Flying to Better Forecasts: Estimating the Impact of Weather Observations from UAS on Forecasts from a Numerical Model

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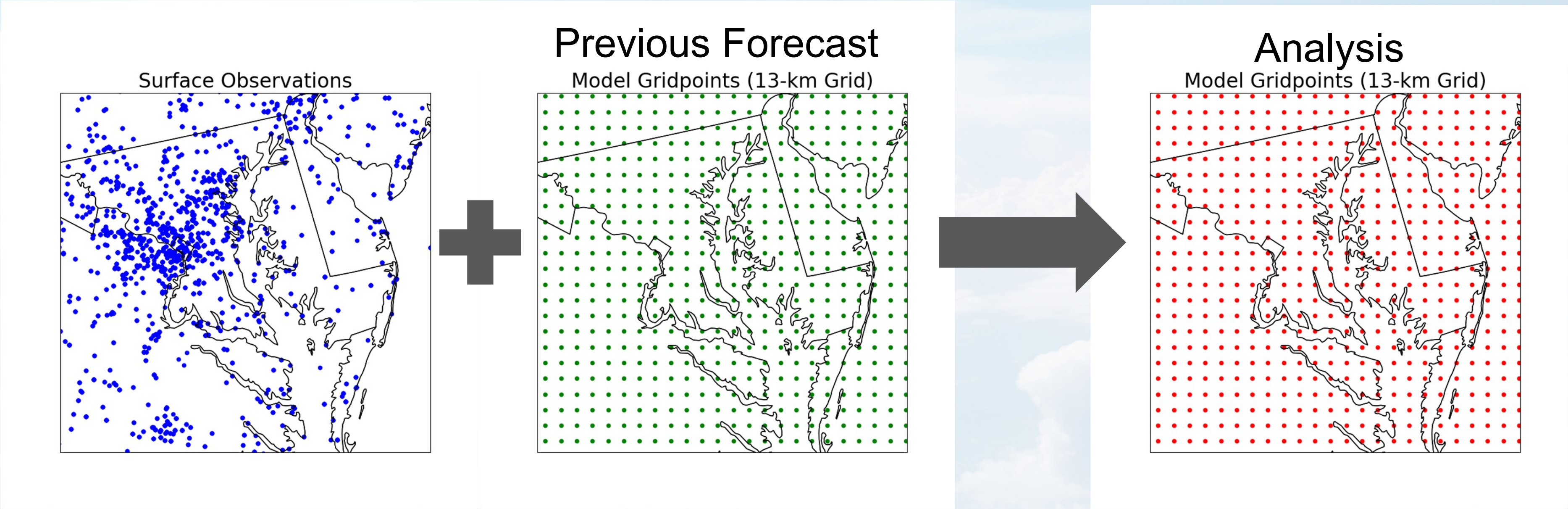
CIRES

Data Assimilation: Creating Initial Conditions for NWP



Just so we're all on the same page…

NWP: Numerical Weather Prediction (aka weather models)

DA: Data Assimilation

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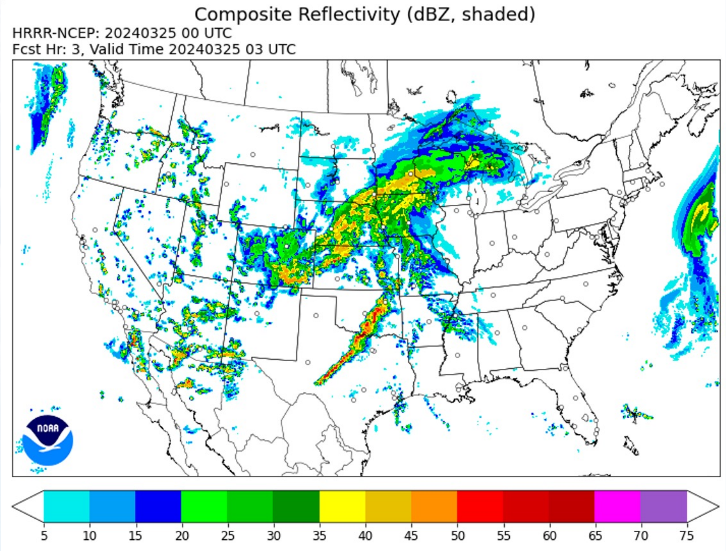
Rapidly Updating, Regional NWP at NOAA

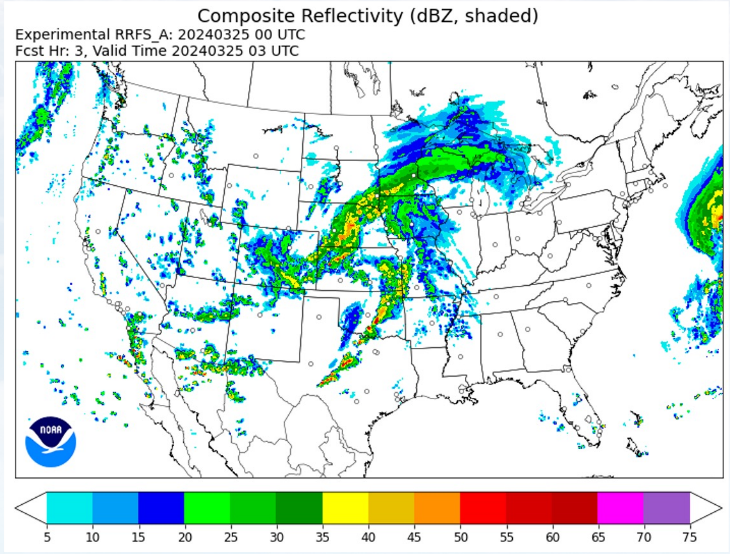
High-Resolution Rapid Refresh (HRRR)

3-km grid spacing, Contiguous USA domain
Operational model
New forecasts every hour (helpful for aviation!)



Rapid Refresh Forecast System (RRFS)

3-km grid spacing, *North American* domain
Experimental model
New forecasts every hour



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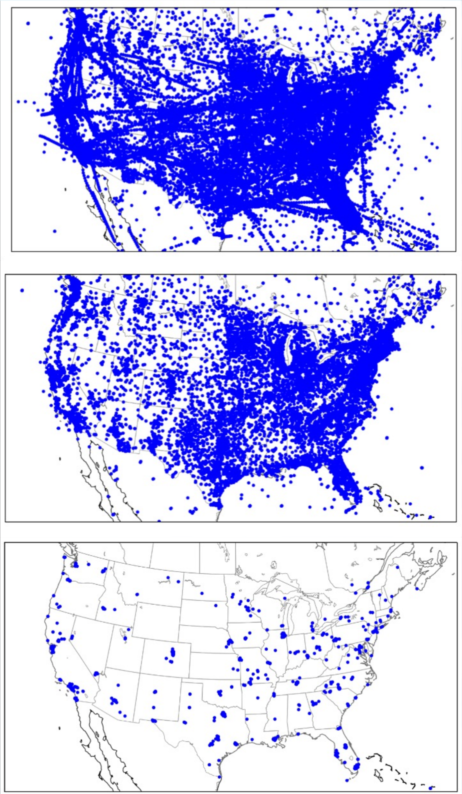
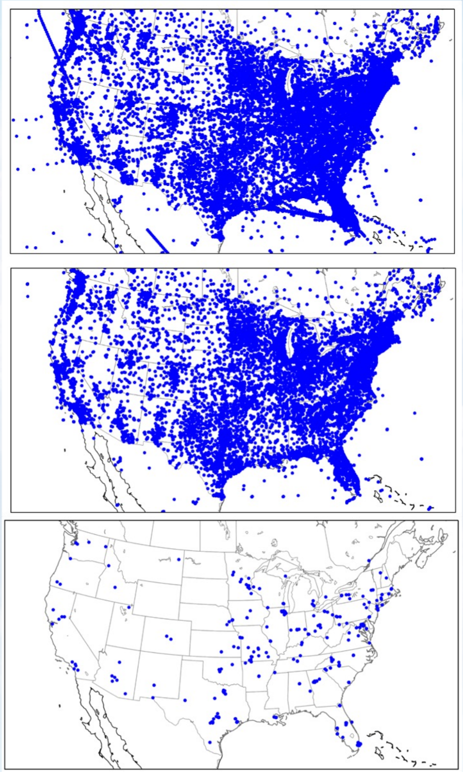
Temperature Observation Coverage

1700 PDT, 3/24/2024



0400 PDT, 3/24/2024

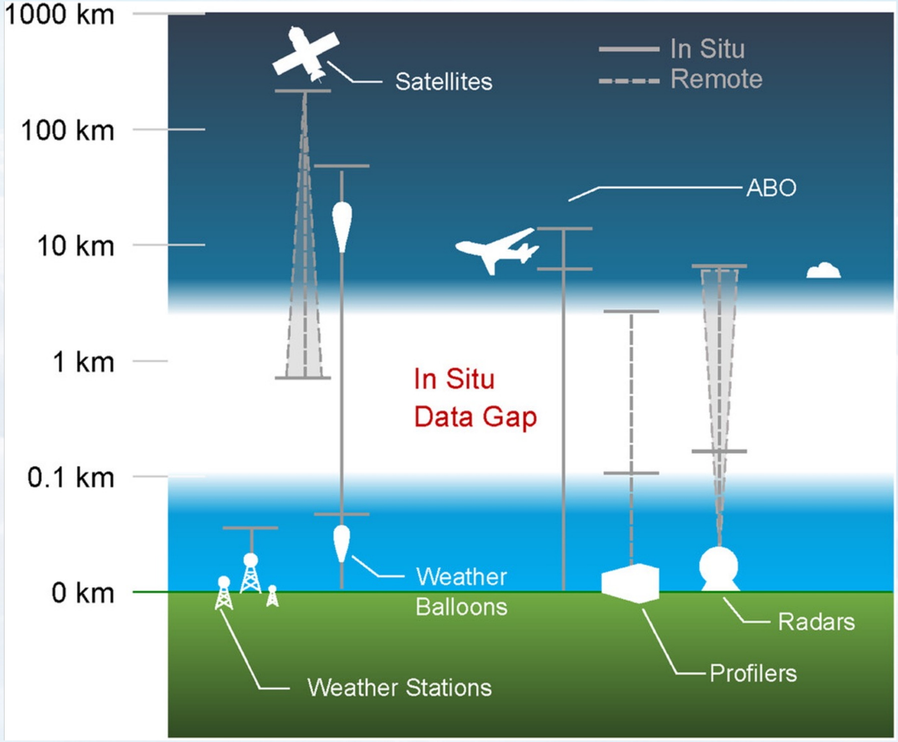


All Observations

Near-Surface Observations

500–1000 m AGL

The Problem: In-Situ Data Gap in PBL



Pinto et al. (2021, *BAMS*)

Why should we care about the planetary boundary layer (PBL)?

https://www.news10.com/weather/weather-101/weather-101-what-cloud-is-that/

https://www.cnn.com/2017/06/05/americas/tornado-lawn-mowing-photo-trnd/index.html

https://www.goldengate.org/exhibits/when-its-foggy-foghorns/

https://www.weather.gov/safety/winter-snow-squall

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Possible Solution: Routine UAS Obs

Fixed sites across the US

Measure T, humidity, and winds

This raises some questions:

- What impact would assimilating UAS obs have on NWP?
- How to configure UAS?
    - Spacing between sites?
    - Vertical vs. horizontal transects?
    - Temporal frequency?
    - Max flight altitude?
    - Targeted obs?

OU CopterSonde (Chilson et al. 2019, *Sensors*)

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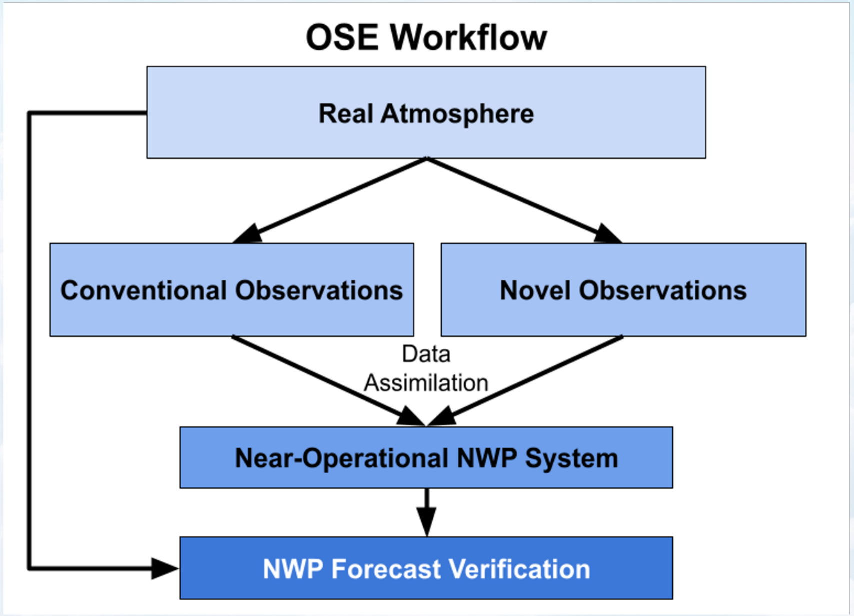
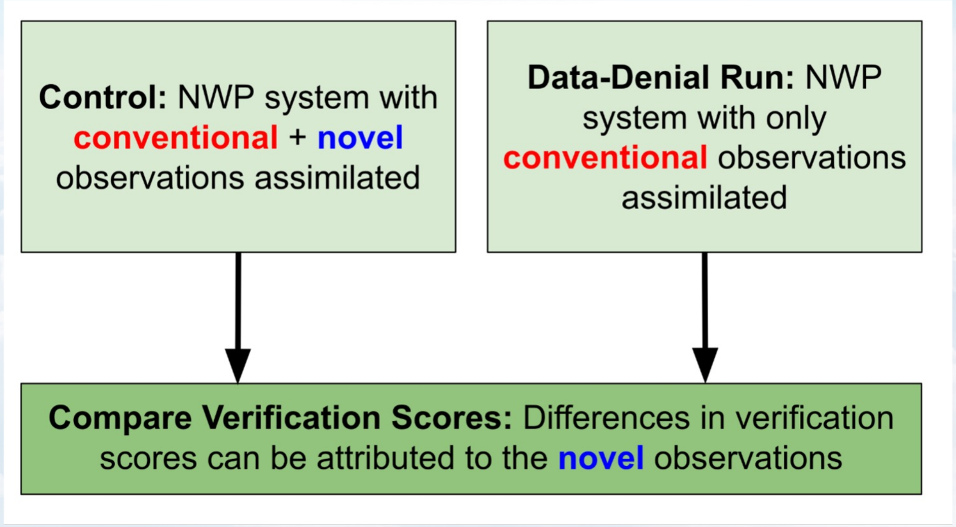
Methodology: Observing System Simulation Experiments (OSSEs)

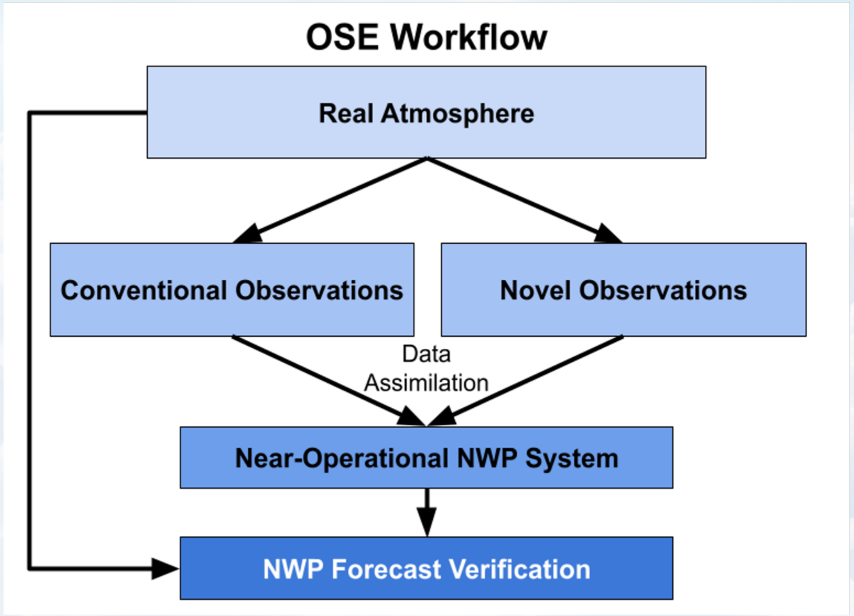
Assessing the Impact of an *Existing* Observation Type





OSE: Observing System Experiment

Assessing the Impact of an *Existing* Observation Type



We have some problems!

- Do not currently have 100s to 1000s of WxUAS
- FAA regulations on UAS
- Expensive! Lots of time & money

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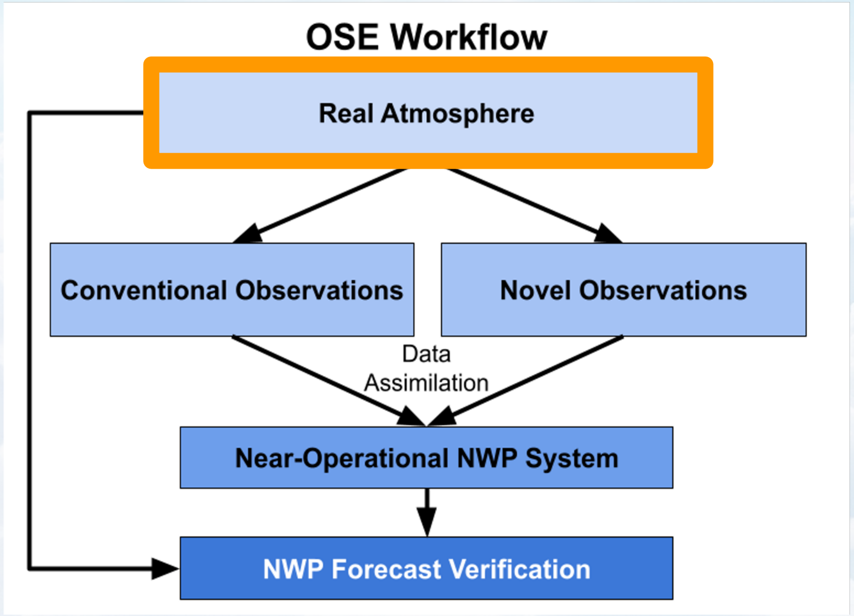
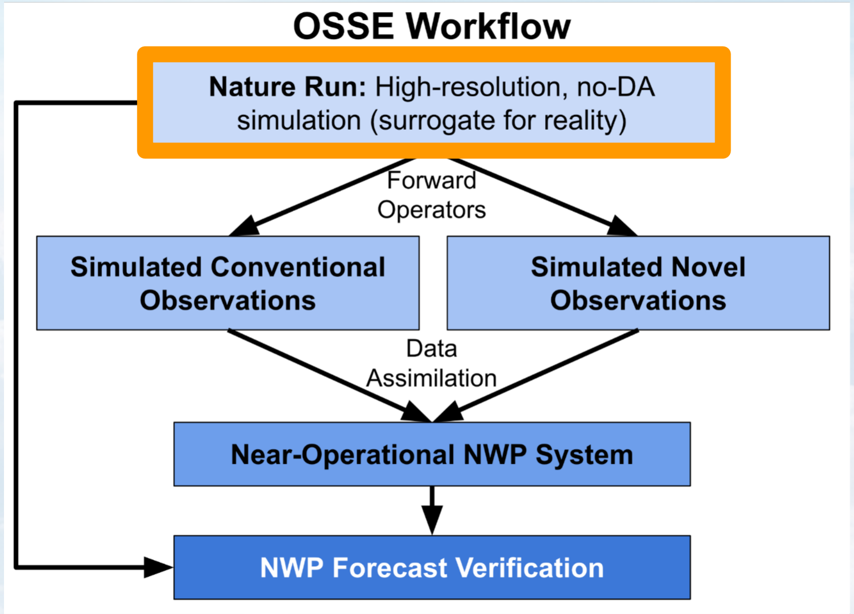
Assessing the Impact of a *Futuristic* Observation Type





OSSE: Observing System Simulation Experiment

Main Difference: OSSEs use a synthetic atmosphere

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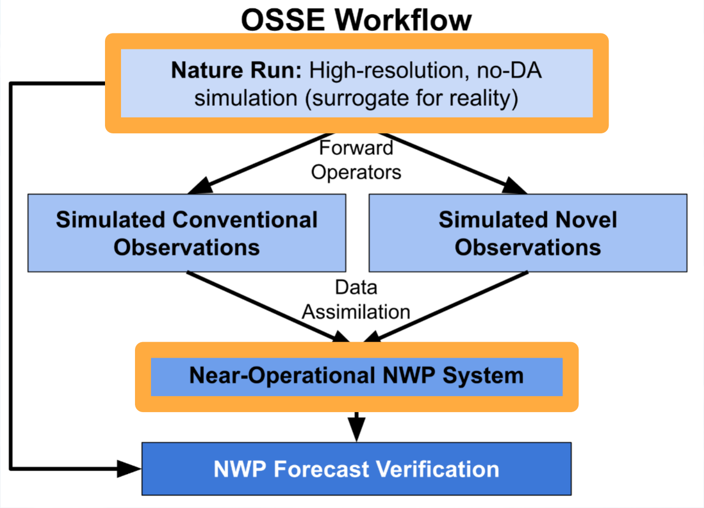
OSSE Framework: Modeling Systems

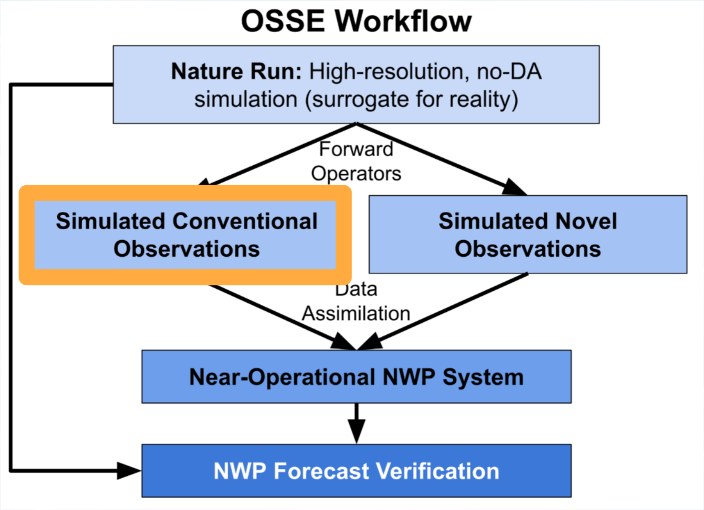


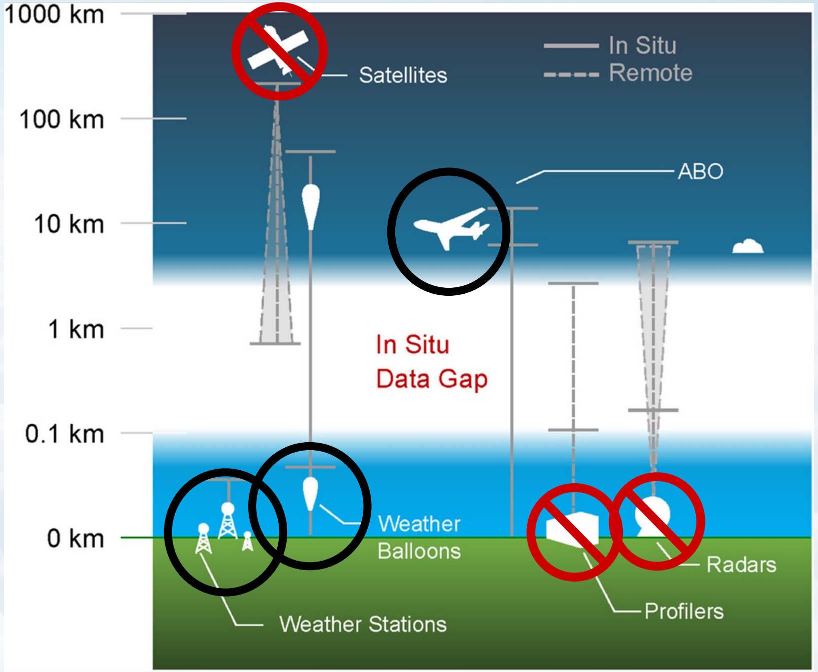
Characteristic	Nature Run (NR)	Forecast System (RRFS)
Dynamical Core	WRF	FV3
Grid Spacing	1 km	3 km
Vertical Levels	101	65
Microphysics Scheme	2-moment NSSL	Thompson
PBL Scheme	MYNN*	MYNN
Initial Conditions	HRRR	GFS
Boundary Conditions	RAP	GFS
DA System	N/A	GSI Hybrid 3DEnVar
Output/Forecast Cadence	15 min	Hourly

Domain: Contiguous US

Two NR weeks: winter 2022 and spring 2022

OSSE Framework: Simulated Observations





GPS PWATs included

Ceilometers omitted

1. Interpolate NR output in time + space to actual observation locations and times
2. Add random errors following Errico et al. (2013, *QJRMS*). Tuning uses winter period.

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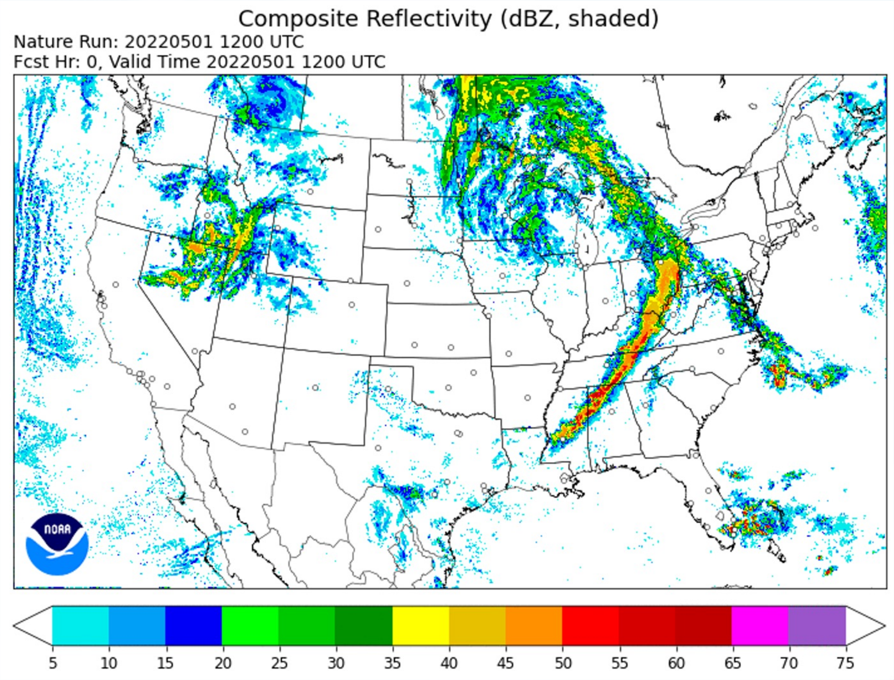
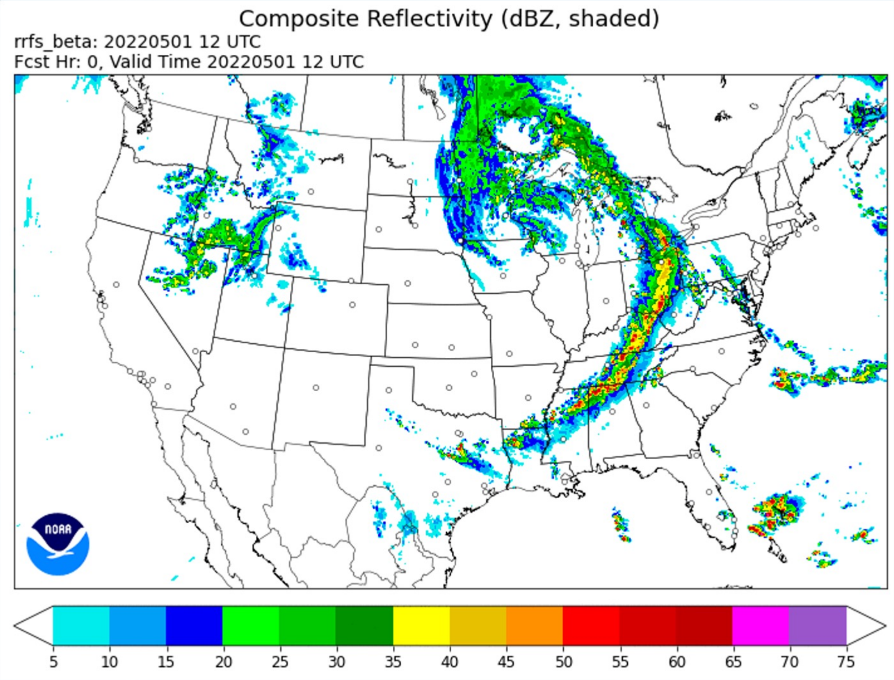
Comparison Between NR and RRFS





Planned UAS Experiments

Experiment	Description
Spatial density	Average distance of 35, 75, 100, and 150 km between stations.
Engineering constraints	Impose limits on UAS flights due to icing and excessive wind speeds (20, 30, or 40 m s^{-1}).
Full tropospheric profiles	Vertical transects to 10 km AGL. Re-test engineering constraints.
Horizontal vs vertical transects	Horizontal transects between UAS site rather than vertical profiles

Default configuration (best-case scenario):

- 35-km horizontal spacing between UAS (same approx spacing as OK Mesonet)
- Vertical profiles with a max flight altitude of 2 km AGL
- Flights every hour

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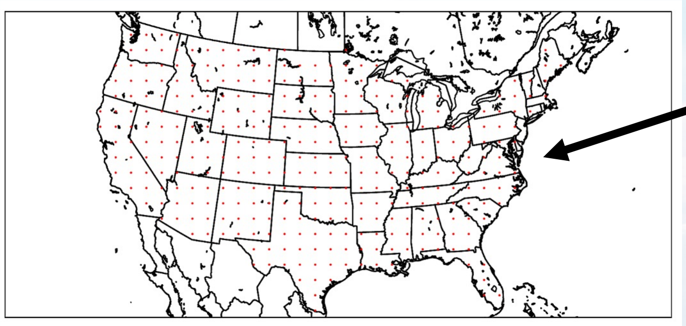
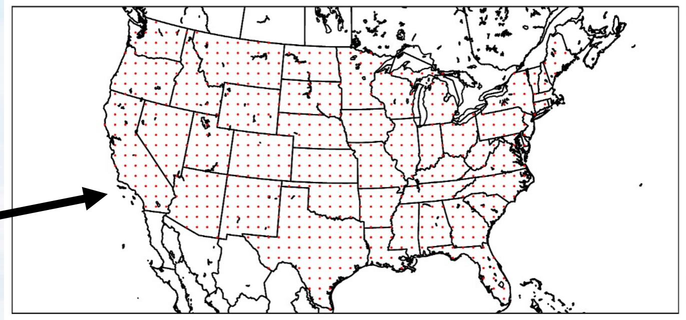
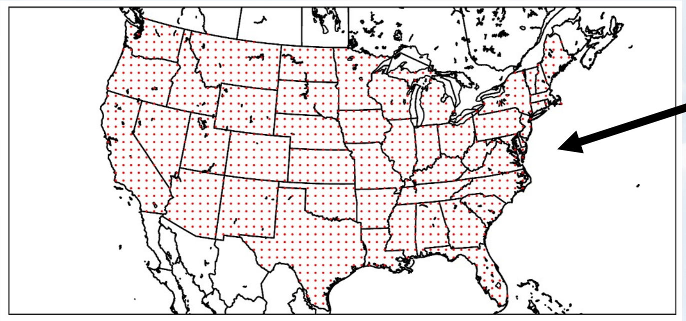
UAS Site Locations for Spatial Density Tests

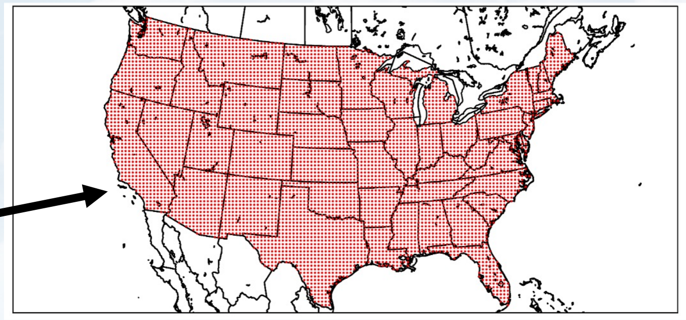




~150 km
(347 sites)

~100 km
(772 sites)





~75 km
(1381 sites)

~35 km
(6335 sites)

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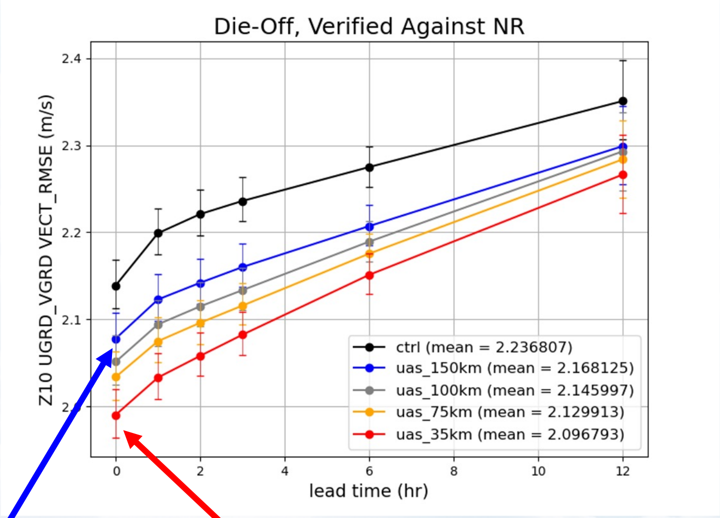
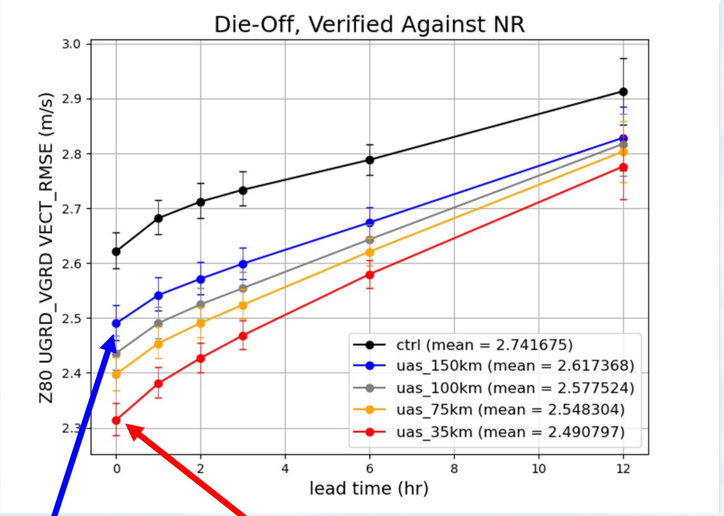
Results: Impact of Assimilating UAS

UAS DA Has a Larger Impact Farther Above the Surface

10-m Winds (Winter)



80-m Winds (Winter)



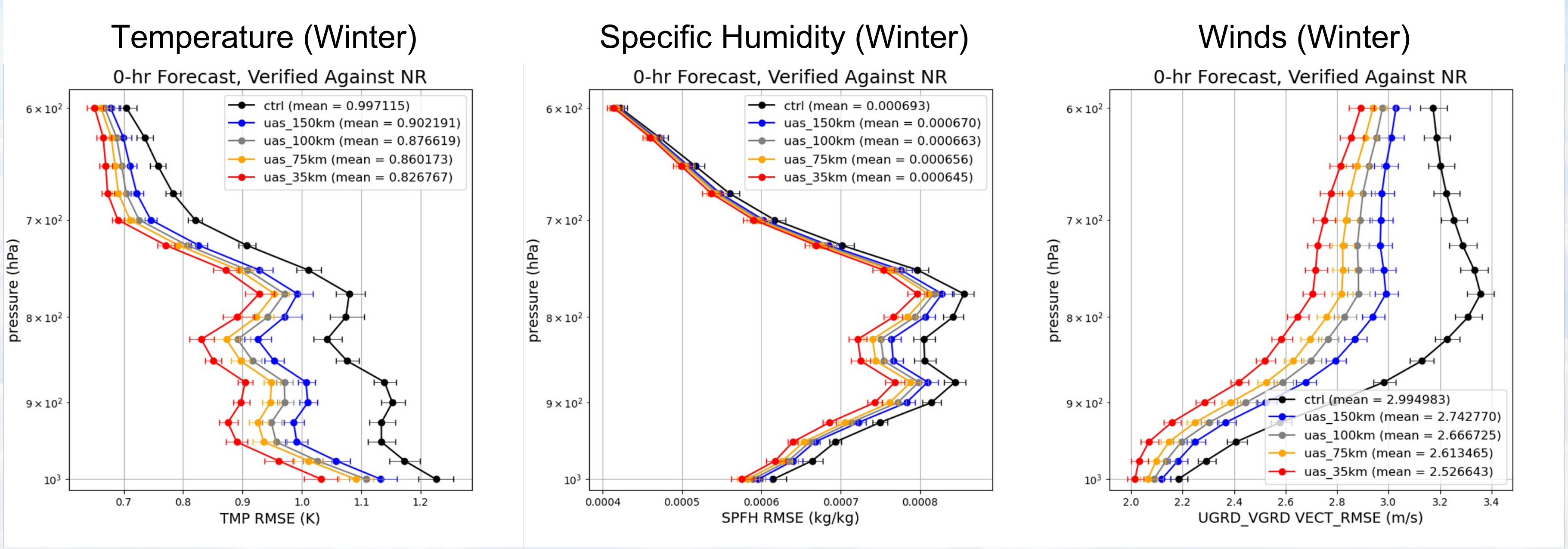
~3.3% reduction in RMSEs

~7% reduction in RMSEs

~5% reduction in RMSEs

~12% reduction in RMSEs

UAS DA Improves Model Analysis in the Lower Atmosphere



Only assimilating UAS every 150 km can **reduce RMSEs by ~10%** at some levels

Assimilating UAS every 35 km can **reduce RMSEs by ~20%** at some levels

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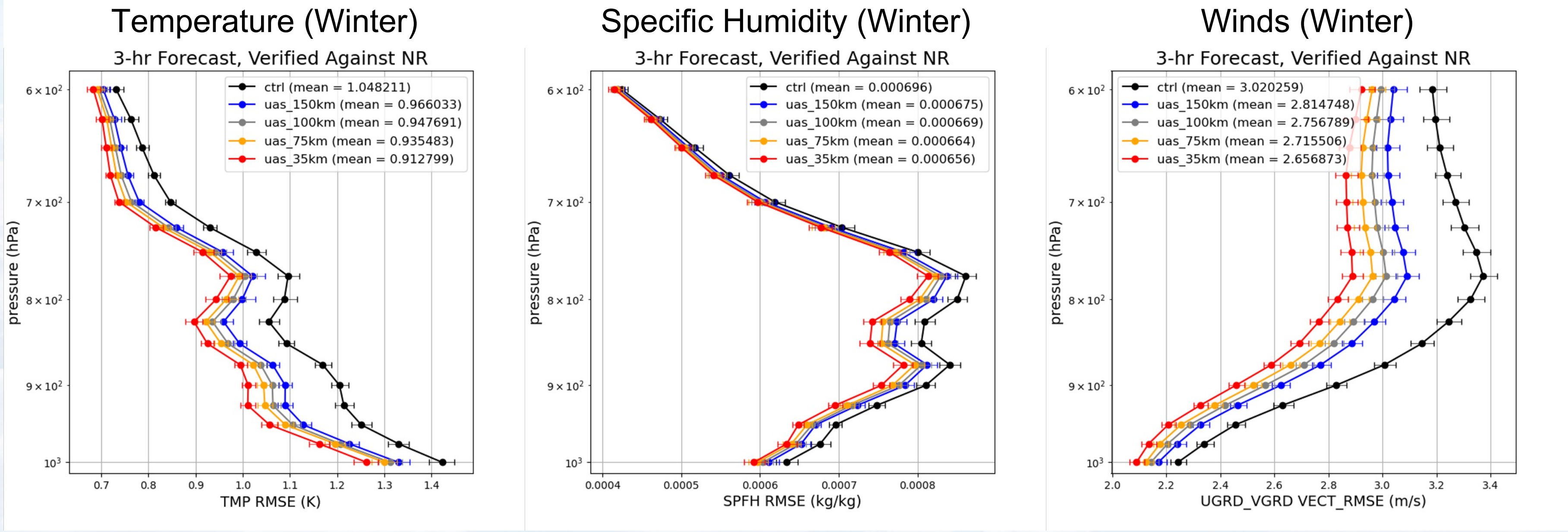
Better Analyses with UAS DA Result in Better Forecasts



Only assimilating UAS every 150 km can **reduce RMSEs by ~10%** at some levels

Assimilating UAS every 35 km can **reduce RMSEs by ~15%** at some levels

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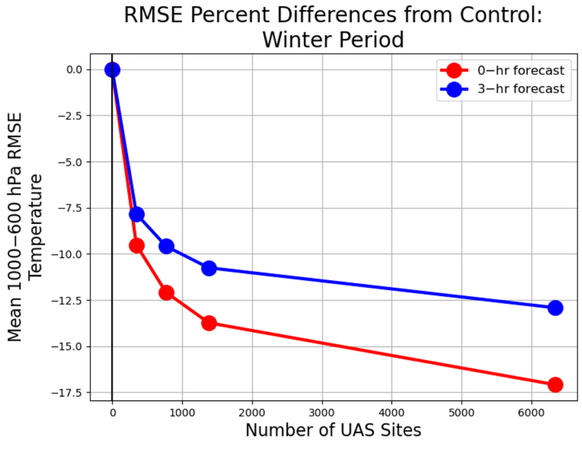
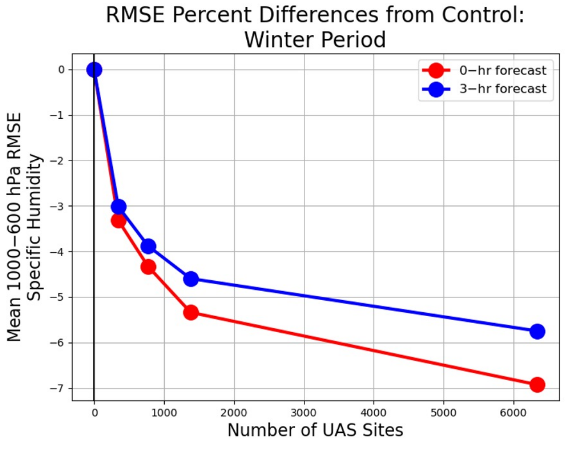
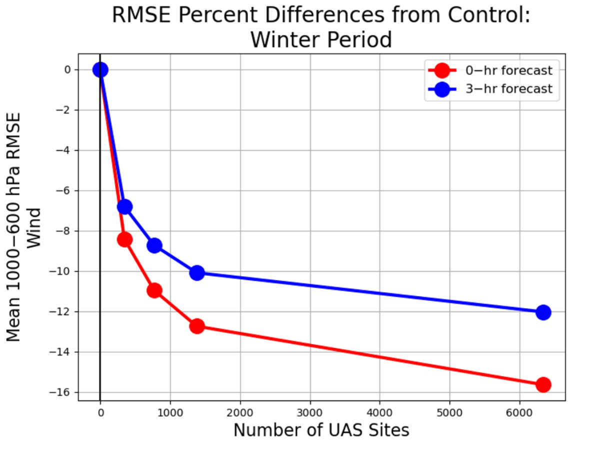
Law of Diminishing Returns When Using More UAS







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Caveats

- OSSEs are not perfect
  - Nature run does not capture all scales of motion
  - Simulated observations may differ from reality
    - No biases
    - No re-routing of aircraft, ships, etc. for local meteorology
    - Non-Gaussian errors largely ignored
  - Forecast error growth in OSSE will not perfectly match reality
- Some currently used observations were withheld (e.g., satellite, radar)
- UAS were not constrained by local meteorology, FAA regulations, etc.
- Only presented bulk statistics
- RRFS is likely too coarse to be useful for urban air mobility

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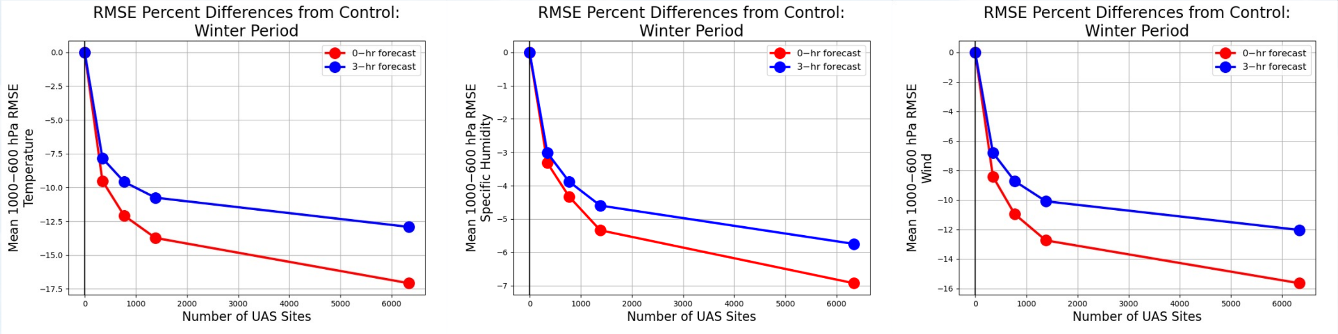
Summary

- Developed an Observing System Simulation Experiment (OSSE) framework to study UAS impact on weather forecast models
  - Nature run: WRF with 1-km grid spacing over CONUS. Surrogate for reality.
  - Forecast model: RRFS with 3-km grid spacing.
- Assimilate different numbers of synthetic UAS flying to 2 km every hour
  - Assimilating UAS can reduce forecast errors by >10% in the lower atmosphere
  - Benefits diminish as more UAS are assimilated



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References

Chilson, P. B., and Coauthors, 2019: Moving towards a network of autonomous UAS atmospheric profiling stations for observations in the Earth’s lower atmosphere: The 3D mesonet concept. *Sensors*, **19** (12), 2720, https://doi.org/10.3390/s19122720.

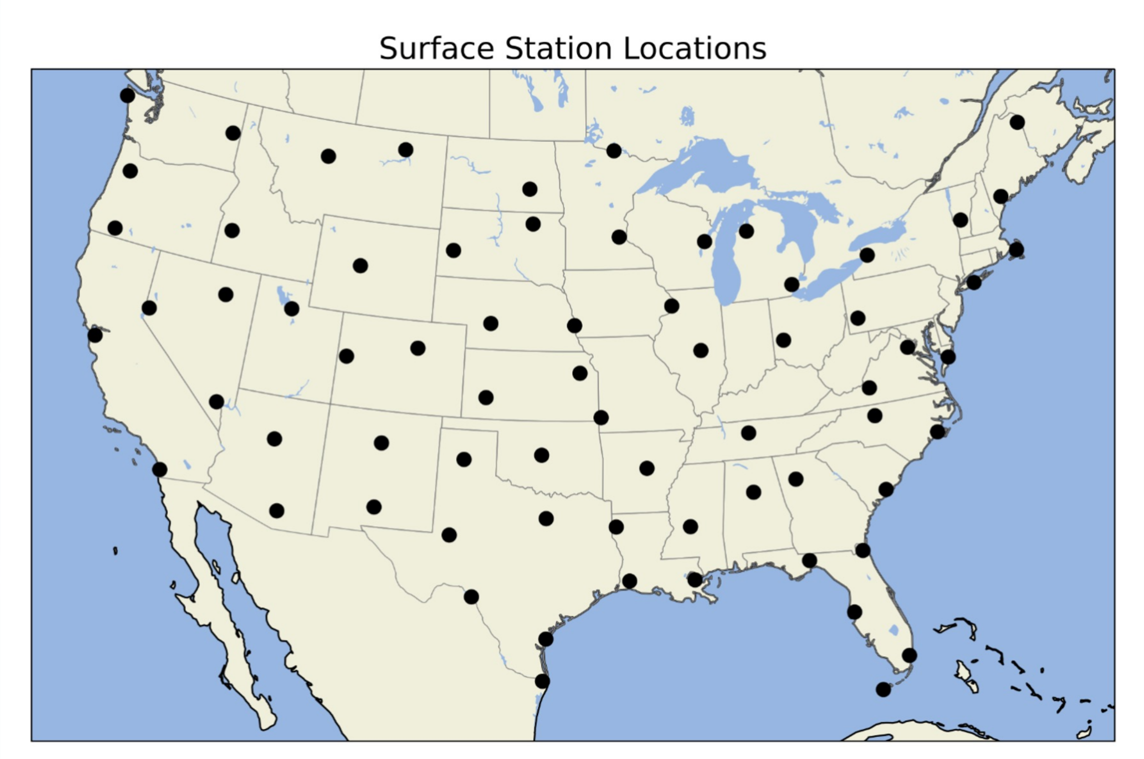
Errico, R. M., R. Yang, N. C. Privé, K.-S. Tai, R. Todling, M. E. Sienkiewicz, and J. Guo, 2013: Development and validation of observing-system simulation experiments at NASA’s global modeling and assimilation office. *Quart. J. Roy. Meteor. Soc.*, **139** (674), 1162–1178, https://doi.org/10.1002/qj.2027.

Pinto, J. O., and Coauthors, 2021: The Status and Future of Small Uncrewed Aircraft Systems (UAS) in Operational Meteorology. *Bull. Amer. Meteor. Soc.*, **102**, E2121–E2136, https://doi.org/10.1175/BAMS-D-20-0138.1.

Extra Slides

NR Comparison: Surface Station Locations

Surface station locations loosely correspond to radiosonde locations



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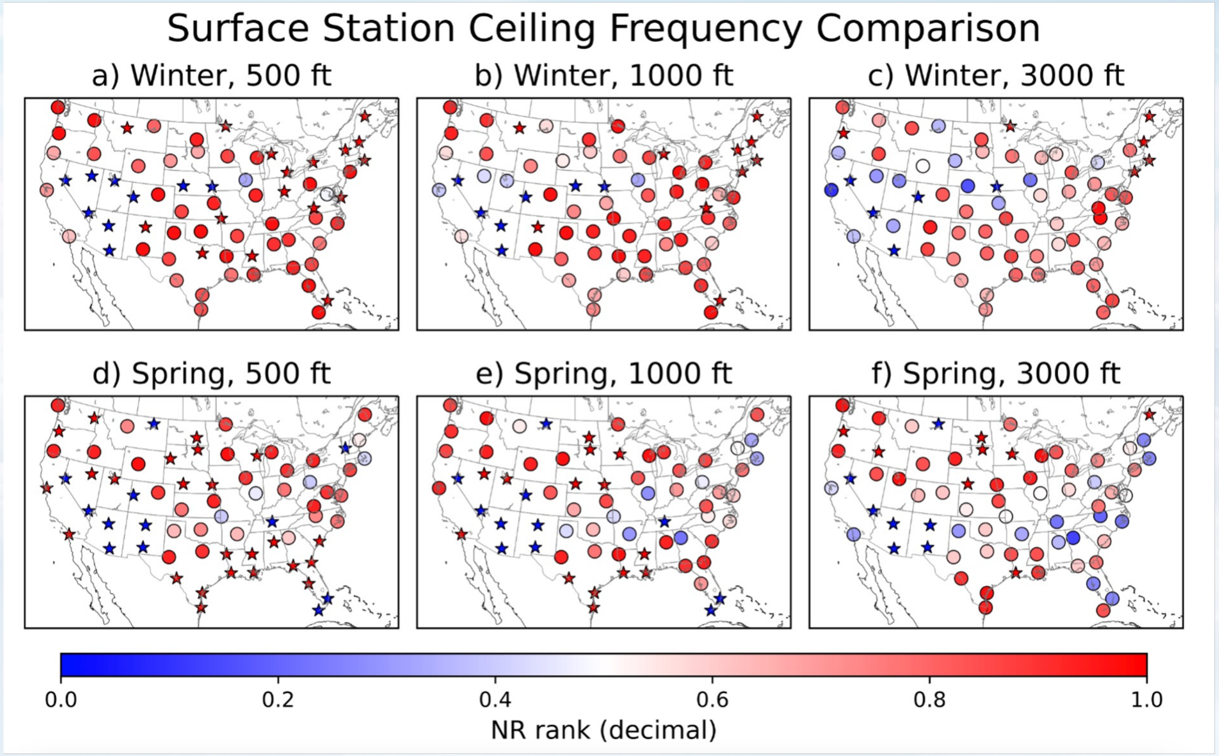
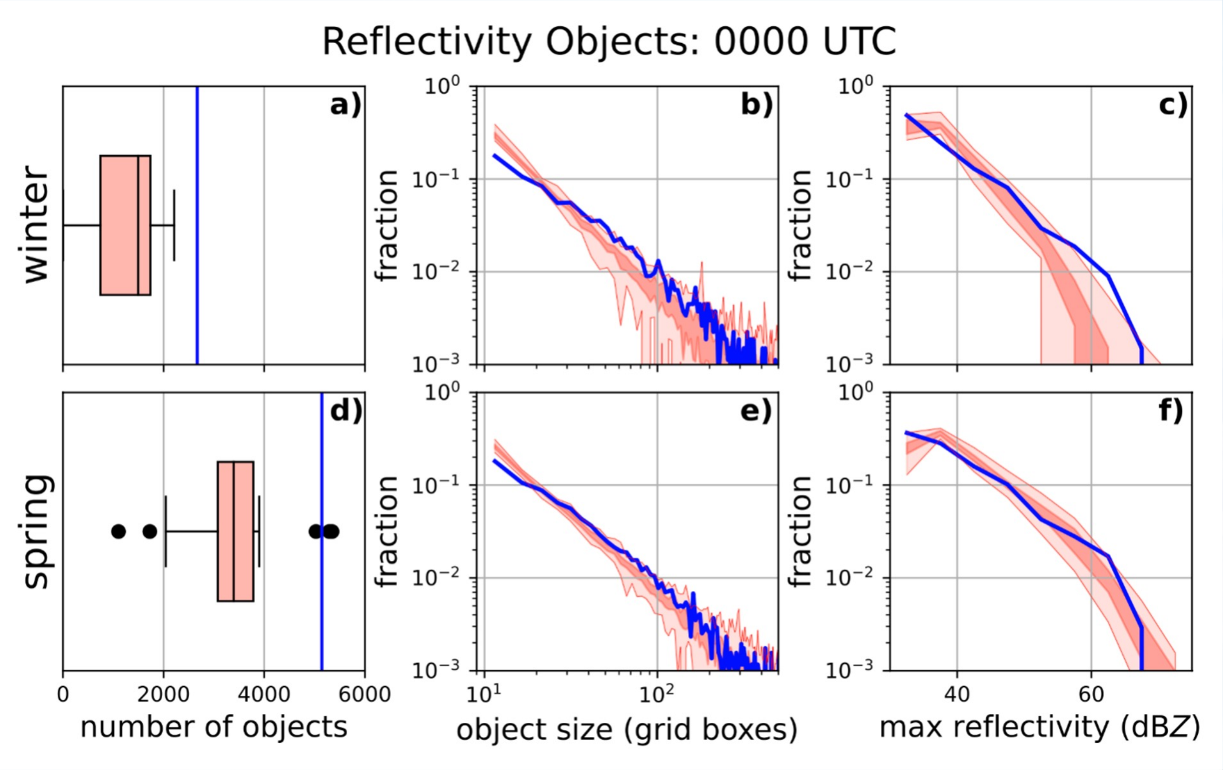
NR Comparison: Surface Station Ceilings

Stars: Rank of ceiling frequency from NR is either 0 or 1 (i.e., ceiling frequency in NR lies outside the surface station climatology)



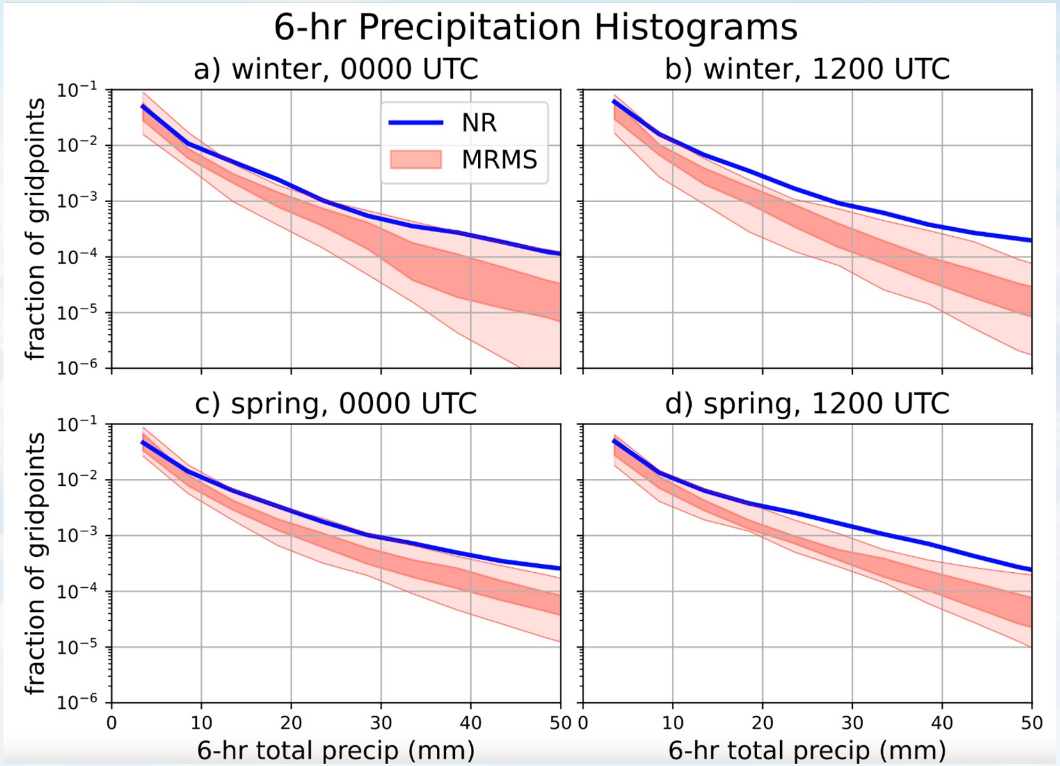
NR Comparison: MRMS Reflectivity Objects

- MRMS climatology: Use week prior, week of, and week after the NR week for 9 years (8 for winter), resulting in 27 (24) weeks for the spring (winter)
- Reflectivity objects:
  - Z > 30 dBZ
  - Size > 9 grid boxes
- Note that MRMS and NR have approximately the same grid spacing



NR Comparison: MRMS Precipitation

- MRMS climatology: Use week prior, week of, and week after the NR week for 6 years, resulting in 18 weeks
- Note that MRMS and NR have approximately the same grid spacing
- Use gauge-corrected QPE or two-pass, multi-sensor QPE from MRMS



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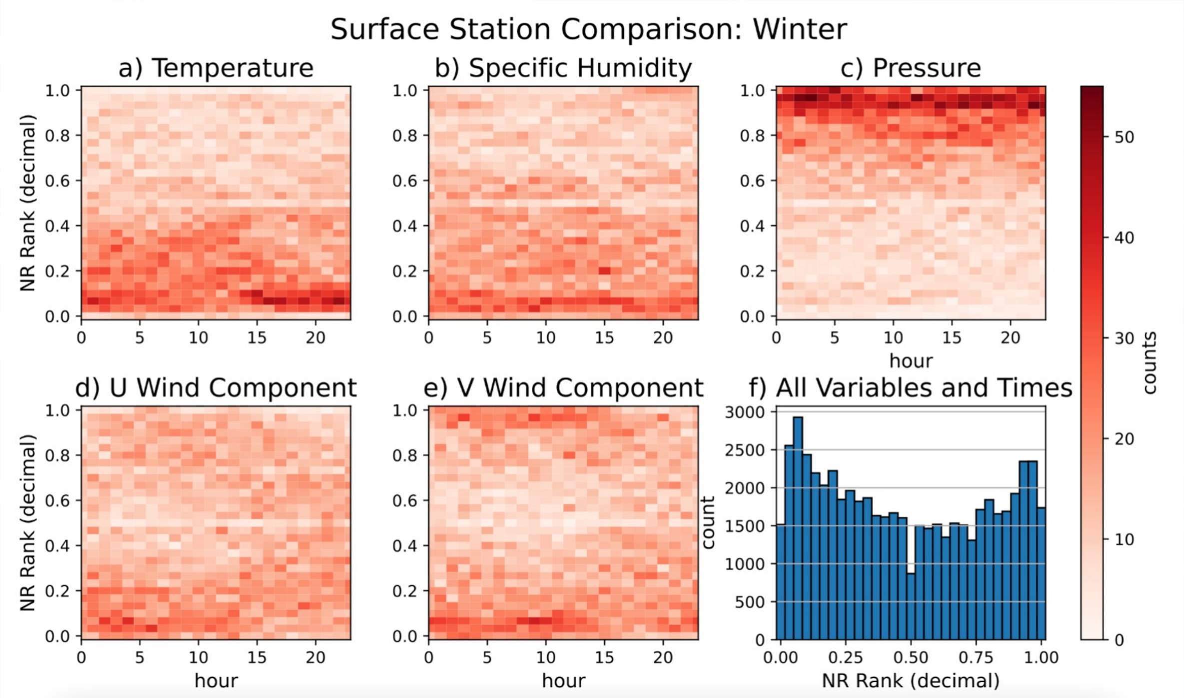
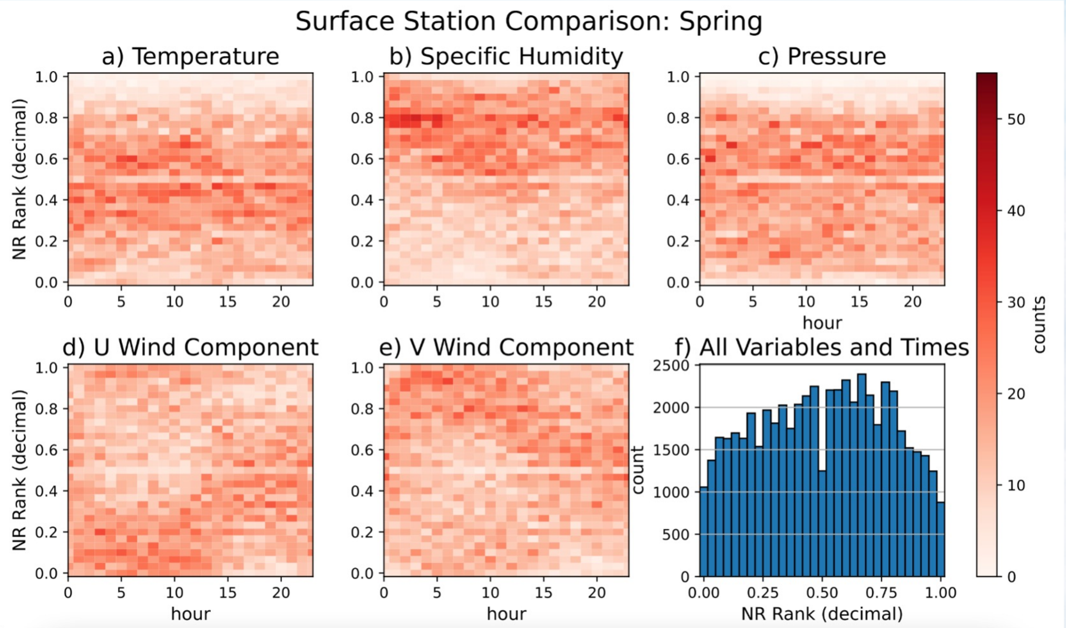
NR Comparison: Surface Stations (Winter)

Agreement is worse for the winter, but NR still tends to lie within the envelope of the 30-year climatology.



NR Comparison: Surface Stations (Spring)

- 69 surface stations
- Create 30-year climatology for each station
- Plot NR rank relative to the 30-year climatology (*same concept as rank histogram*)
    - Convert rank to a decimal
    - Goal: Have the NR rank **not** be 0 or 1
    - Each column in the heatmap shows the NR ranks for all 69 sites and all 7 days for a single hour



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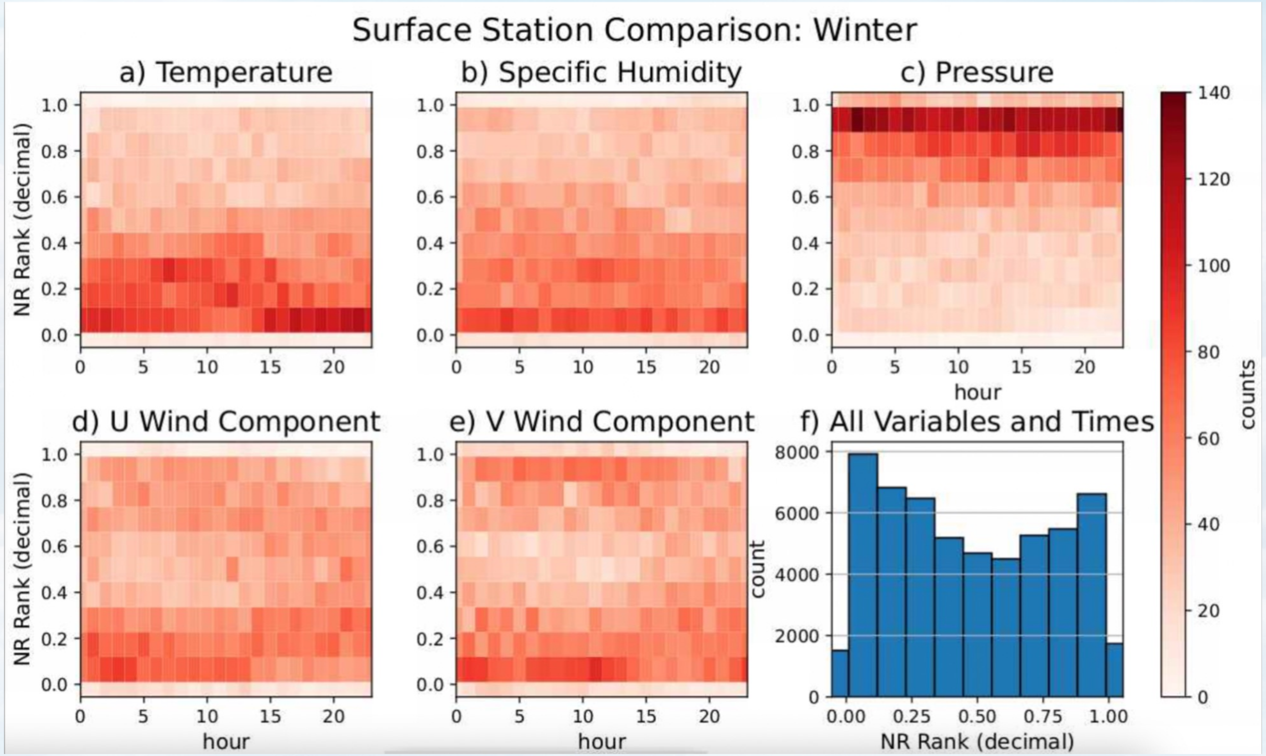
NR Comparison: Surface Stations (Winter)



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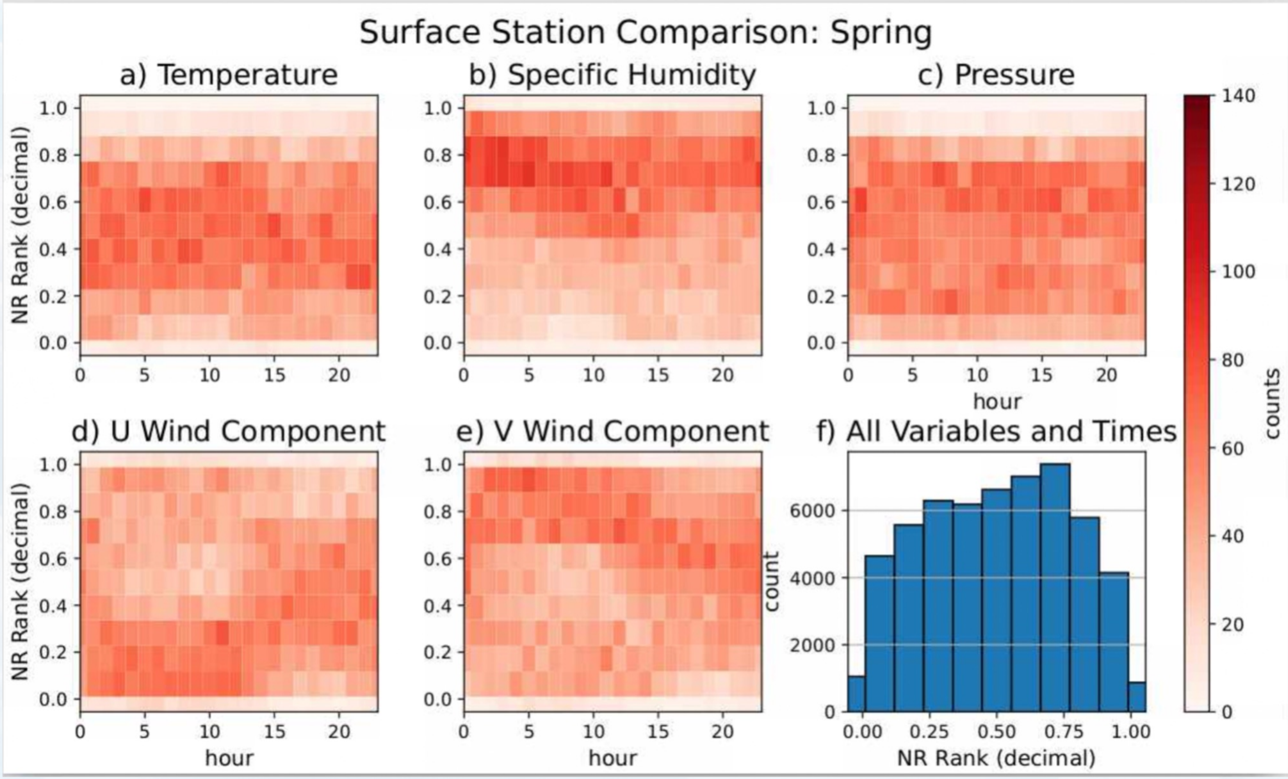
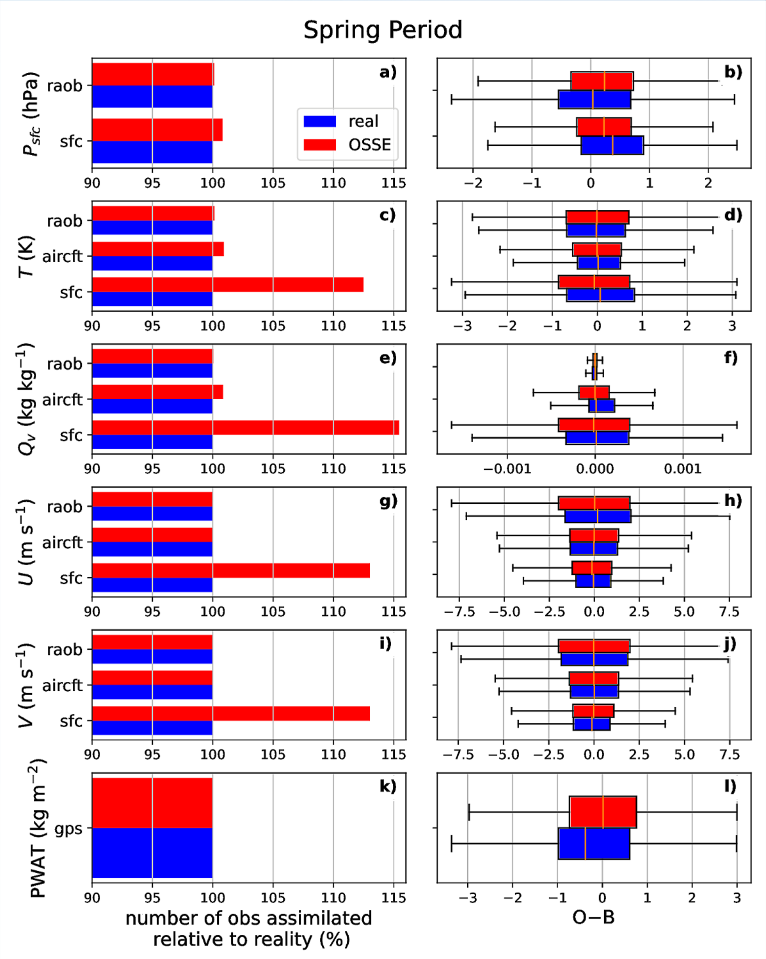
NR Comparison: Surface Stations (Spring)



DA Statistics: Spring

- First 69 hrs of spring period with all obs assimilated
- 10–15% more sfc obs are assimilated in OSSE
  - B/c GSI removes consecutive sfc obs with the same pressure
- O–Bs tend to be…
  - Larger in OSSE for T and Q_v
  - Smaller in OSSE for P_{sfc}



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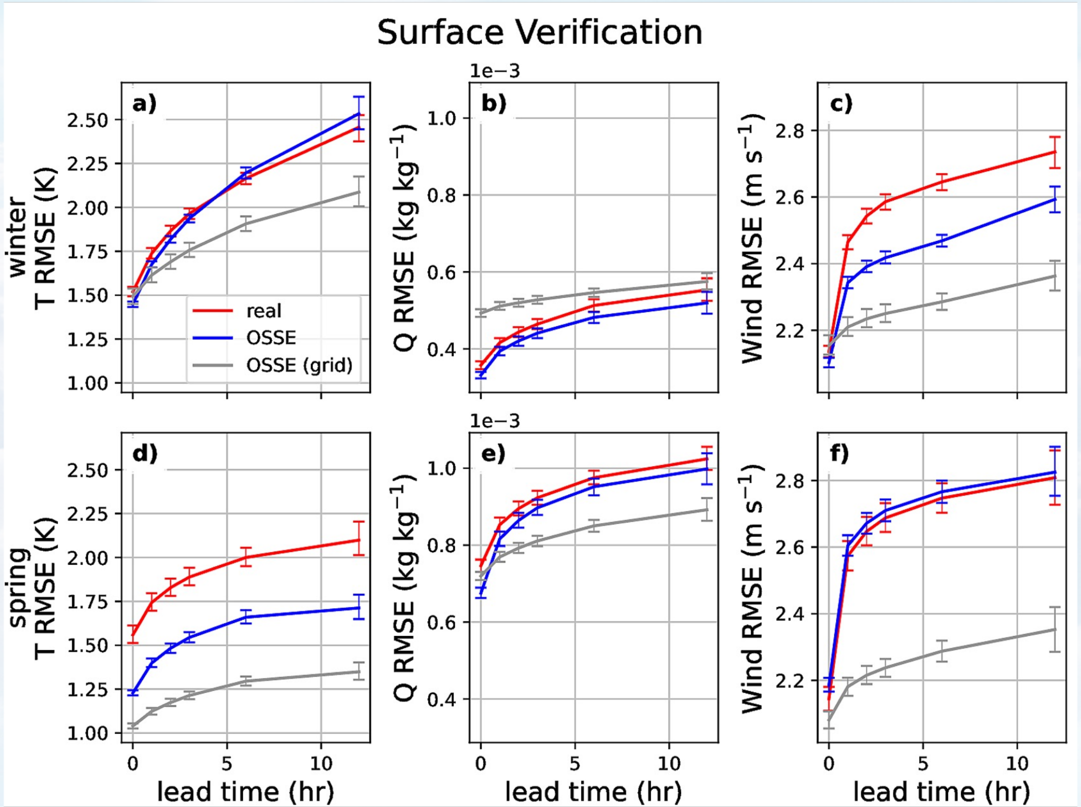
Control Runs: Surface Verification



- OSSE verification is against synthetic obs with errors (blue) or NR grids (gray)
- Errors are systematically smaller in the OSSE for 2-m T in the spring and 10-m winds in the winter
- No clear “identical twin” issue

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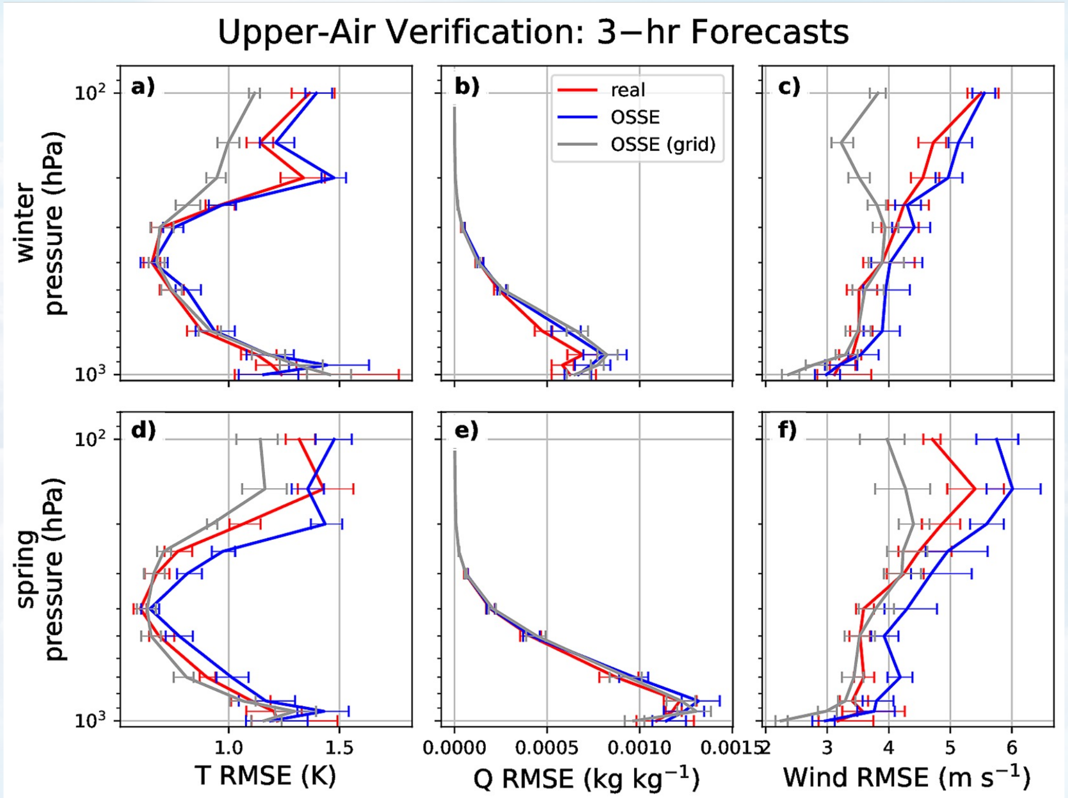
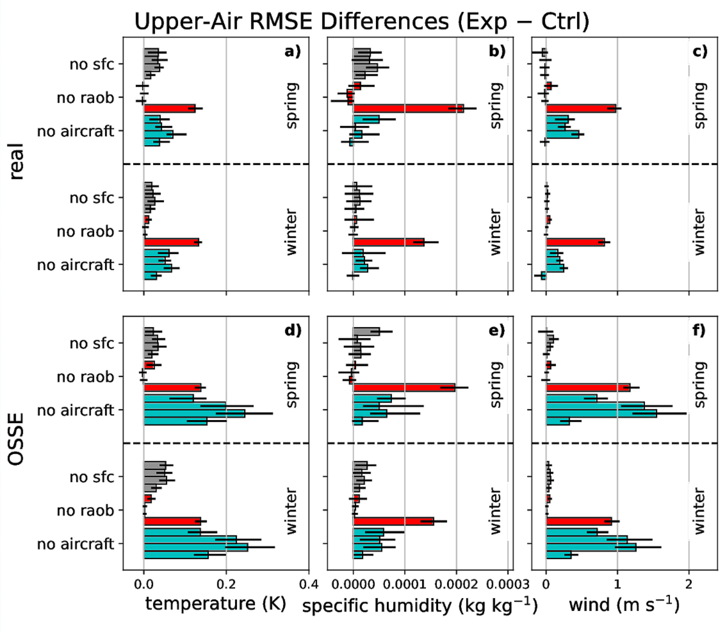
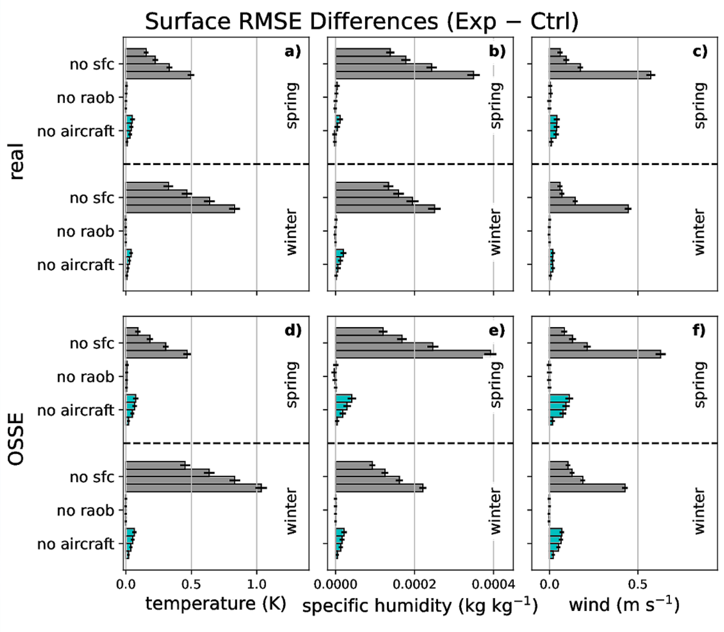
Control Runs: Upper-Air Verification



- OSSE verification is against synthetic obs with errors (blue) or NR grids (gray)
- Forecast errors generally agree between OSSe and reality, particularly in the lower atmosphere
- No clear “identical twin” issue

Data-Denial Experiments





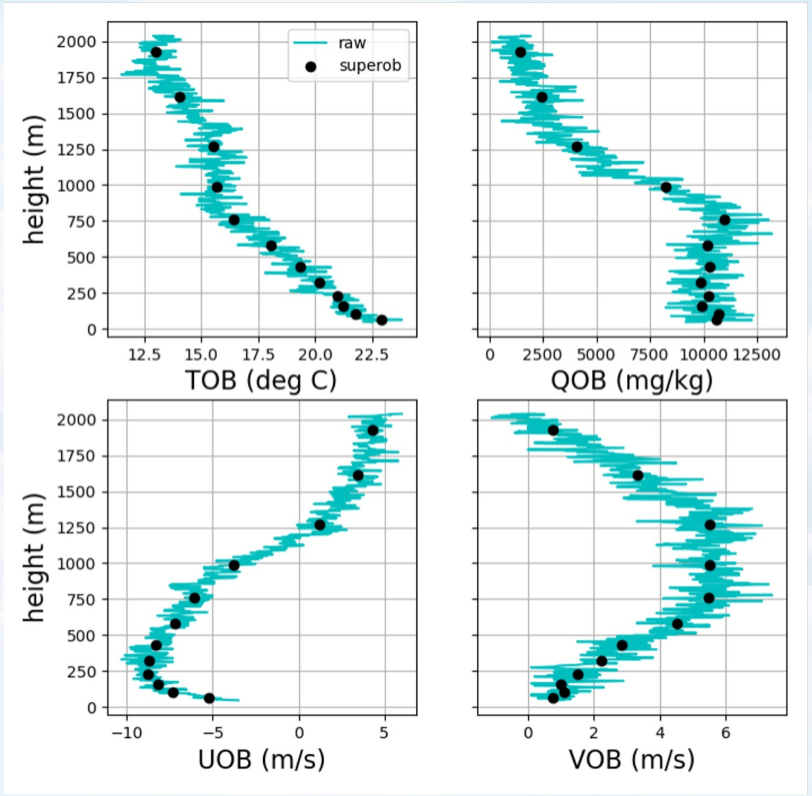
Bars for each subset:
6-hr fcst
3-hr fcst
1-hr fcst
Analysis

Lines: 95% confidence interval

Positive values indicate obs have positive impact on forecast

Trends are similar, except commercial aircraft are more impactful in the OSSE

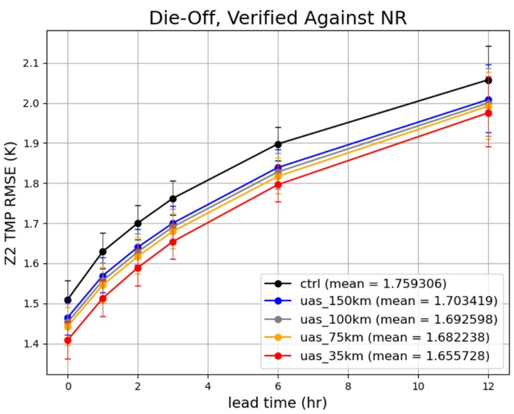
UAS Superobbing Procedure



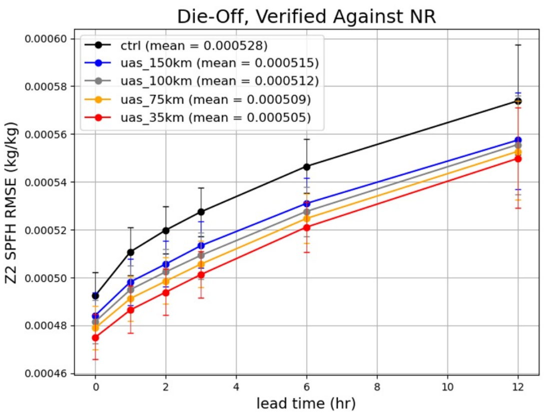
- Raw UAS data are at 1 Hz with an ascent rate of 3 m s^{-1}
- Superob bins are created using every other vertical model level (i.e., each bin spans two vertical model layers)
- All raw obs within a bin are combined using a 1D Cressman average

UAS DA Modestly Improves Near-Surface Forecast Skill

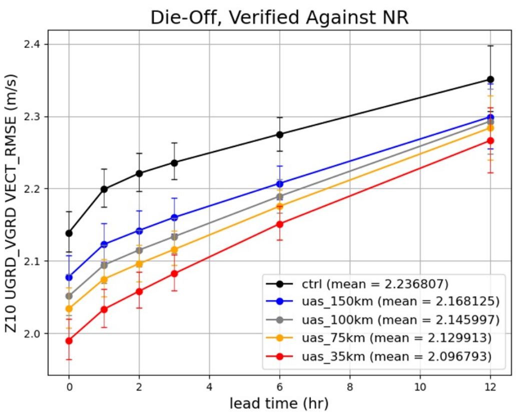
2-m Temperature



2-m Specific Humidity



10-m Winds



Largest improvement for winds, smallest for temperature

We already have lots of surface observations, so we wouldn't expect a large impact from UAS

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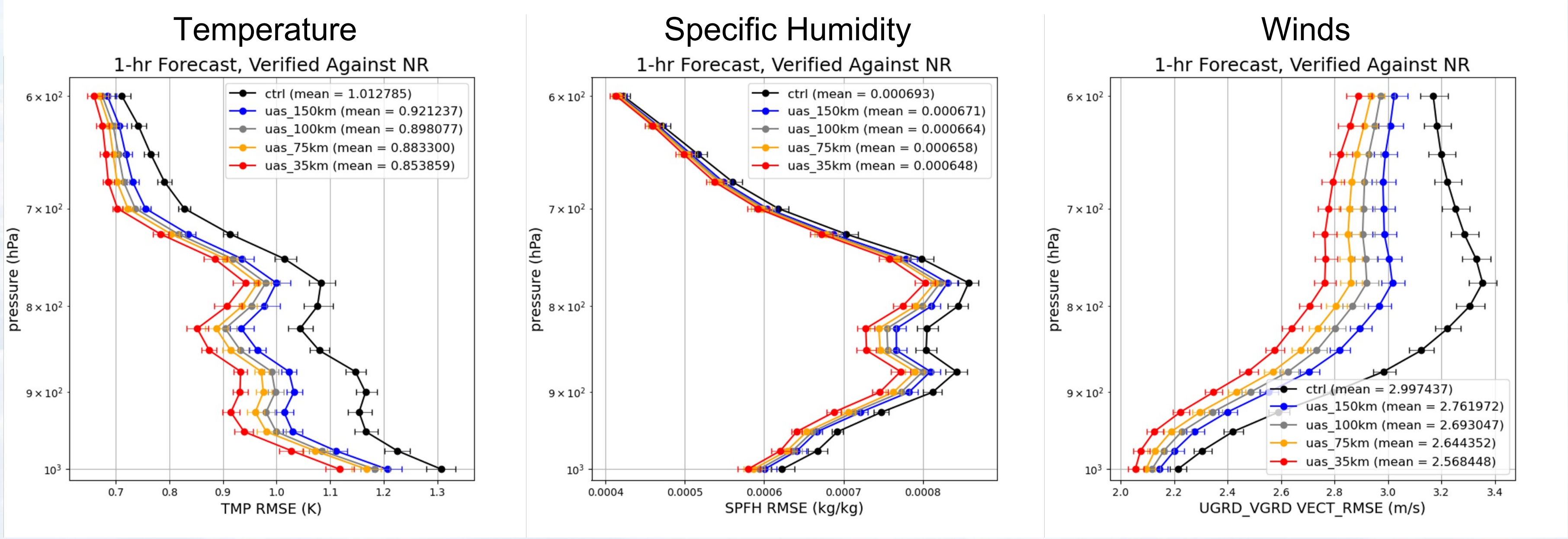
UAS Impact on 1-Hour Forecasts



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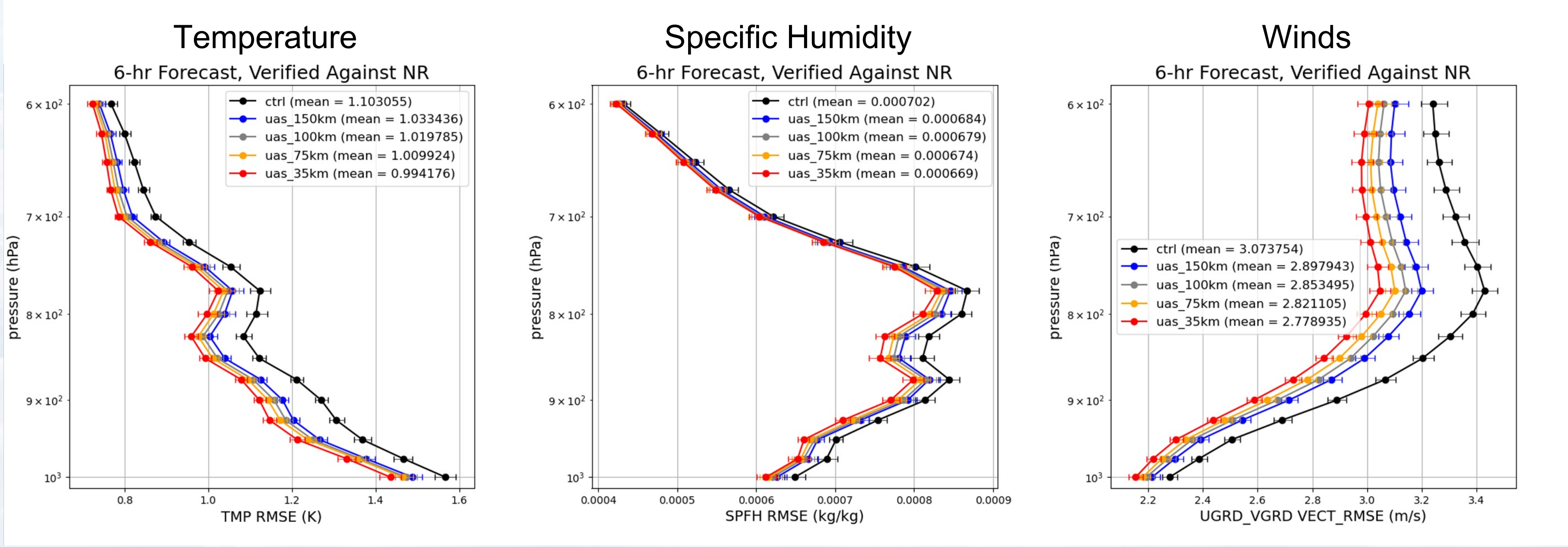
UAS Impact on 6-Hour Forecasts



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