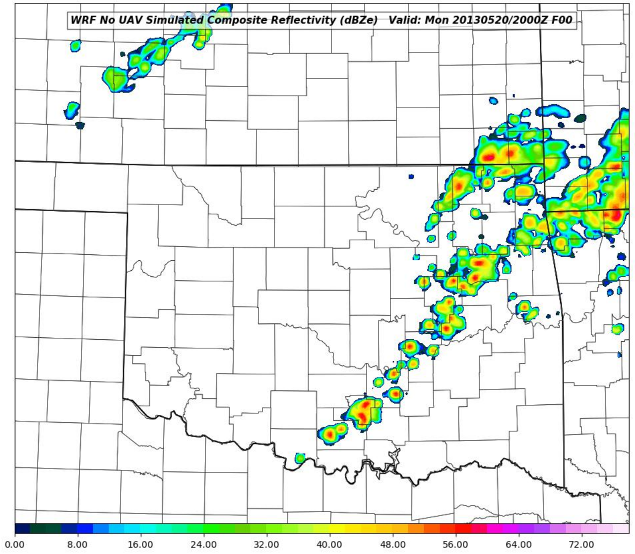
Nature Run



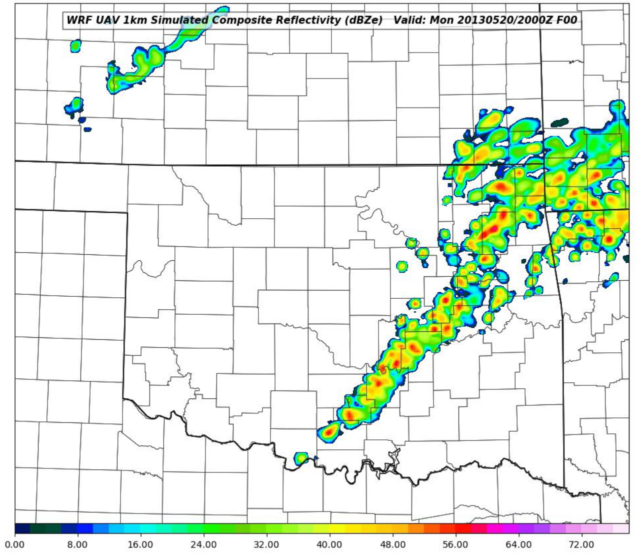
WRF Control

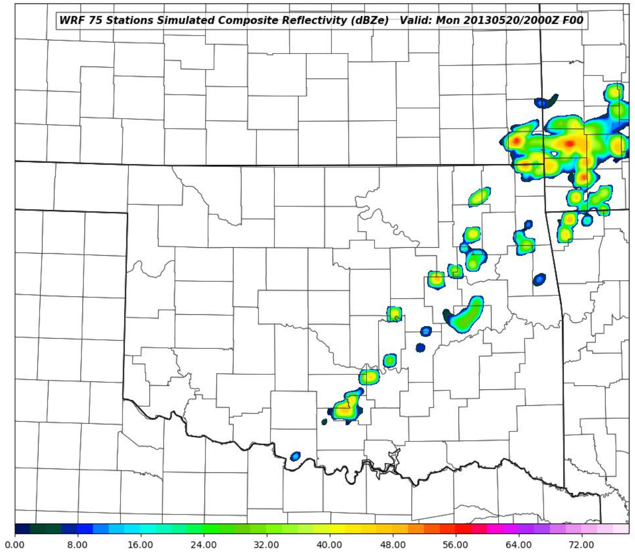


No UAV

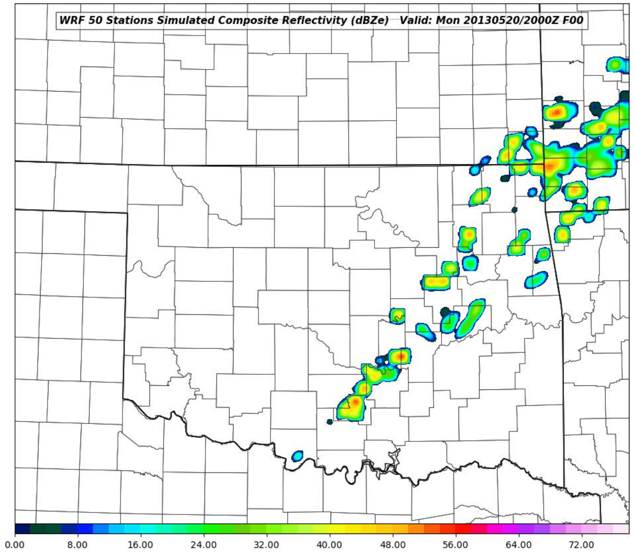


110 Stations

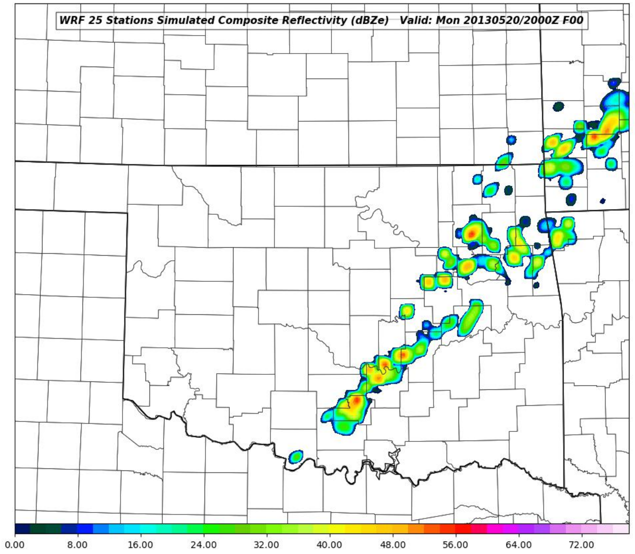




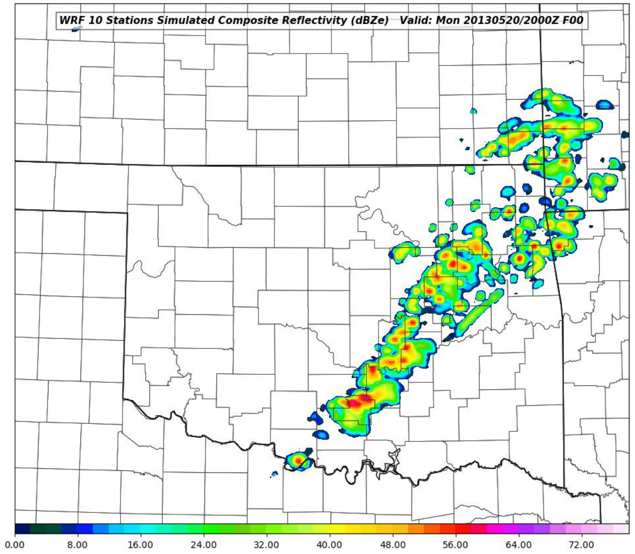
75 Stations



50 Stations

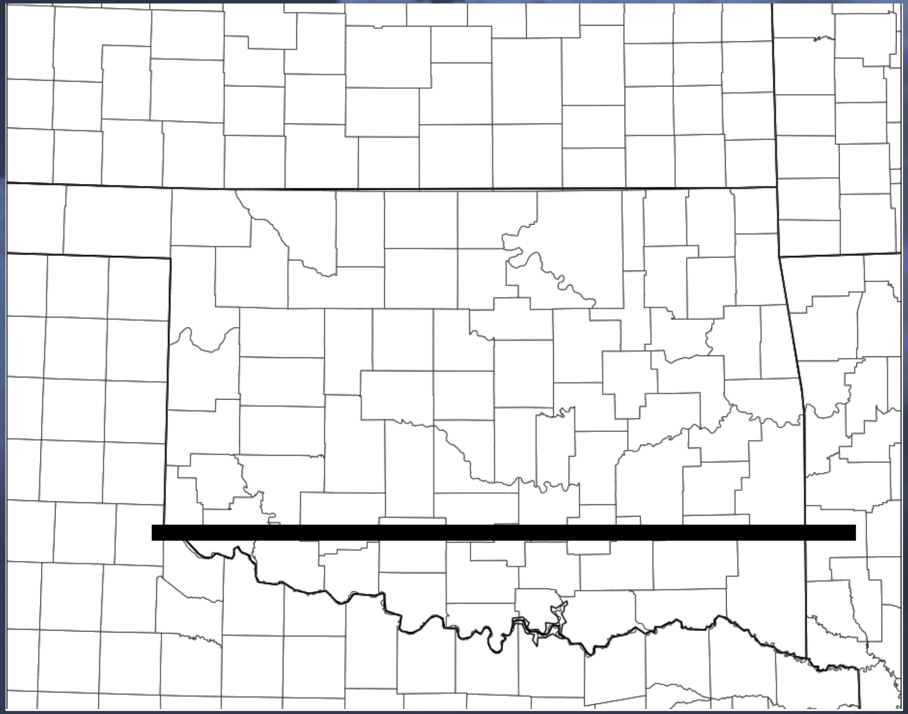


25 Stations



10 Stations

Network Density Results: Mixing Ratio Cross Sections

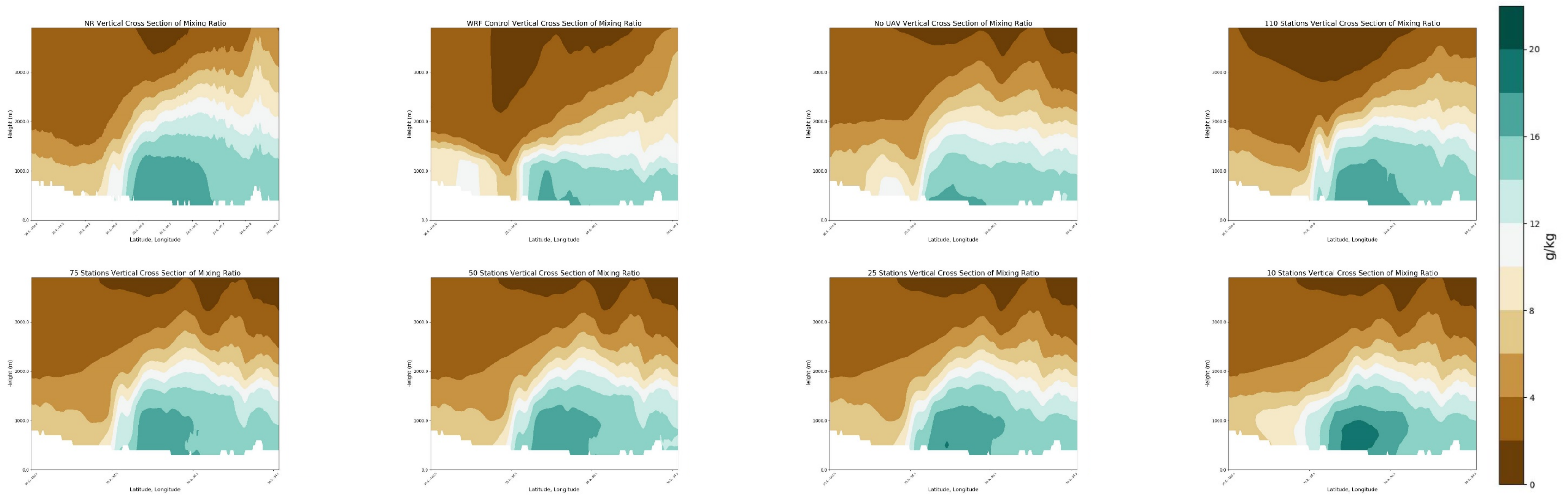


Cross Section Sample Line

Gives view of warm sector PBL and dryline structure

Net. Density Results: Vertical Cross Sections 18 UTC

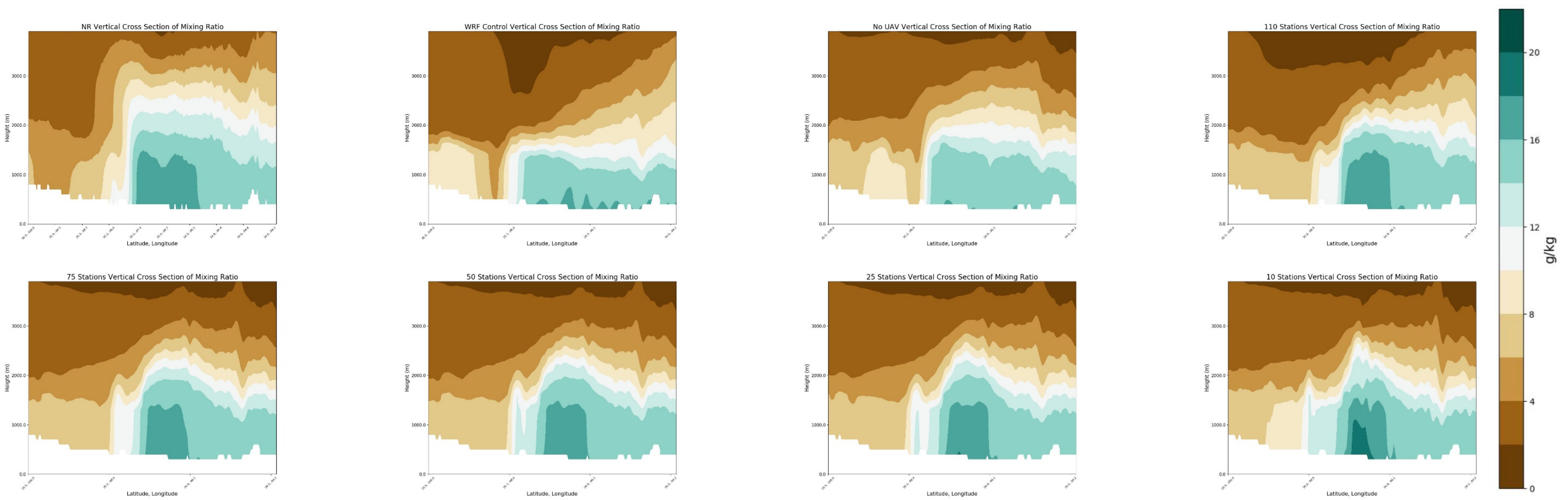
Nature Run | **WRF Control** | **No UAV** | **110 Stations**



75 Stations | **50 Stations** | **25 Stations** | **10 Stations**

Net. Density Results: Vertical Cross Sections 19 UTC

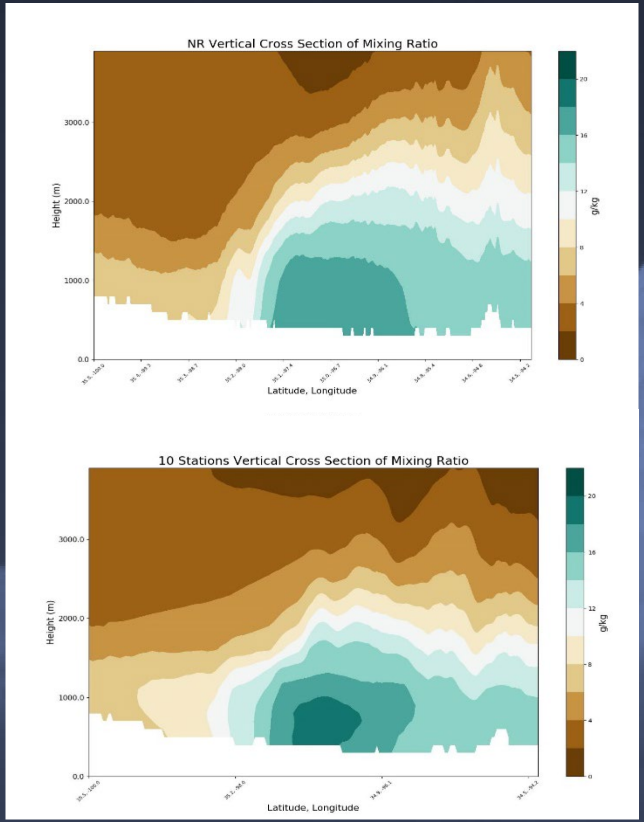
Nature Run | **WRF Control** | **No UAV** | **110 Stations**



75 Stations | **50 Stations** | **25 Stations** | **10 Stations**

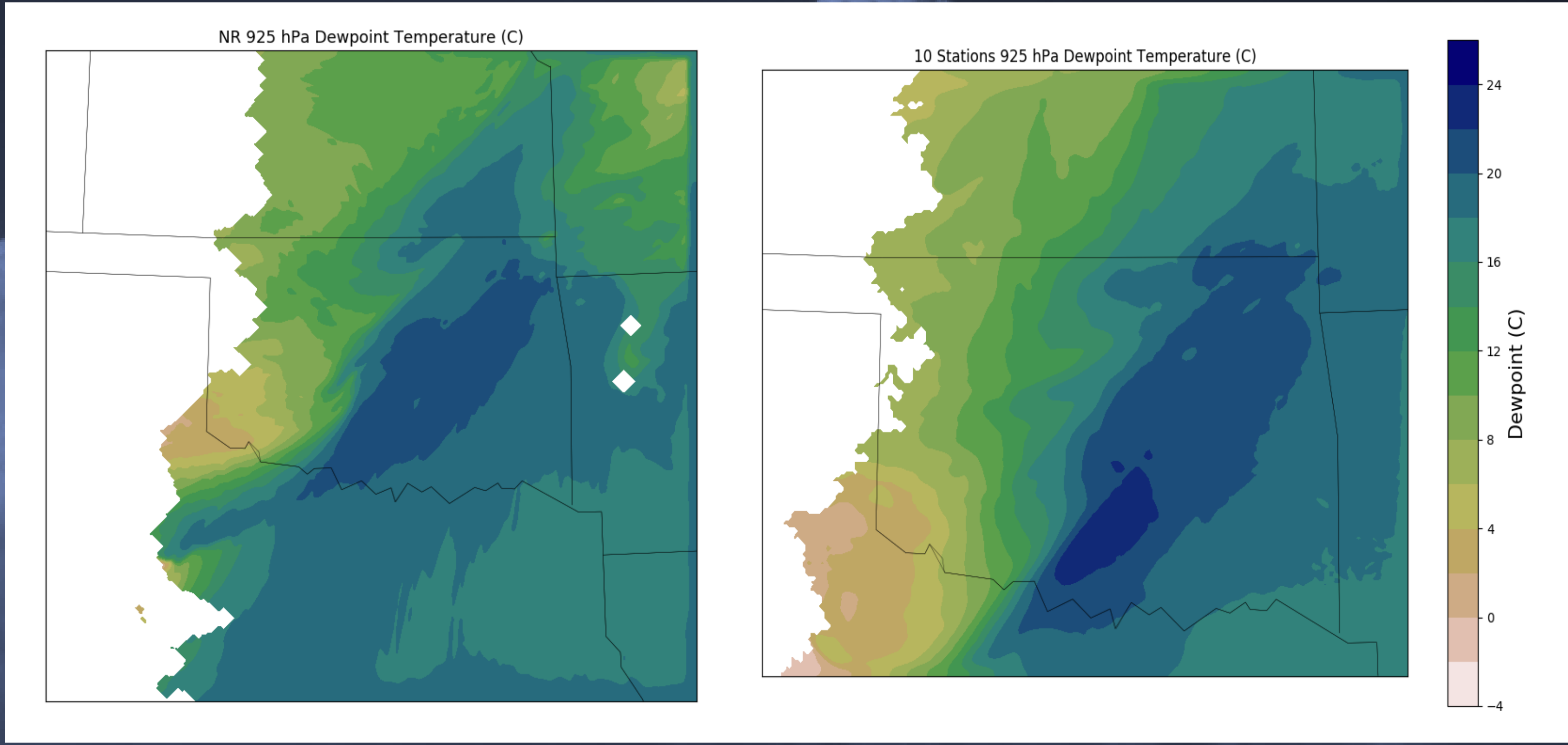
Excess Moisture?

Nature Run



10 Stations

1800 UTC 925 hPa dewpoint temperature (C)



Nature Run

10 Stations

Conclusions: MFA

- <u>The addition of UAV observations improves the short term forecast and PBL analysis.</u>

  - The depth of low level moisture is analyzed better with greater depth of UAV obs.
    - This helps with the placement and persistence of instability.

  - This lead to a better convective initiation forecast compared to the No UAV test by up to half an hour (though higher-temporal output may show earlier CI start).

  - However, improved forecast skill is lost after the first 3 hours when non-linear, convective processes begin to dominate.

- <u>Flights up to 1 km may be sufficient.</u>

  - While the 3 km UAV MFA test performed the best, the results between the 1, 2, and 3 km UAV MFA tests were largely similar.
  - This suggests that 1 km may be a fair compromise between 400 ft and 3 km flights.

Conclusions: Network Density

- <u>Higher network density leads to better convective forecast and PBL analysis.</u>

  - The 110 station network performed the best overall, though only slight differences were noted between the 75, 50, and 25 station network tests.
    - All of these were able to capture the PBL moisture structure as well as instability fields fairly well.

  - 10 stations appears to be a lower limit.
    - Worst PBL moisture analysis
    - Poor dryline gradient
    - Contained extra, unrealistic moisture compared to the Nature Run

- <u>There may be a sensitivity to spatial configuration of sites and to moisture observations</u>

Ongoing & Future Work

- Repeating Data Density Experiment
  - Examine sensitivity to analysis parameters
- Test of UAV observation intervals (30 min, 1 hr, 2 hr)
- Calibration OSE using actual Oklahoma Mesonet Observations
- Additional Cases:
  - MCS
  - Winter Precip – Type determination

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