Can a Fleet of Drones Improve Your Weather Forecast? Experiments with 3D Mesonet

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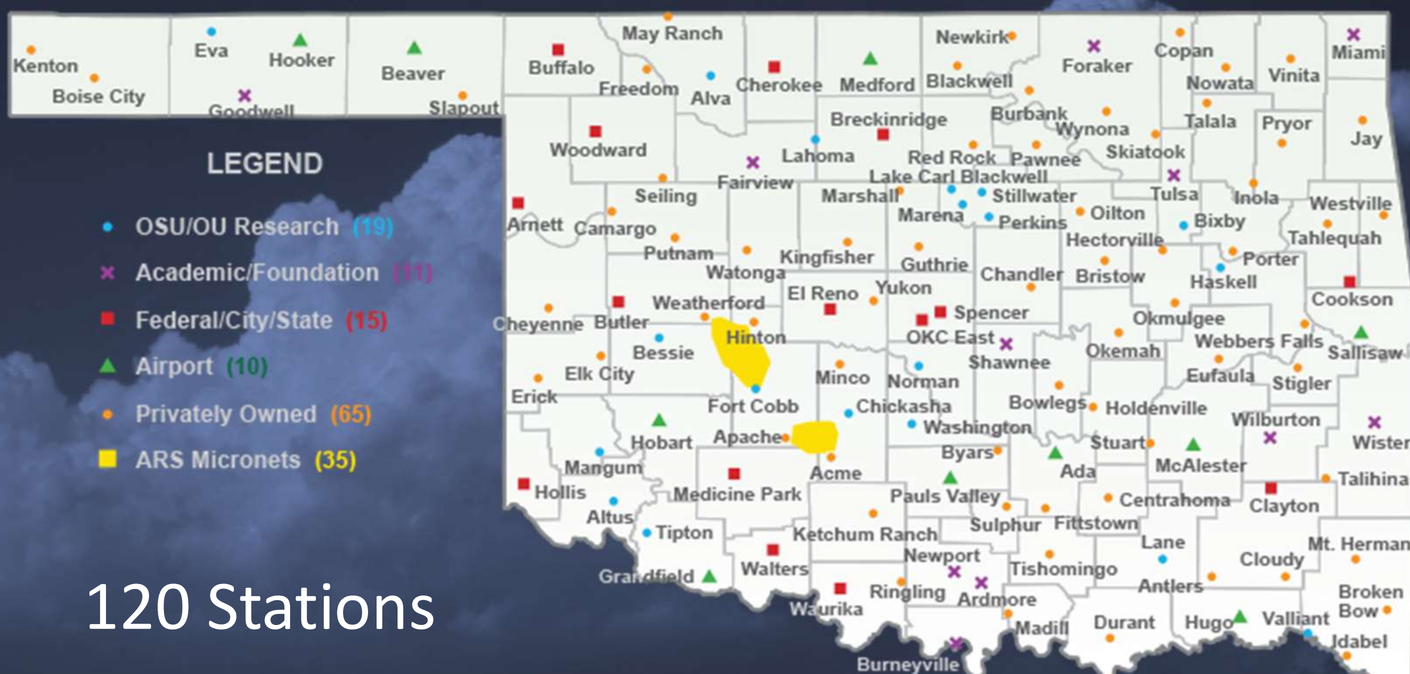
3 – Center for Autonomous Sensing and Sampling

Oklahoma Mesonet



120 Stations

Surface Observations Only

Atmospheric Profiles

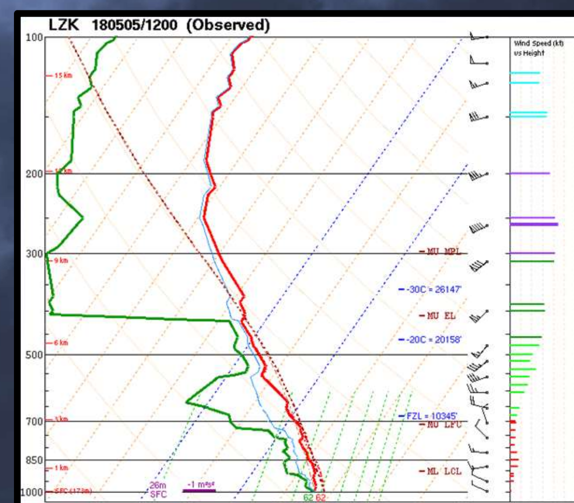
Important to observe the change of temperature and wind with height, especially in the Planetary Boundary Layer (PBL).

Current in-situ observing networks (radiosondes, surface observations, aircraft observations) sample the PBL poorly.

Remote sensing techniques (radars, satellite) also struggle to accurately sample the PBL.

Radiosonde (Weather Balloon) Network

- **<u>U.S. Radiosonde Network:</u> Twice daily vertical profiles of the atmosphere. Low spatial and temporal frequency**

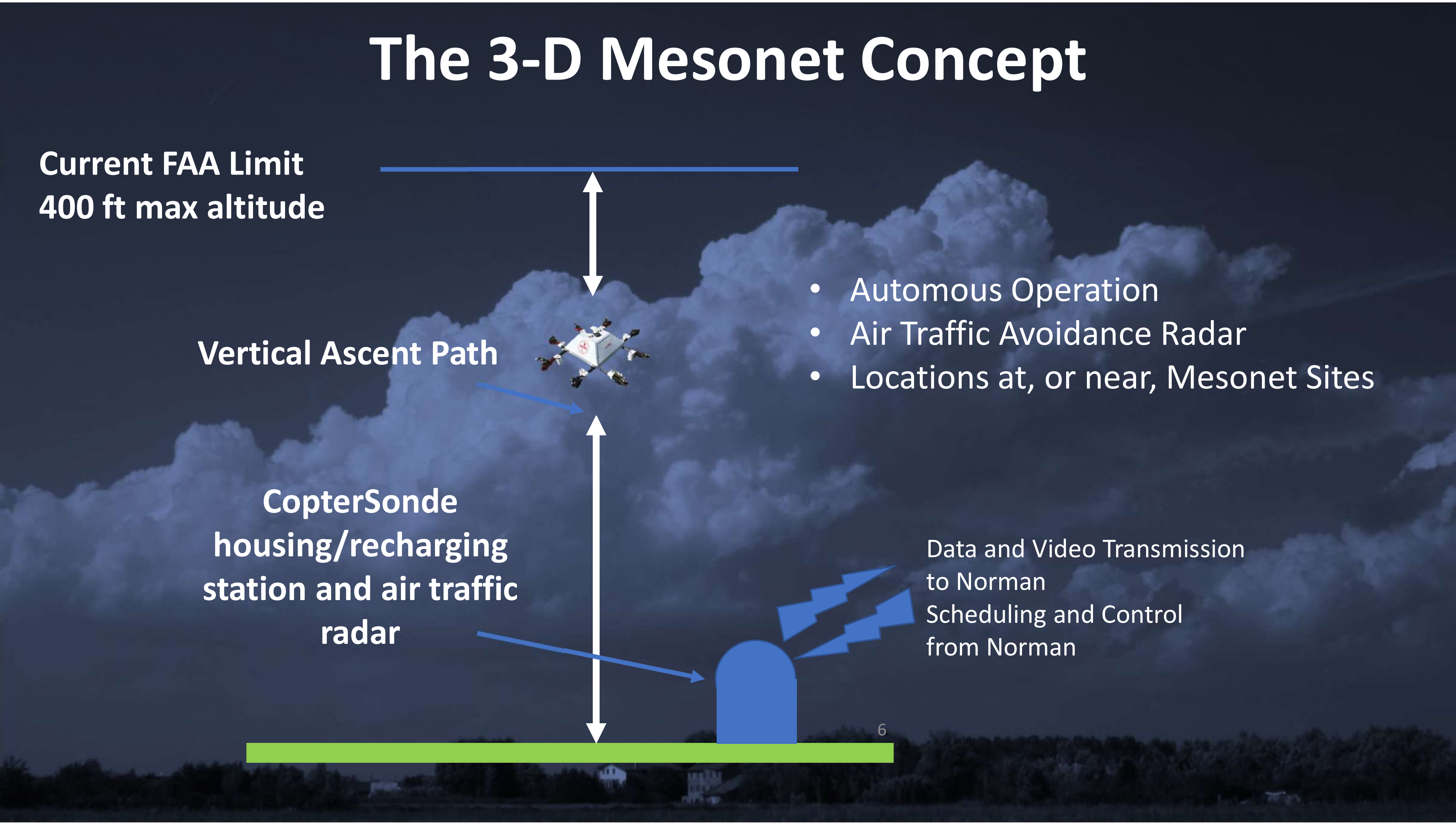


Small Unmanned Aerial System (sUAS)

OU CopterSonde

CopterSonde Specifications

- **Designed by OU Center for Autonomous Sensing and Sampling (CASS) for PBL obs.**
- **Octo-rotor design**
- **Pixhawk (PX4) running APM Copter**
- **Differential GPS**
- **Positional accuracy of 2-8 cm in flight**
- **Stable flight in the event of a motor failure**
- **Stable flight in winds up to 50 knots**


The 3-D Mesonet Concept
Current FAA Limit
400 ft max altitude
Vertical Ascent Path
CopterSonde housing/recharging station and air traffic radar
• Automous Operation
• Air Traffic Avoidance Radar
• Locations at, or near, Mesonet Sites
Data and Video Transmission to Norman
Scheduling and Control from Norman
6

Research Questions

Primary Question: Can observations from a network of small Unmanned Aerial Systems (sUAS or "drones") improve PBL analyses and short-range convective forecasts?

Secondary Questions: If so, what is an ideal network configuration?

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

Method: OSSE

- **An Observing System Simulation Experiment (OSSE) finds the *potential* value of *simulated* observation networks.**
- **OSSEs can save both time and money.**
- **OSSEs have been used extensively for**
  - **New Satellites**
  - **Profilers**
  - **Radar Networks**
  - **and many more!**

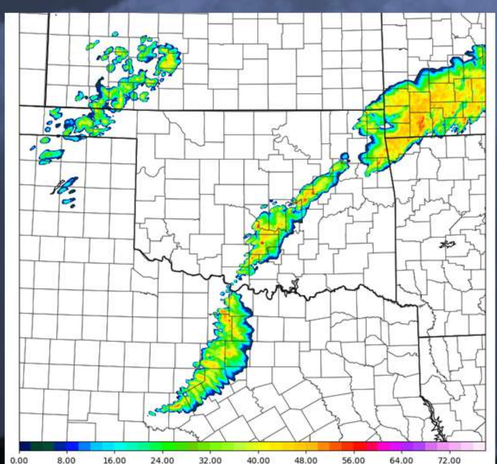
Components of an OSSE

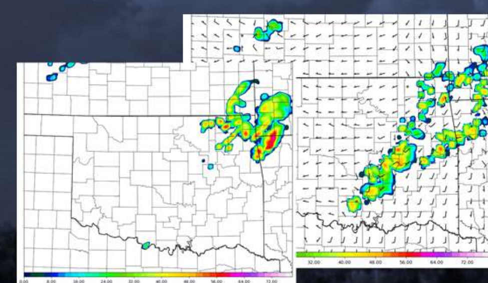
1) **Numerical Atmosphere**
   - Called the Nature Run
   - Long integrated, high resolution numerical model
   - Needs to resemble the real atmosphere

2) **Simulated Observations**
   - Sample simulated obs from the Nature Run for both current and proposed observing networks
   - Must mimic expected observational frequency and error

3) **Numerical Experiments**
   - 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.

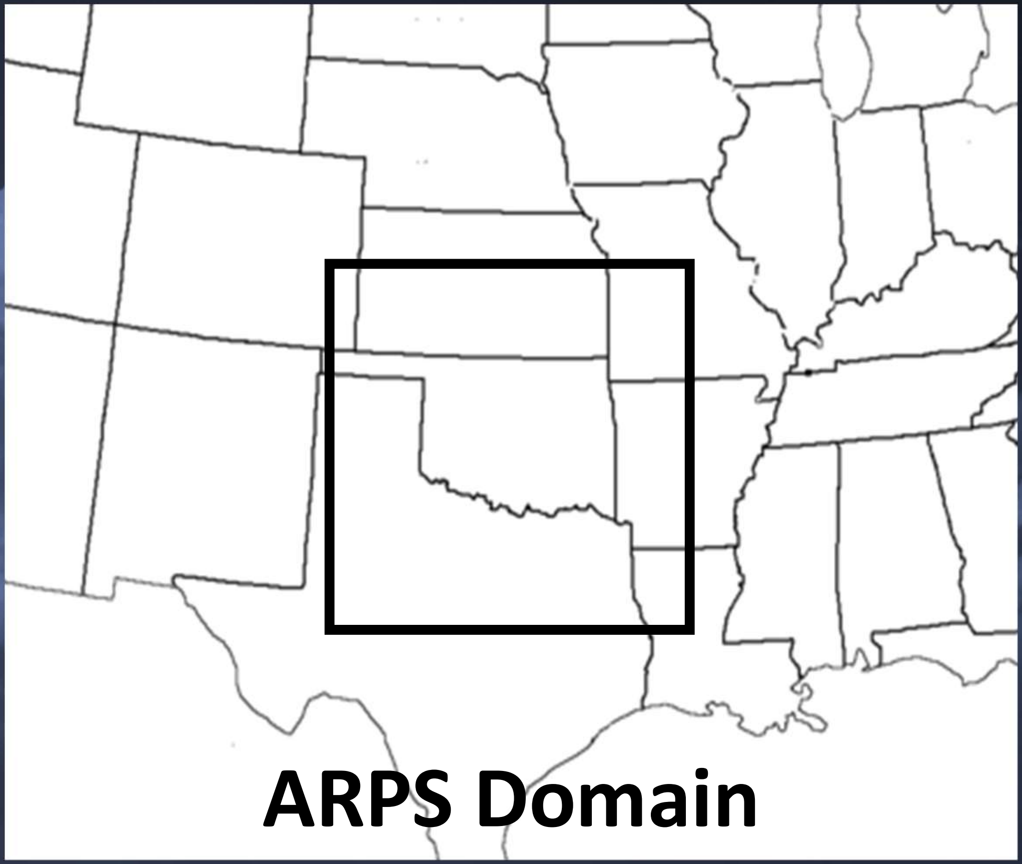
4) **Calibration OSE**
   - Complete an OSE using one of the current observing networks
   - Perform OSSE using simulated obs for existing network and compare to OSE results; should be similar.





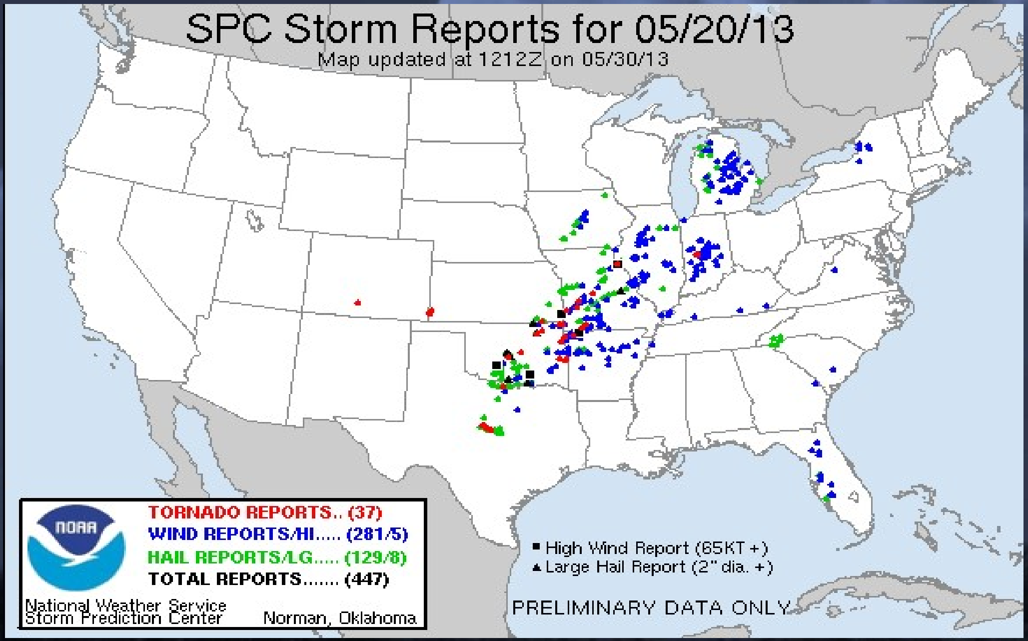
Numerical Atmosphere/Nature Run

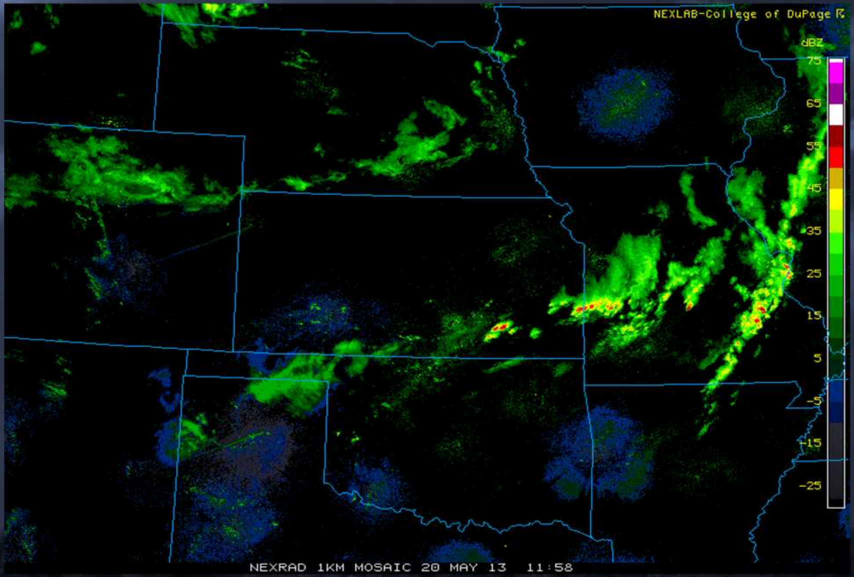
- The Nature Run was created using the Advanced Regional Prediction System (ARPS)
  - Horizontal Resolution: 900 x 900 grid at 1 km resolution
  - Vertical Resolution: Cubic stretching function with 61 vertical levels
  - Temporal Resolution: 2 second time step, output every 5 minutes
  - Initial Conditions and Lateral Boundary Conditions: 12 km NAM
  - Data Assimilation: ARPS 3DVAR cycled every 2 hours for a six hour period prior to free forecast
  - Employed surface, upper air, radar, and satellite observations



Numerical Atmosphere/Nature Run

- Study Event: May 20, 2013: Convective Initiation across Oklahoma
  - Data Assimilation with ARPS 3DVAR begins at 06 UTC on May 20, 2013
  - Free forecast begins at 12 UTC on May 20, 2013
  - Forecast ends at 06 UTC on May 21, 2013



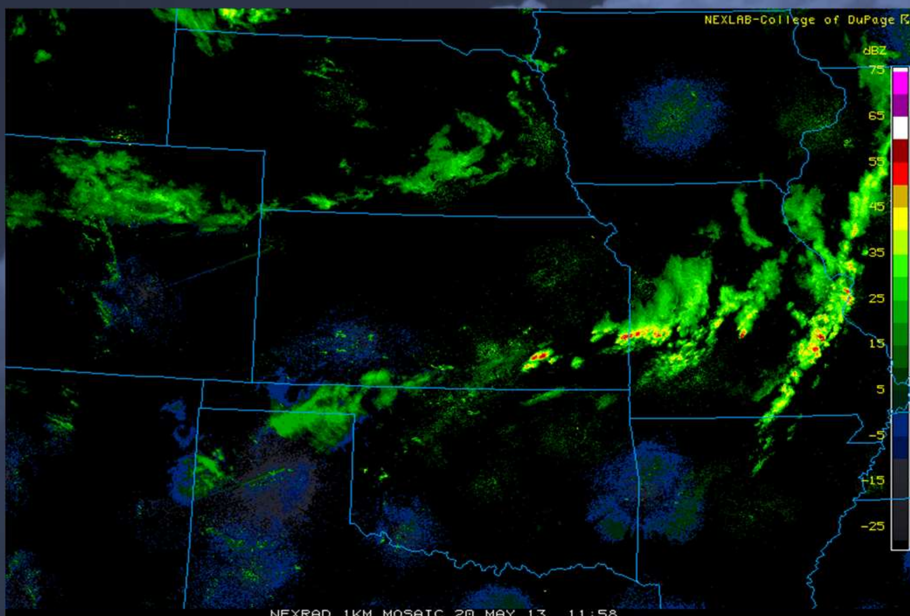


Observed Radar 20 May 12 UTC – 21 May 06 UTC

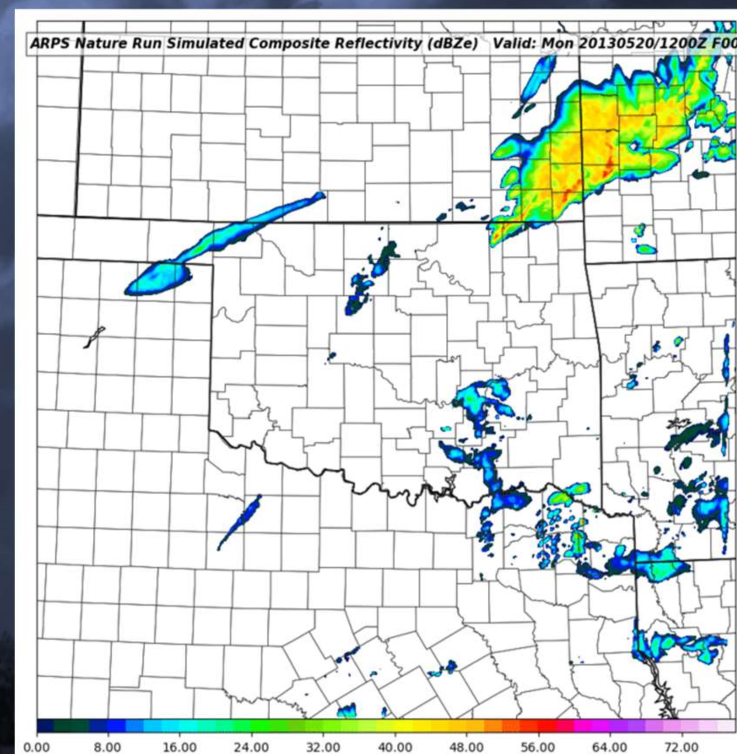
Nature Run vs. Reality

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

Observed Radar
20 May 12 UTC – 21 May 06 UTC



ARPS Nature Run
20 May 12 UTC – 21 May 06 UTC



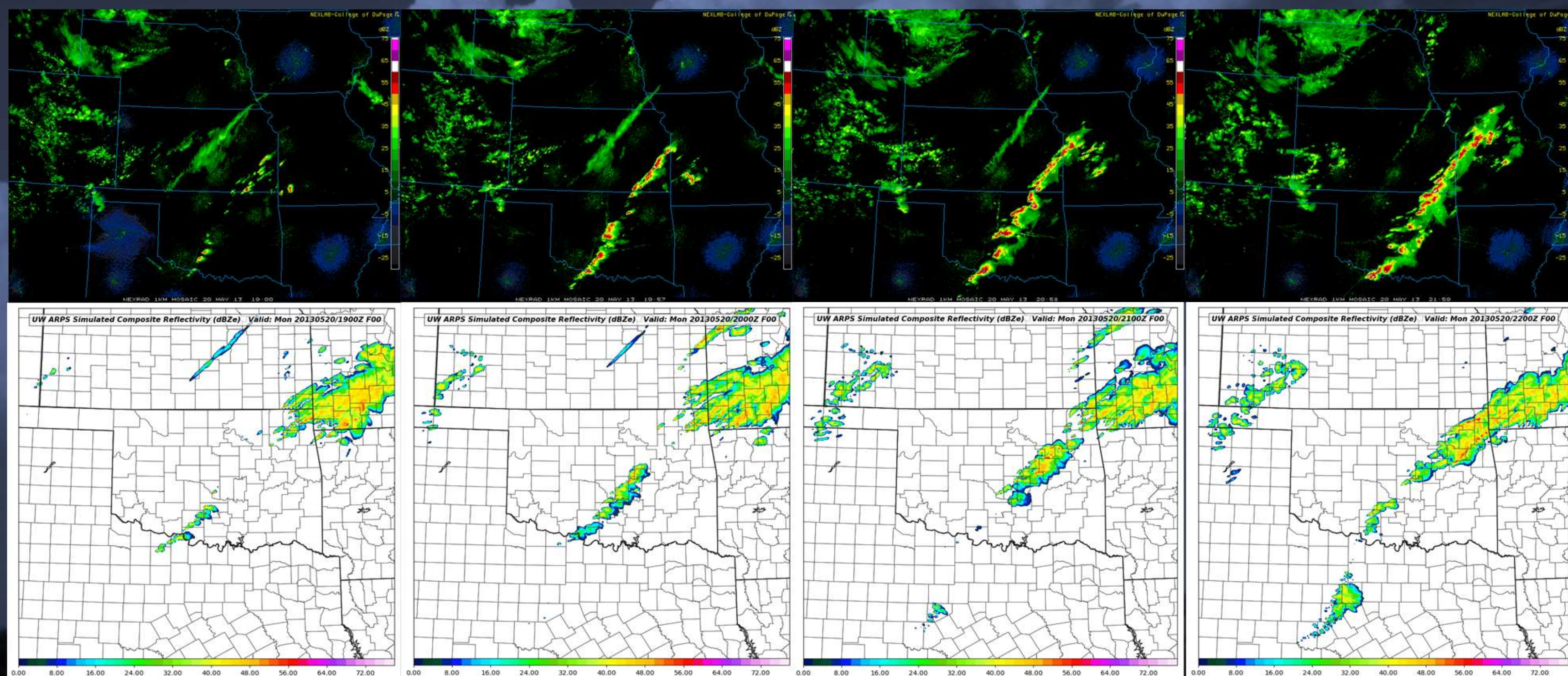
Nature Run vs. Reality

- 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

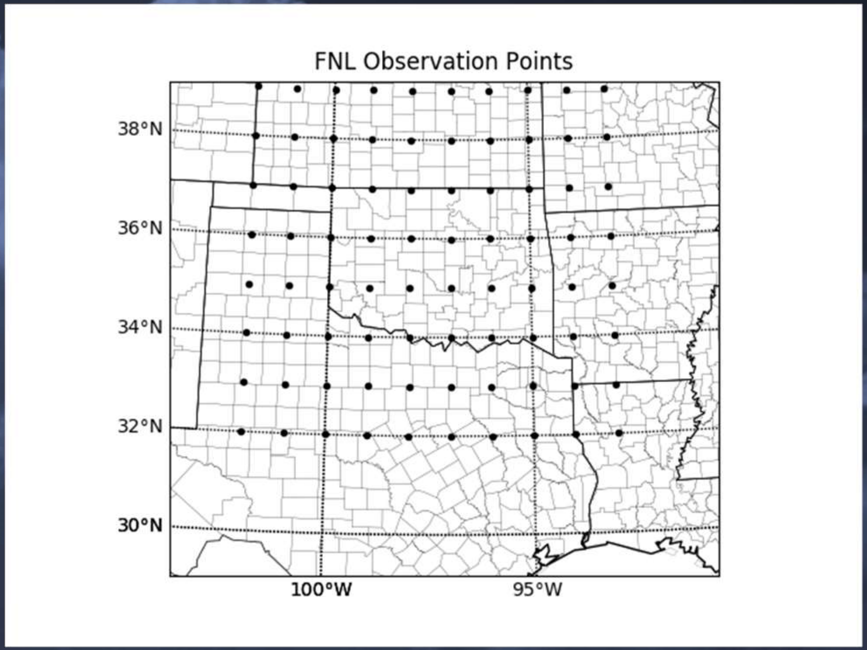
Three types of simulated observations:

1. Global Forecast System Final Analyses (GFS FNL)
2. Oklahoma Mesonet
3. UAV (3-D Mesonet)

Simulated Observations

Why GFS Final Analyses?

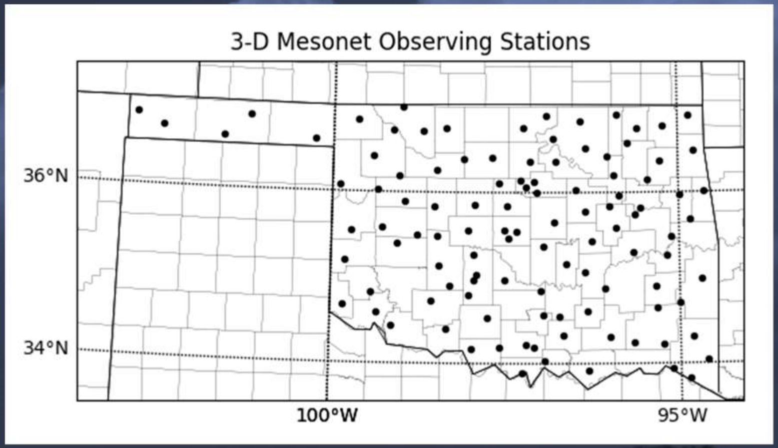
- In most OSSEs *all* possible current observing systems are individually simulated, including satellite, radar, radiosondes, all surface networks, aircraft obs, etc…
- This is a highly time intensive process!
- To expedite the OSSE, GFS Final Analyses (FNL) are used as a proxy for the data collected by all current observing networks.



80 FNL Observation Points

Simulated UAV Observations

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

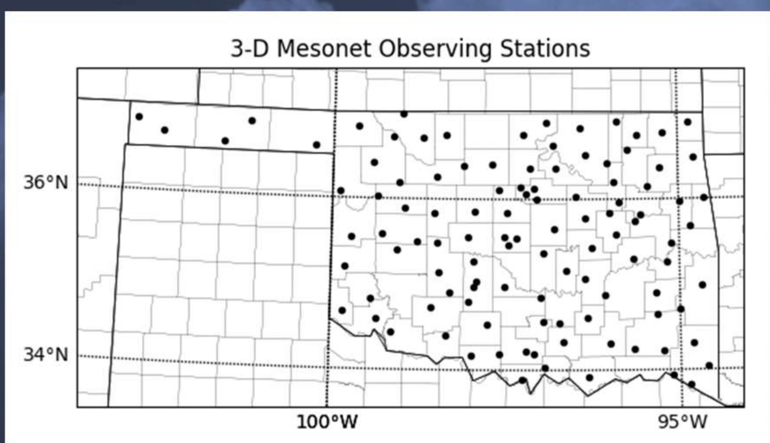


110 3-D Mesonet Observation Points

- 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

- <u>Time adaptive</u> – 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.
- <u>Cloud Checking</u> – 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).
- Assumes non-biased instruments and Gaussian error distribution.

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	

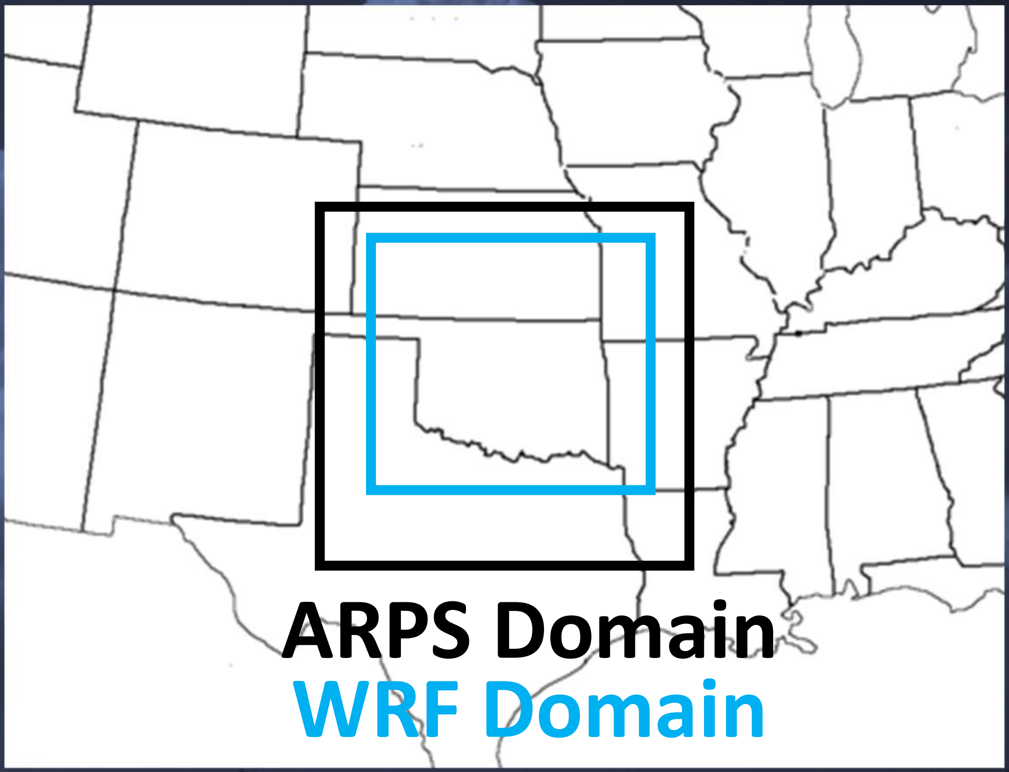
Numerical Experiments
WRF Control Run

- WRF-ARW used for OSSE experiments in order to avoid the “Identical Twin” problem
- The WRF Control run needs to be sufficiently different from the Nature Run, so that it is possible to observe any changes when data are assimilated in the OSSE experiments.
- In this case, WRF Control run begins 24 hours before the Nature Run at 12 UTC on May 19, 2013 and ends at 06 UTC May 21, 2013.
- This allows enough time for the WRF to diverge sufficiently from the ARPS Nature Run

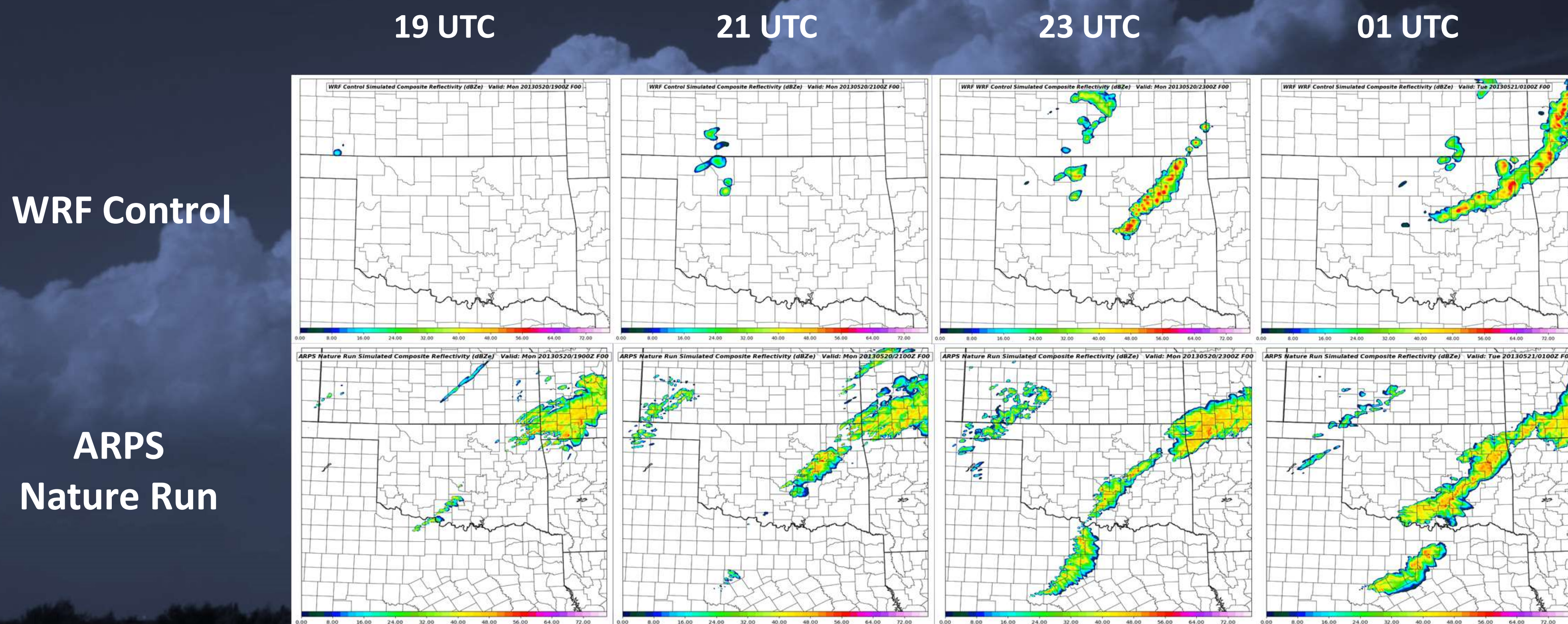
Numerical Experiments
WRF Control Run

WRF Set Up Specifications:

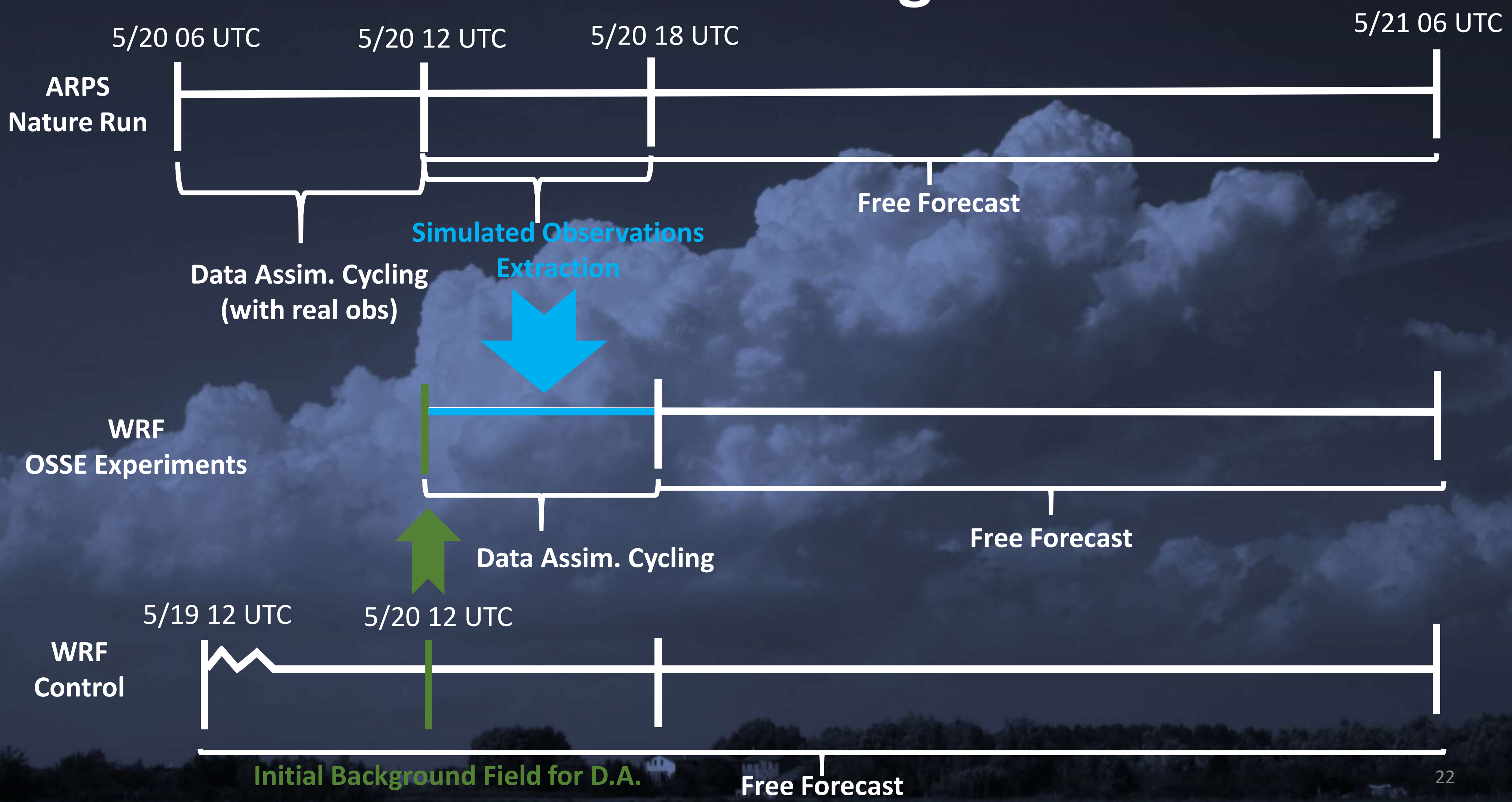
- Horizontal Grid: 237 x 201 single domain with 3 km resolution.
- Vertical Grid: 50 vertical layers
- Time Step: 9 sec
- Microphysics: Thompson MP
- PBL Physics: MYNN Scheme
- Cumulus: None
- Radiation: Dudhia (shortwave)
  RRTM (longwave)



Numerical Experiments
WRF Control Run vs. Nature Run



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
Data Assim. Cycling
Free Forecast
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
  - 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?

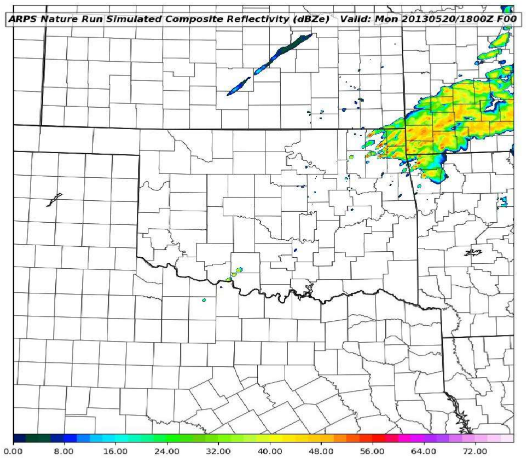
First OSSE Experiment: Create forecasts using UAV data collected through a depth of:

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

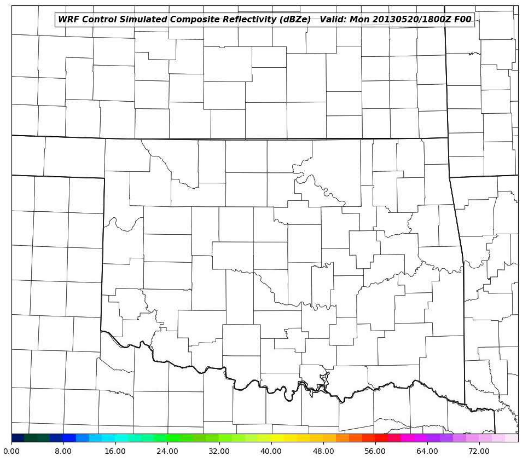
MFA Results: Composite Reflectivity

MFA Results: Comp. Reflectivity 1800 UTC

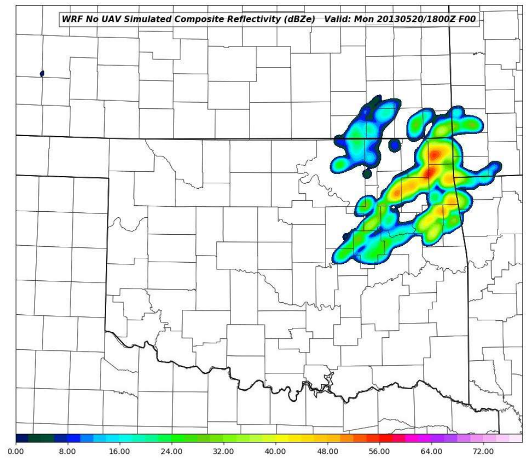
Nature Run



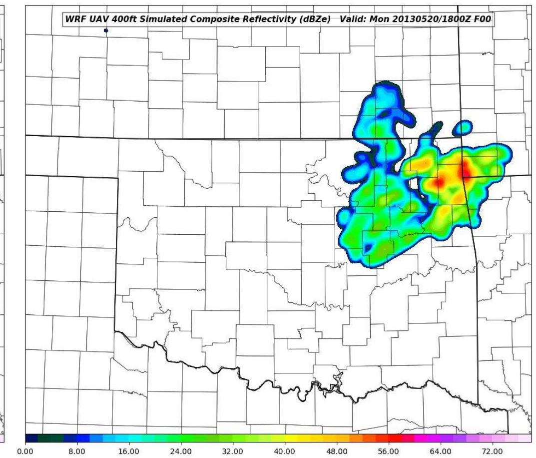
WRF Control

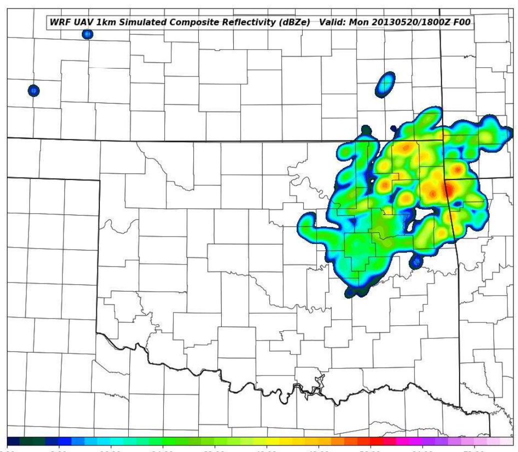


No UAV

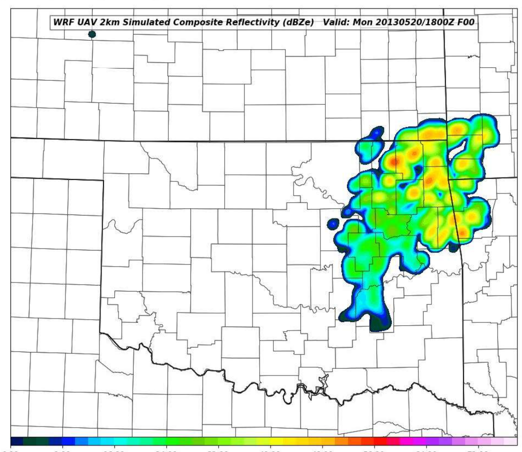


UAV 400 ft

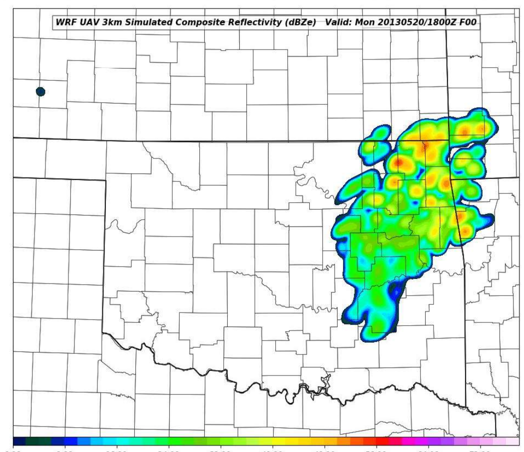




UAV 1km



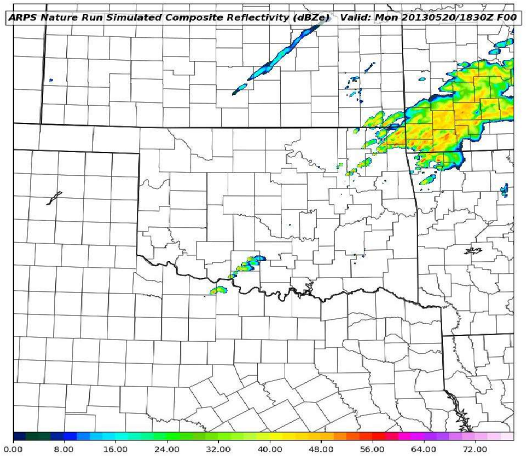
UAV 2km



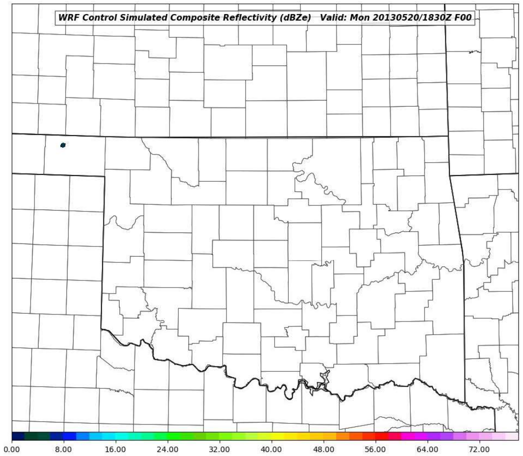
UAV 3km

MFA Results: Comp. Reflectivity 1830 UTC

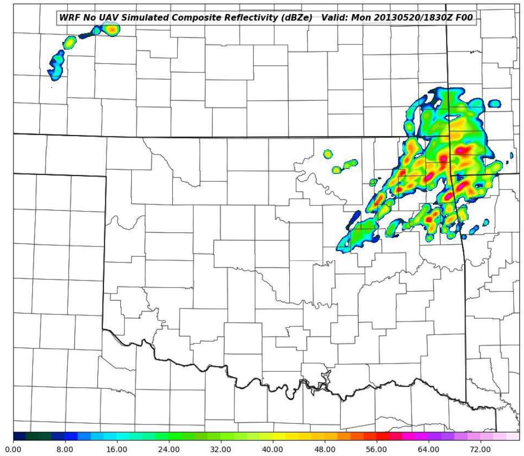
Nature Run



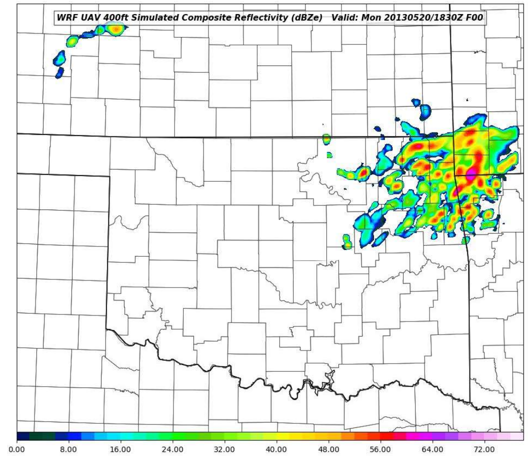
WRF Control

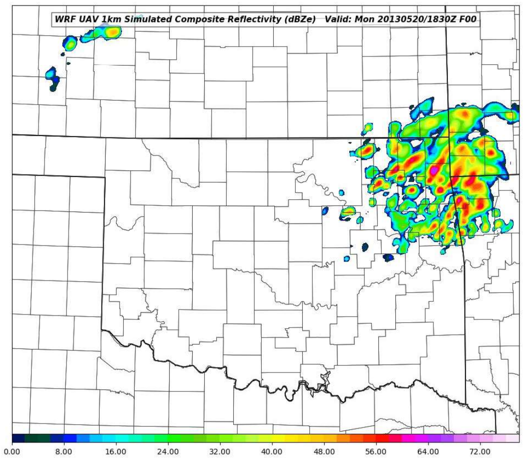


No UAV

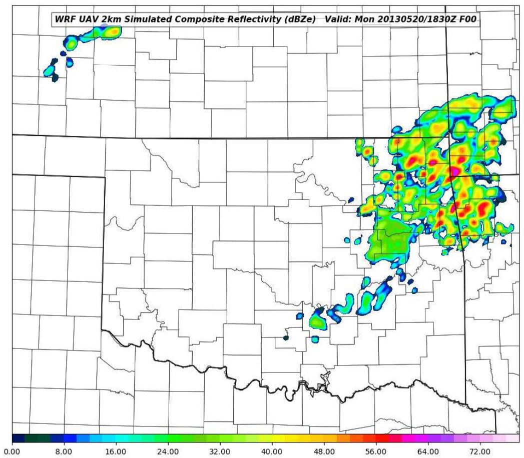


UAV 400 ft

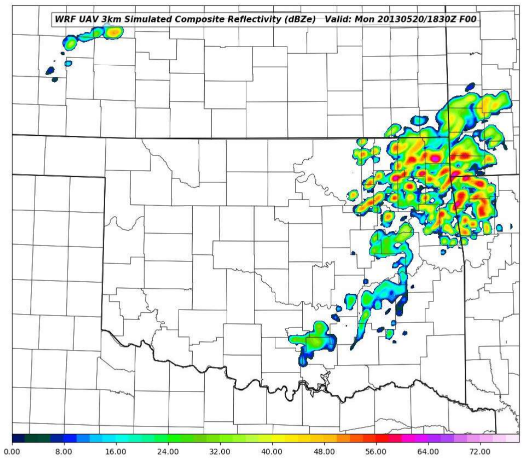




UAV 1km



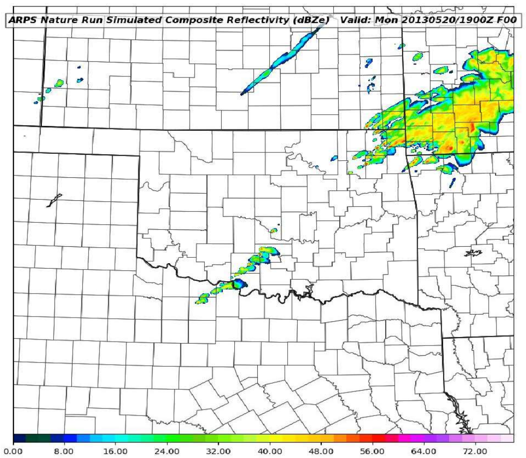
UAV 2km



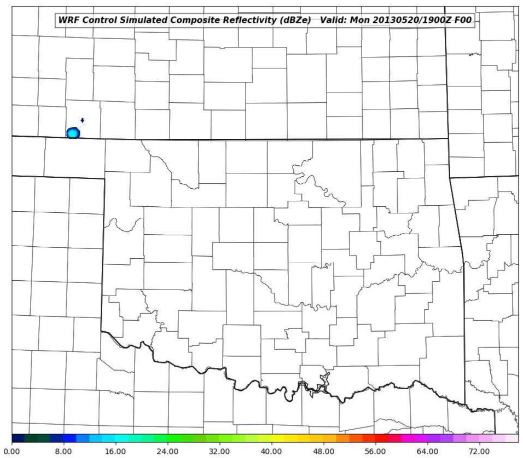
UAV 3km

MFA Results: Comp. Reflectivity 1900 UTC

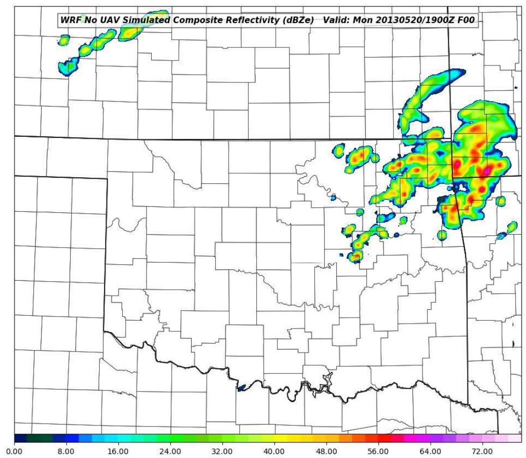
Nature Run



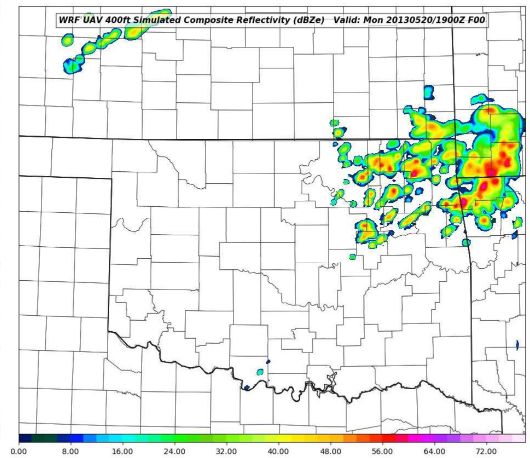
WRF Control

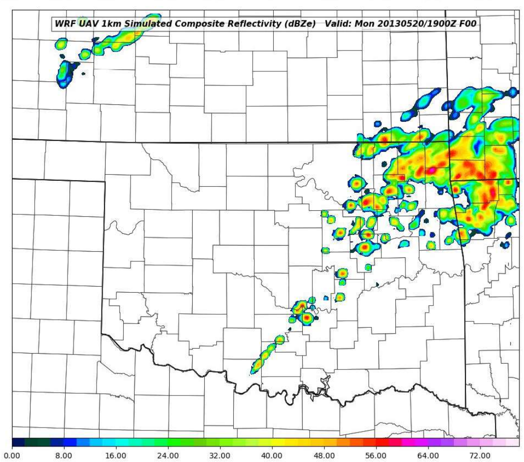


No UAV

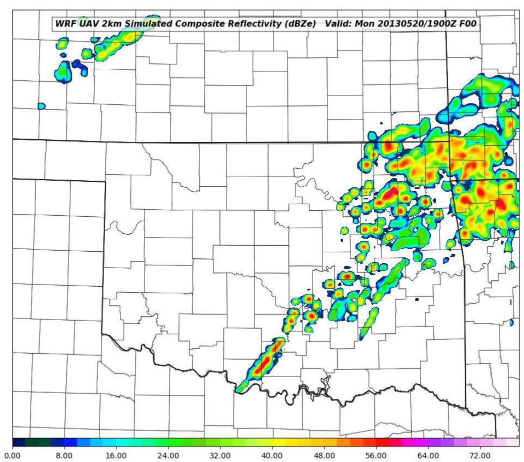


UAV 400 ft

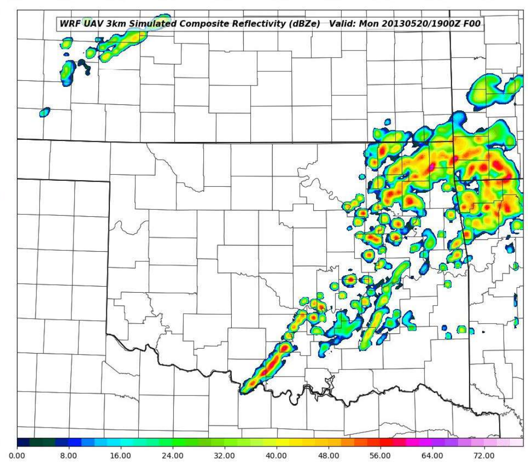




UAV 1km



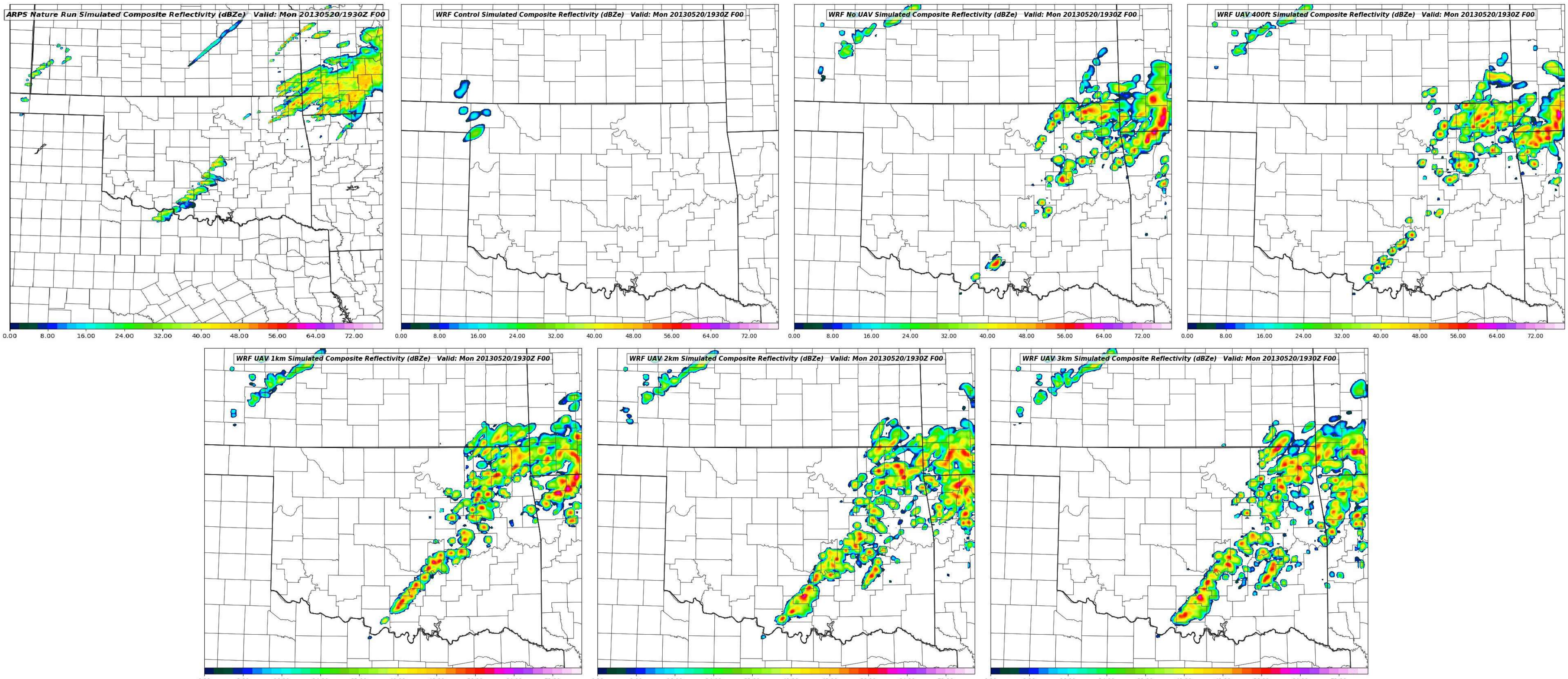
UAV 2km



UAV 3km

MFA Results: Comp. Reflectivity 1930 UTC

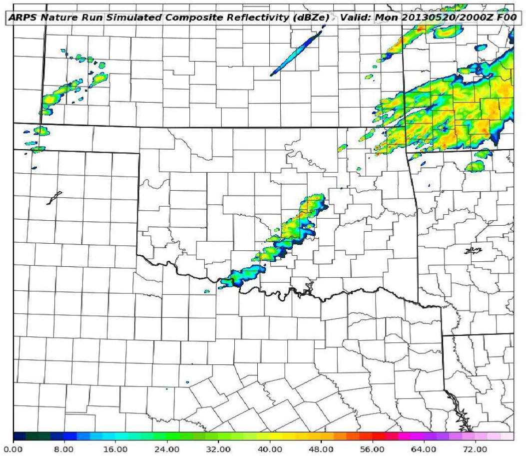
Nature Run | WRF Control | No UAV | UAV 400 ft

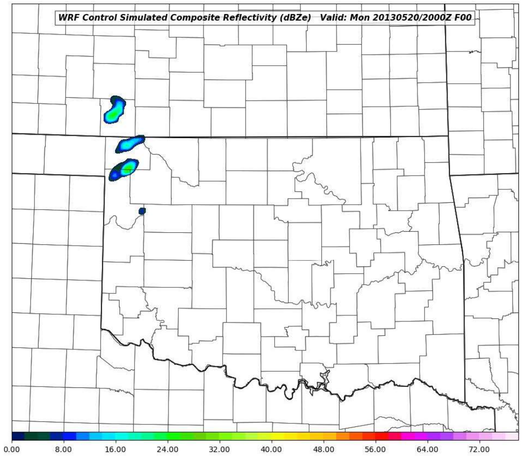


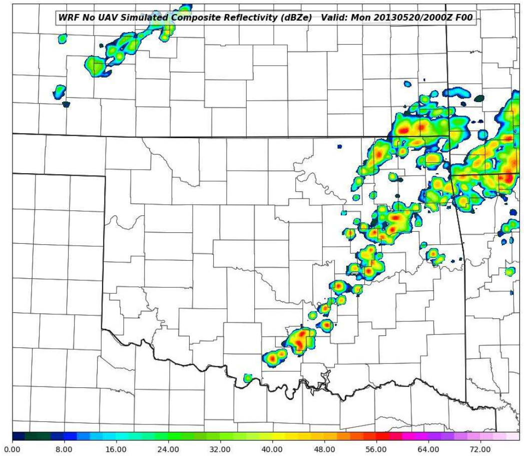
UAV 1km | UAV 2km | UAV 3km

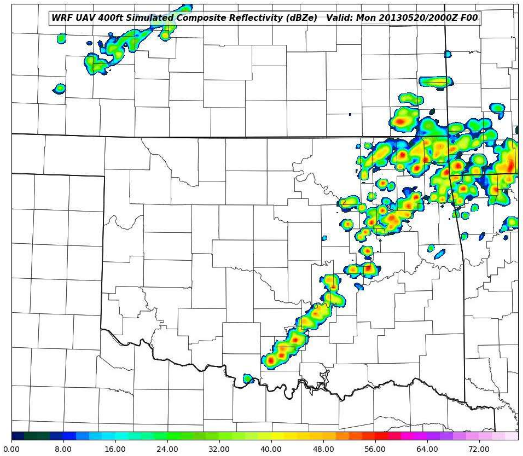
MFA Results: Comp. Reflectivity 2000 UTC

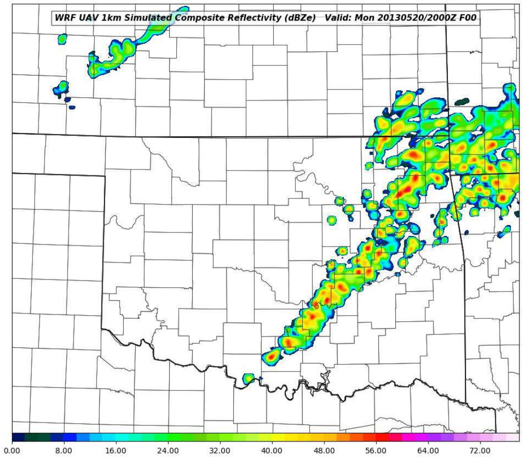
Nature Run | **WRF Control** | **No UAV** | **UAV 400 ft**

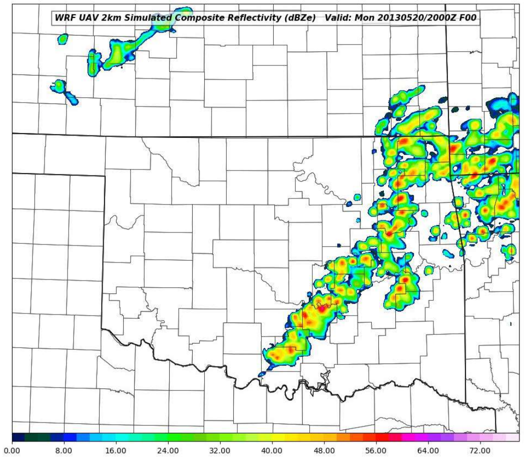


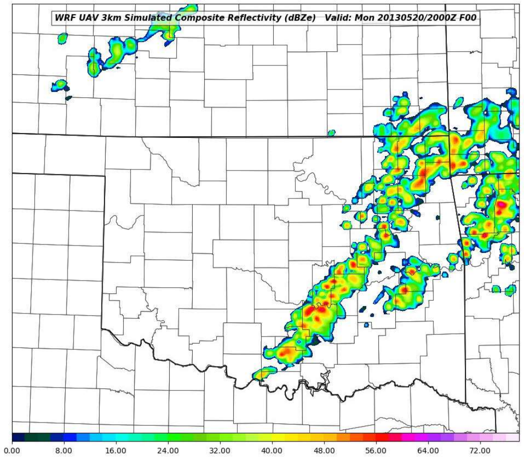






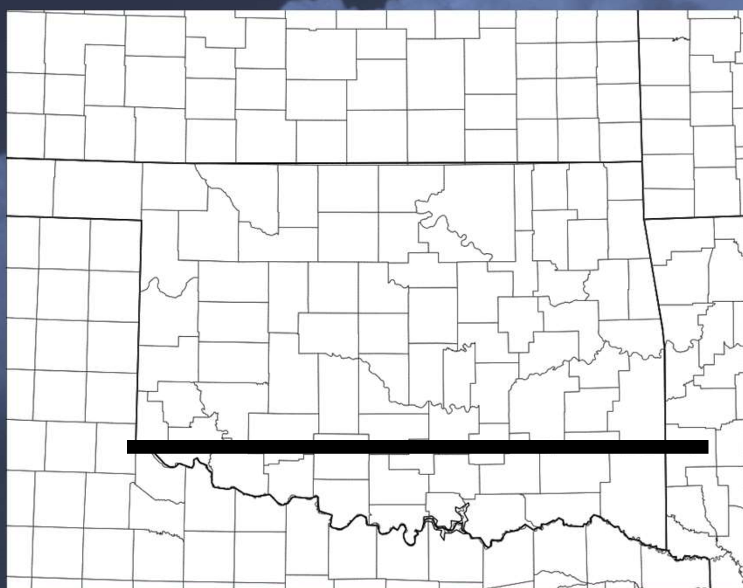






UAV 1km | **UAV 2km** | **UAV 3km**

MFA Results: Mixing Ratio Cross Sections

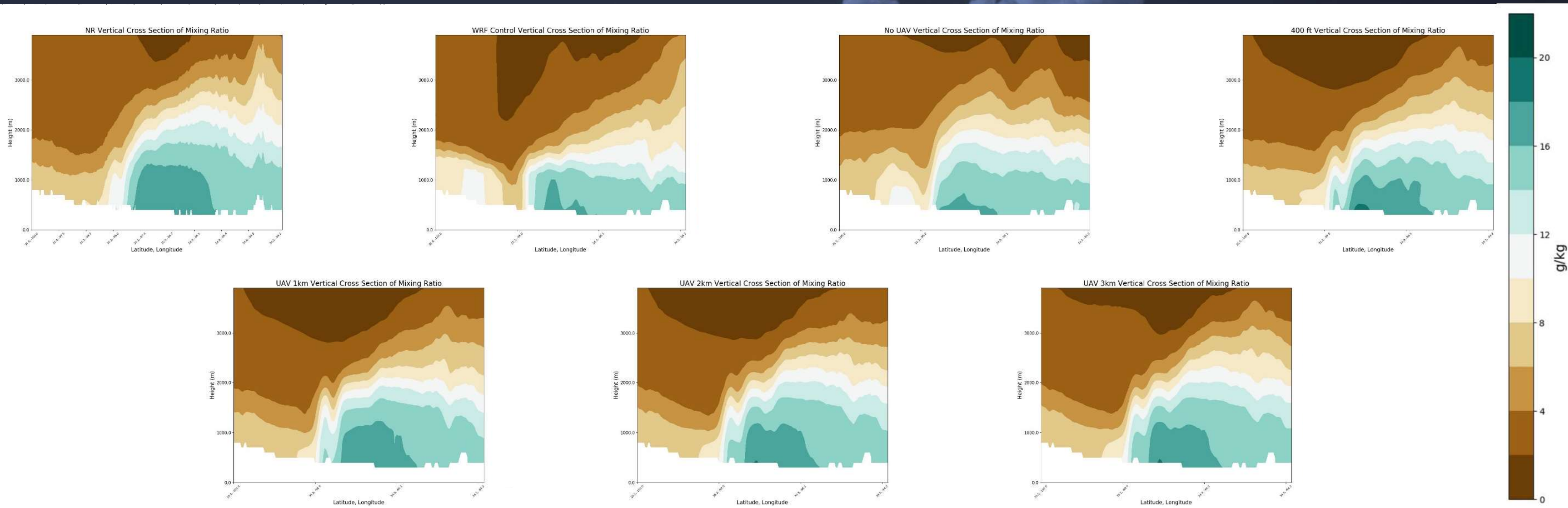


Cross Section Sample Line

Gives view of warm sector PBL and dryline structure

MFA Results: Vertical Cross Sections 18 UTC

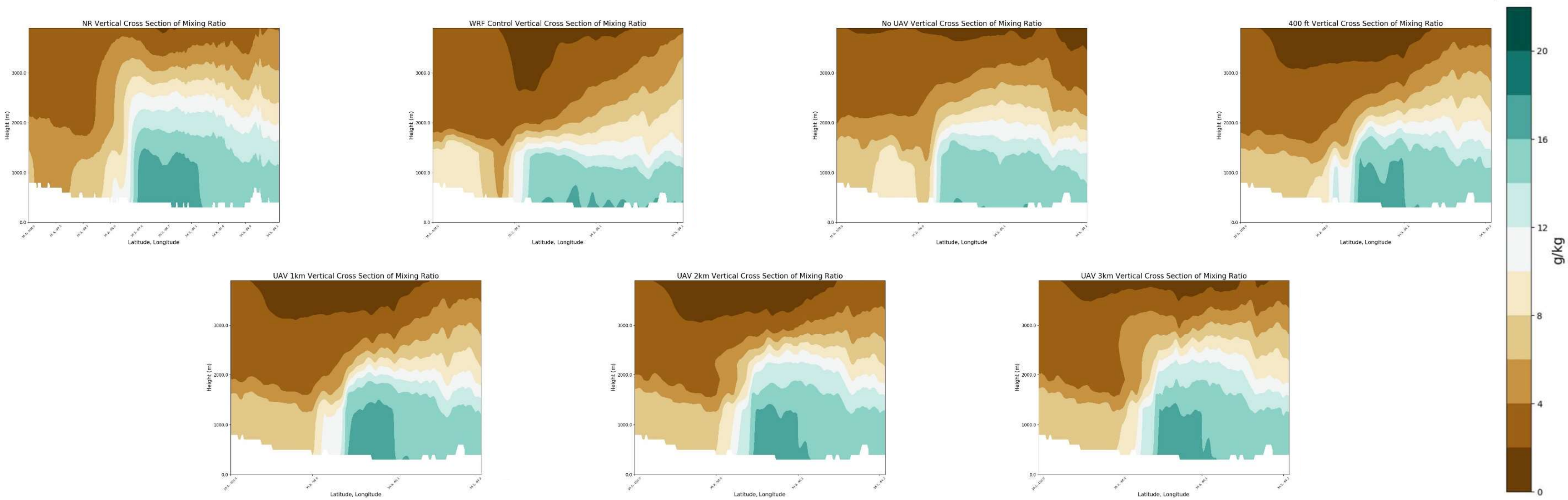
Nature Run | WRF Control | No UAV | UAV 400 ft



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.

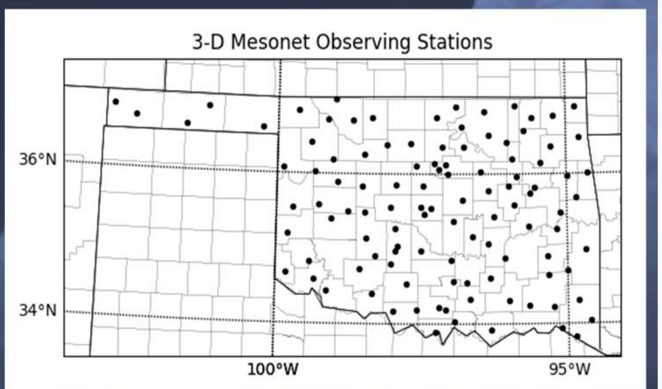
Currently, there are 110 possible 3-D Mesonet locations, but is this too many?

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

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

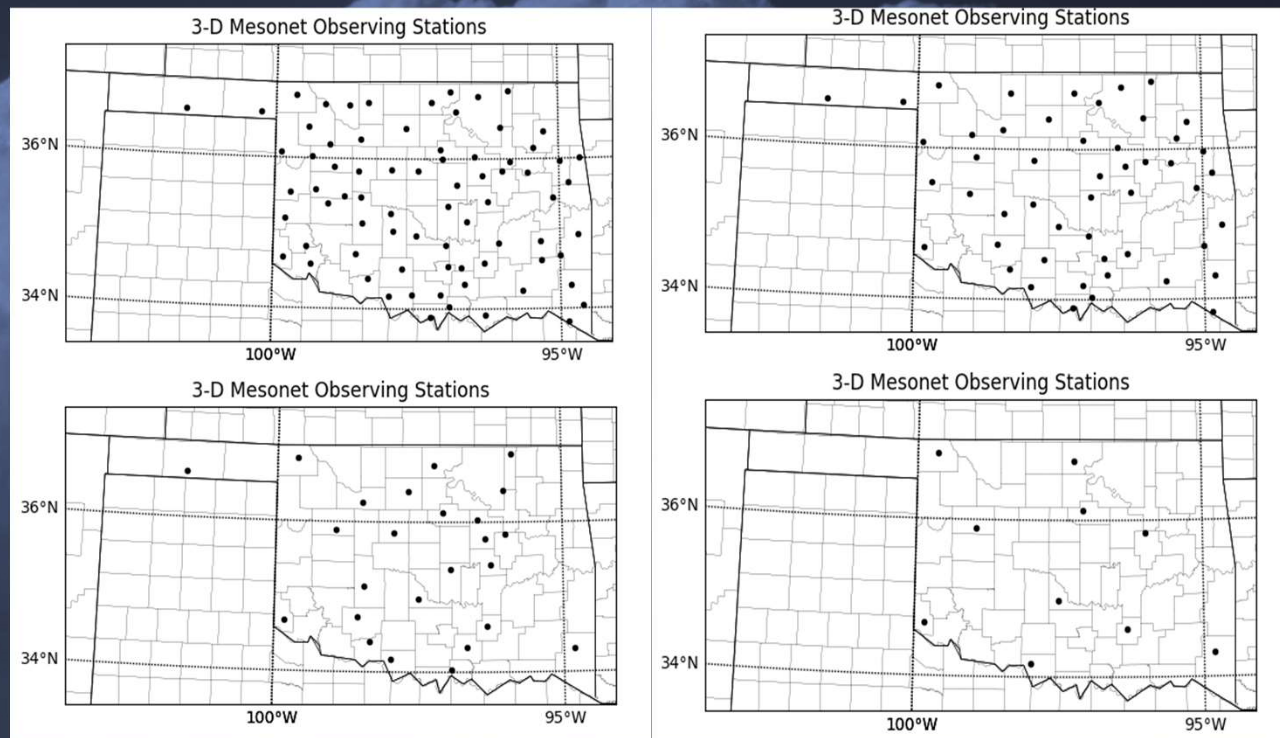
Numerical Experiment #2: Network Density

110 Stations



75 Stations

50 Stations



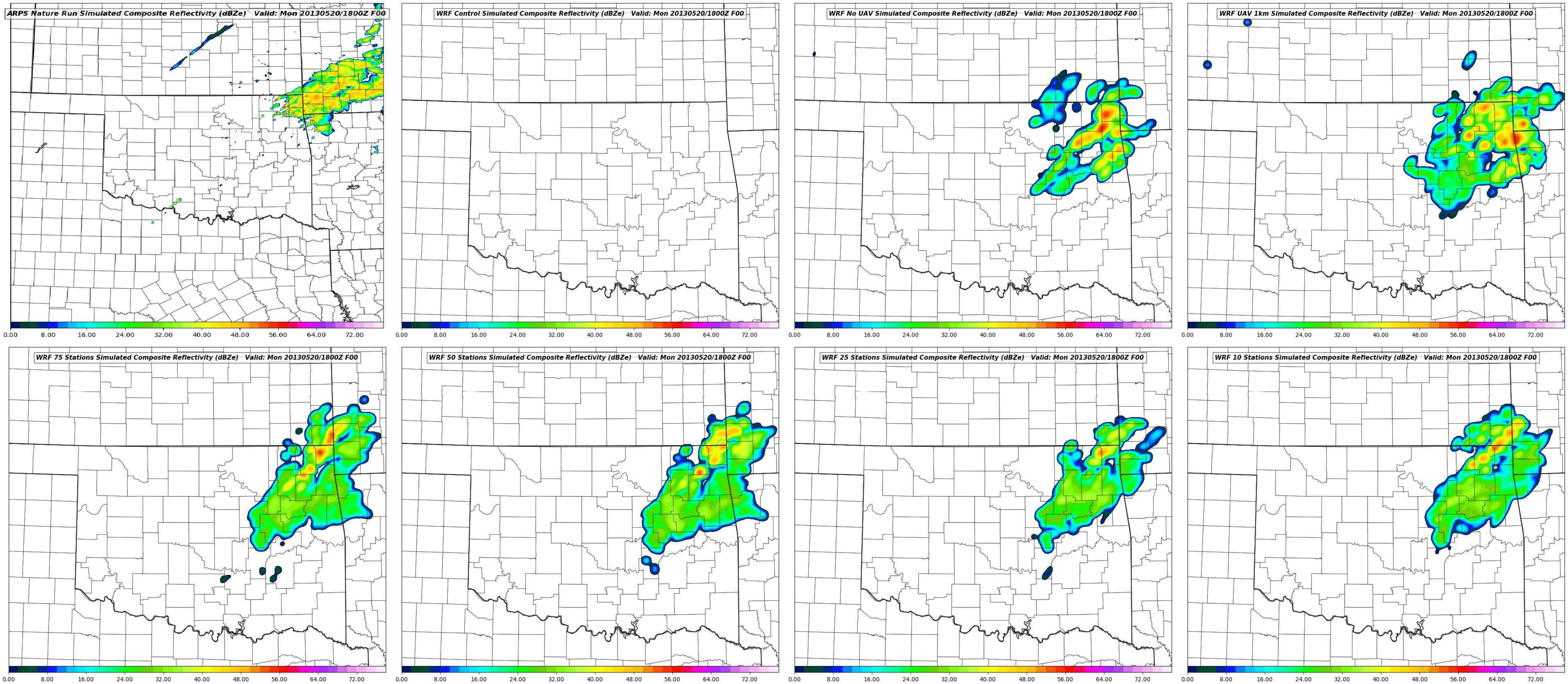
25 Stations

10 Stations

Network Density Results: Composite Reflectivity

Net. Density Results: Comp. Reflectivity 1800 UTC

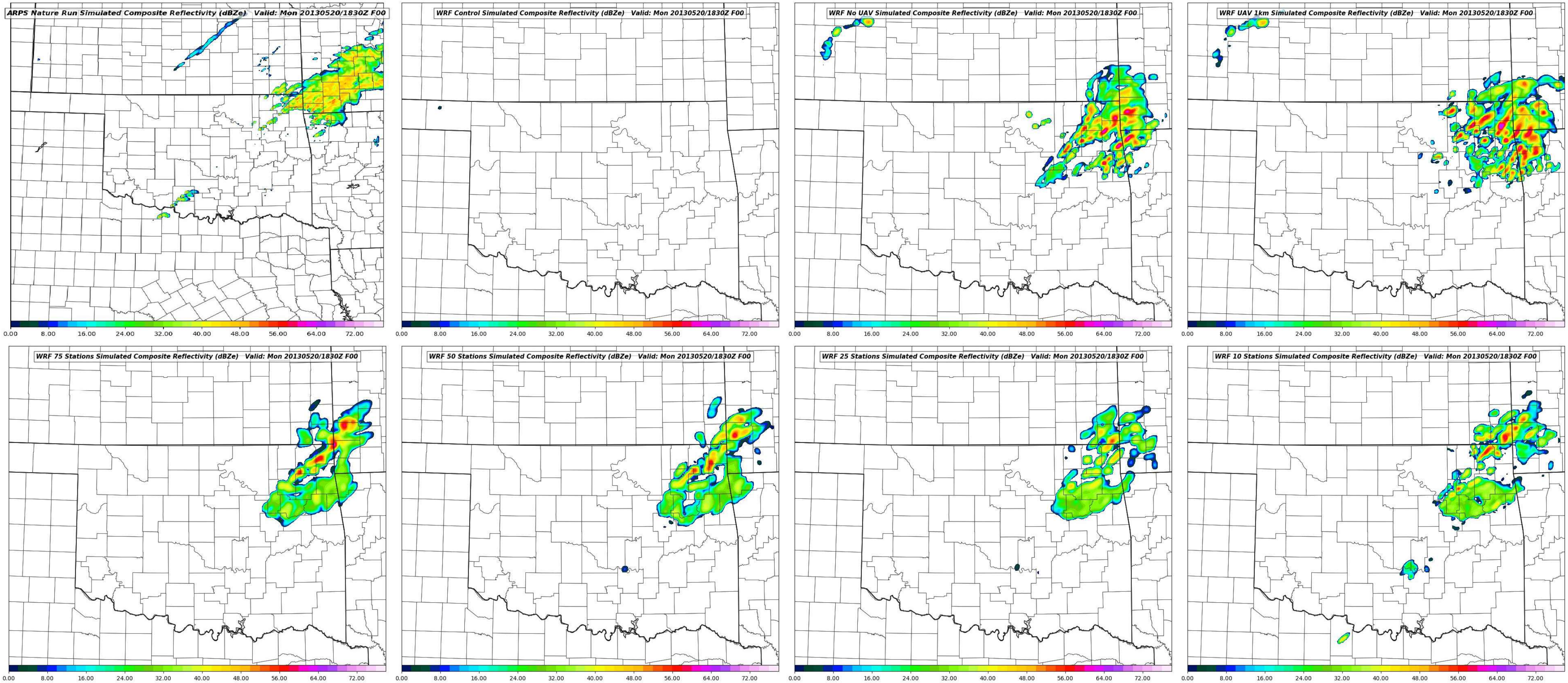
Nature Run | WRF Control | No UAV | 110 Stations



75 Stations | 50 Stations | 25 Stations | 10 Stations

Net. Density Results: Comp. Reflectivity 1830 UTC

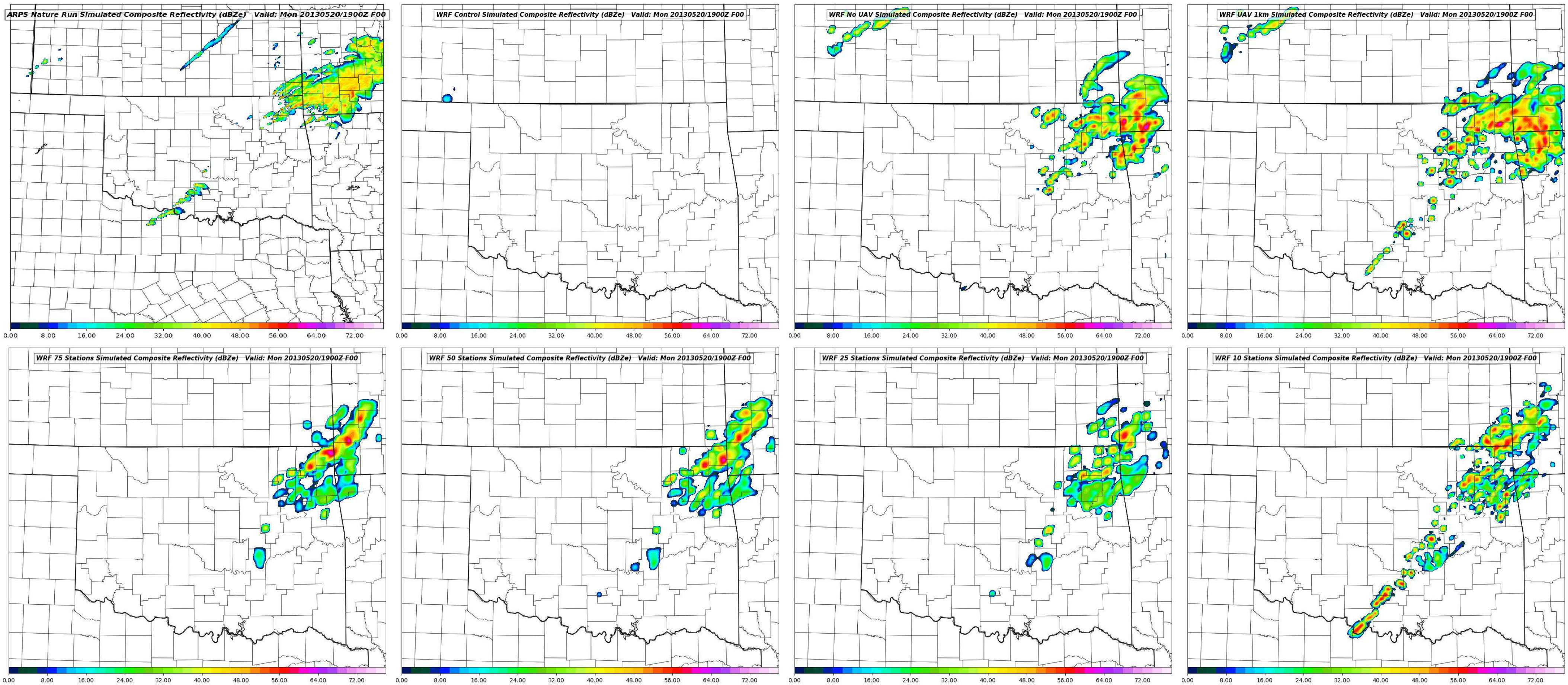
Nature Run | WRF Control | No UAV | 110 Stations



75 Stations | 50 Stations | 25 Stations | 10 Stations

Net. Density Results: Comp. Reflectivity 1900 UTC

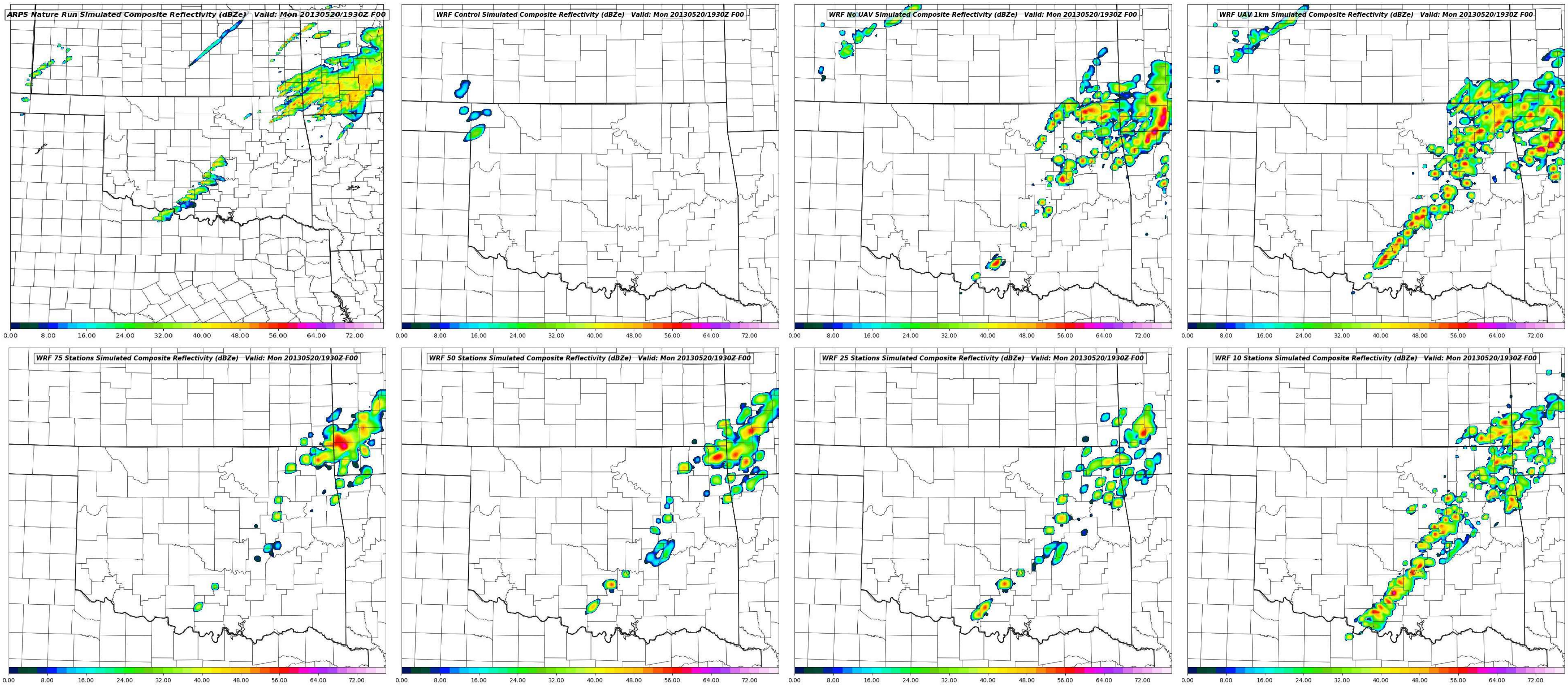
Nature Run | WRF Control | No UAV | 110 Stations



75 Stations | 50 Stations | 25 Stations | 10 Stations

Net Density Results: Comp. Reflectivity 1930 UTC

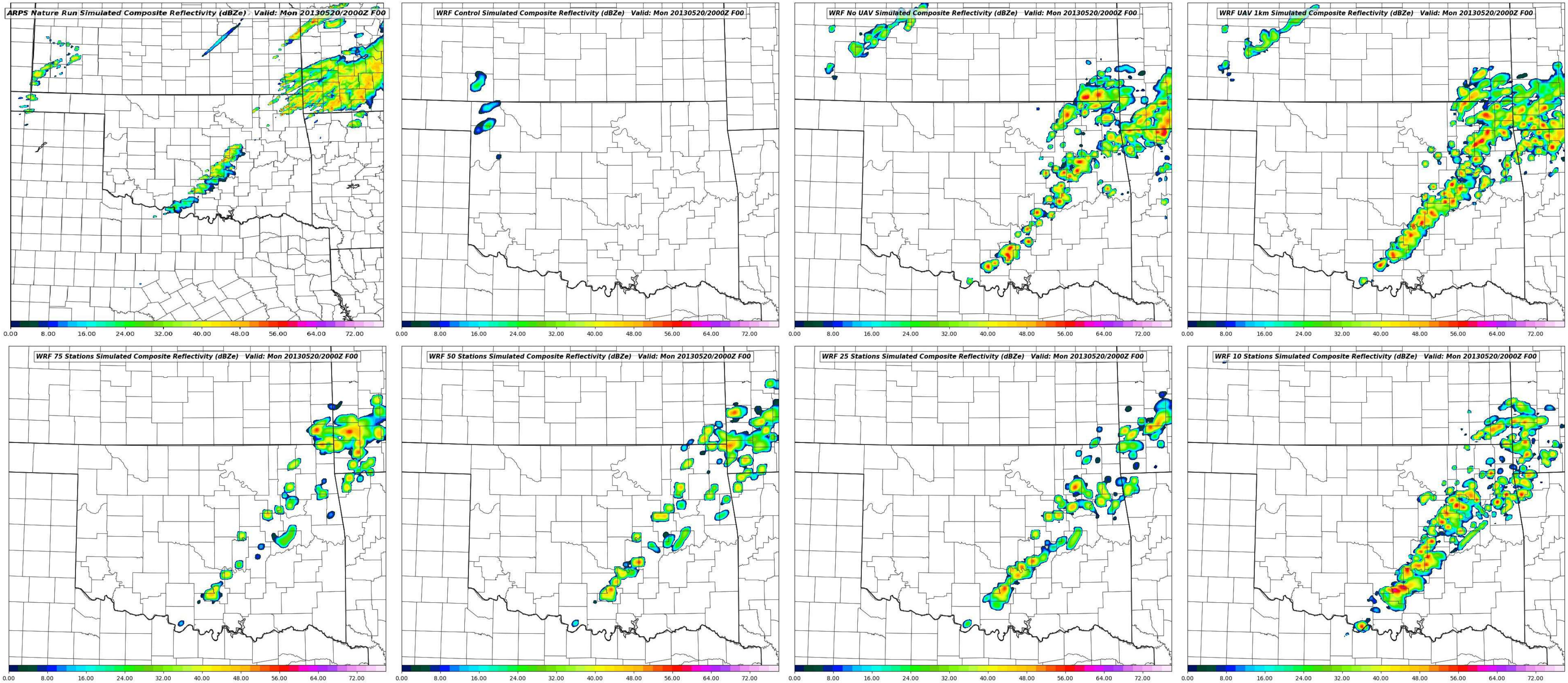
Nature Run | WRF Control | No UAV | 110 Stations



75 Stations | 50 Stations | 25 Stations | 10 Stations

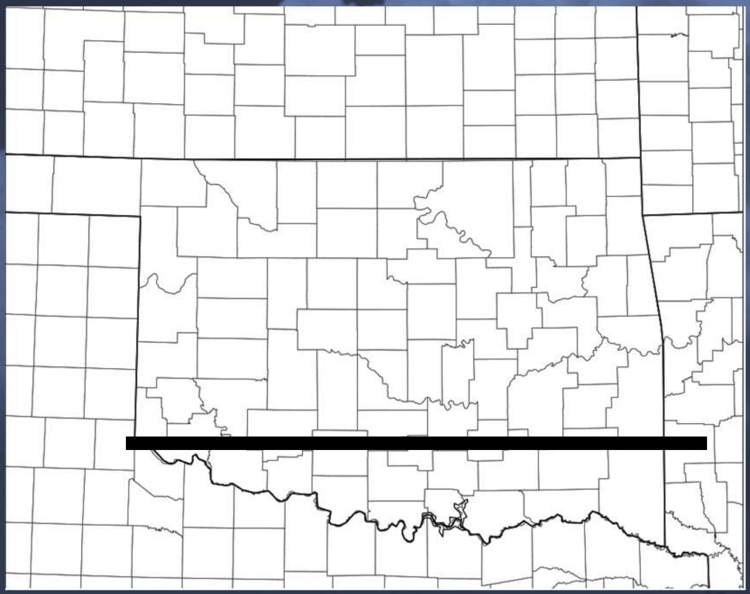
Net. Density Results: Comp. Reflectivity 2000 UTC

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



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

Network Density Results: Mixing Ratio Cross Sections

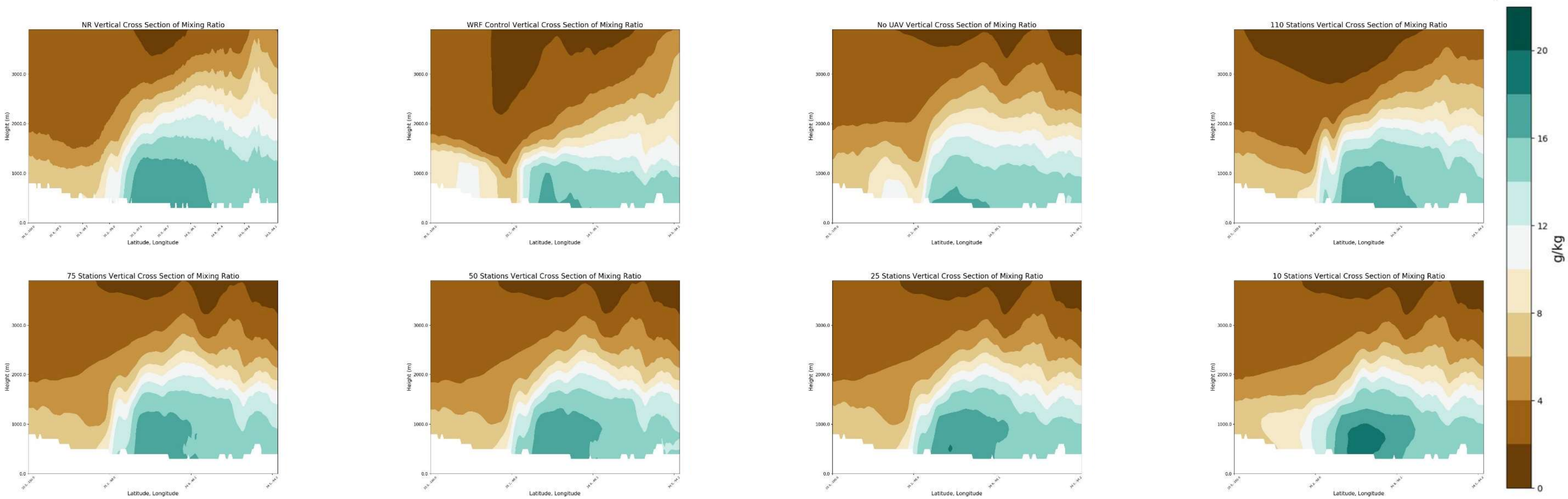


Cross Section Sample Line

Gives view of warm sector PBL and dryline structure

Net. Density Results: Vertical Cross Sections 18 UTC

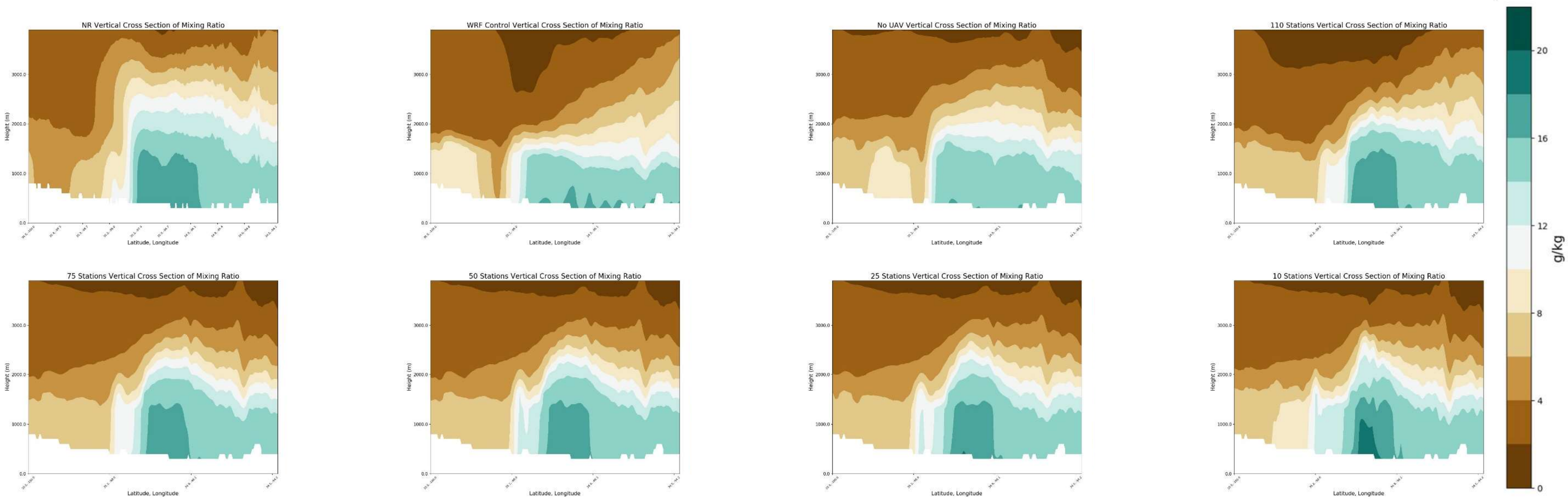
Nature Run | **WRF Control** | **No UAV** | **110 Stations**



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

Net. Density Results: Vertical Cross Sections 19 UTC

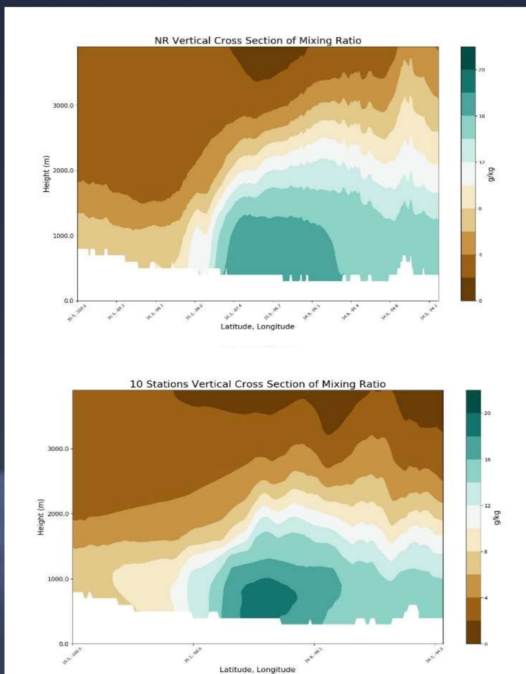
Nature Run | WRF Control | No UAV | 110 Stations



75 Stations | 50 Stations | 25 Stations | 10 Stations

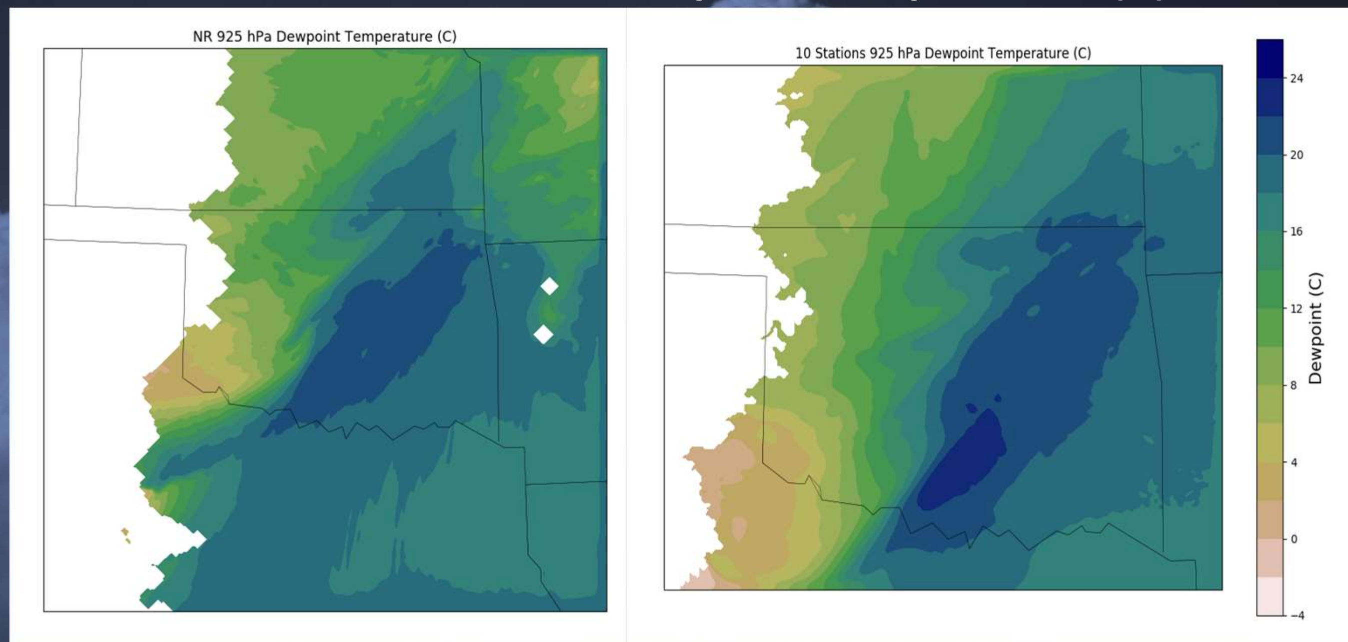
Excess Moisture?

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>**

Caveats

- <u>OSSE Sensitivity to:</u>
  - Observation errors and their propagation – particularly moisture obs
  - Station configuration
  - Initial & Boundary conditions
  - WRF domain and physics choices
- <u>Impact of sampling noise from the Nature Run.</u>
  - Suspected noise sampling from the Nature Run may be adding additional error into the simulated observations. This may lead to worse performance than expected, and may help account for the excess moisture in the 10-station experiment.
- <u>Case dependency:</u> Will similar results be observed in different convective environments?
  - Example: MCS vs. super cell initiation


Thank you!
Questions?
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