PERiLS PBL Profiling:
CLAMPS and CopterSonde UAS

Dr. Elizabeth Smith Research Meteorologist–NOAA National Severe Storms Laboratory
Affiliated Assistant Professor–OU School of Meteorology

Tyler Bell, Joshua Gebauer, Tony Segales – OU CIWRO

Our Context: PERiLS

Similar goals – understand storms and environments, etc – and building on VORTEX-SE lessons while going *partly mobile* to target **q**uasi-**l**inear **c**onvection **s**ystems (QLCSs)

Southeast US complexity invites innovation to meet mission needs:

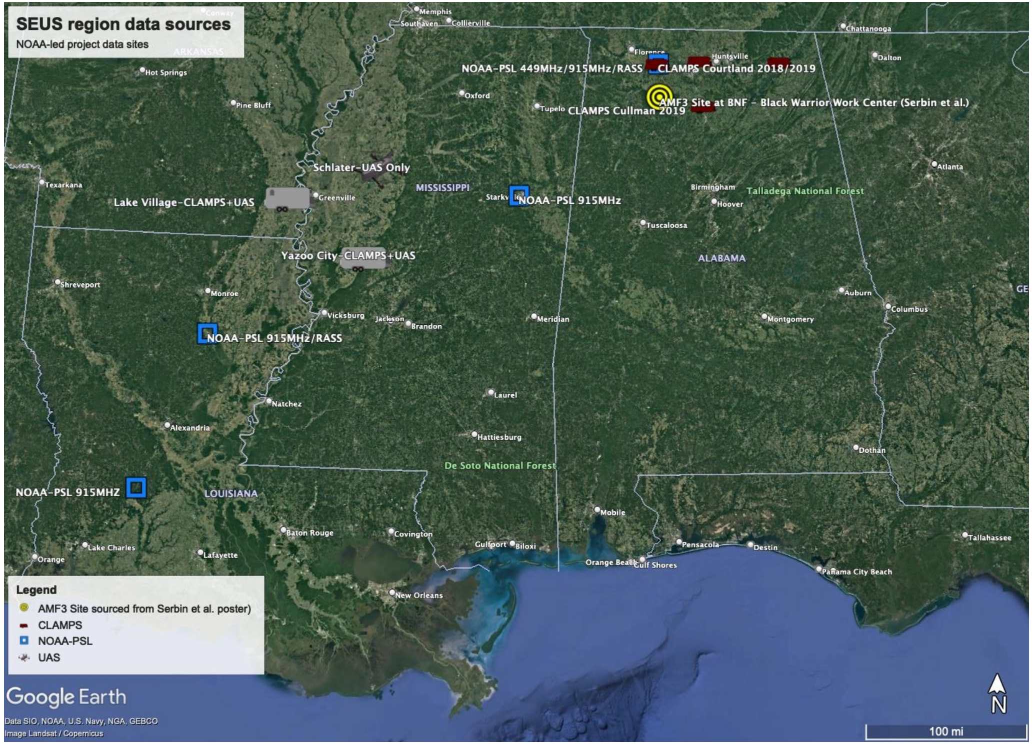
- Observation platforms
- Observation strategies
- Observation analysis products

VORTEX-USA/PERiLS

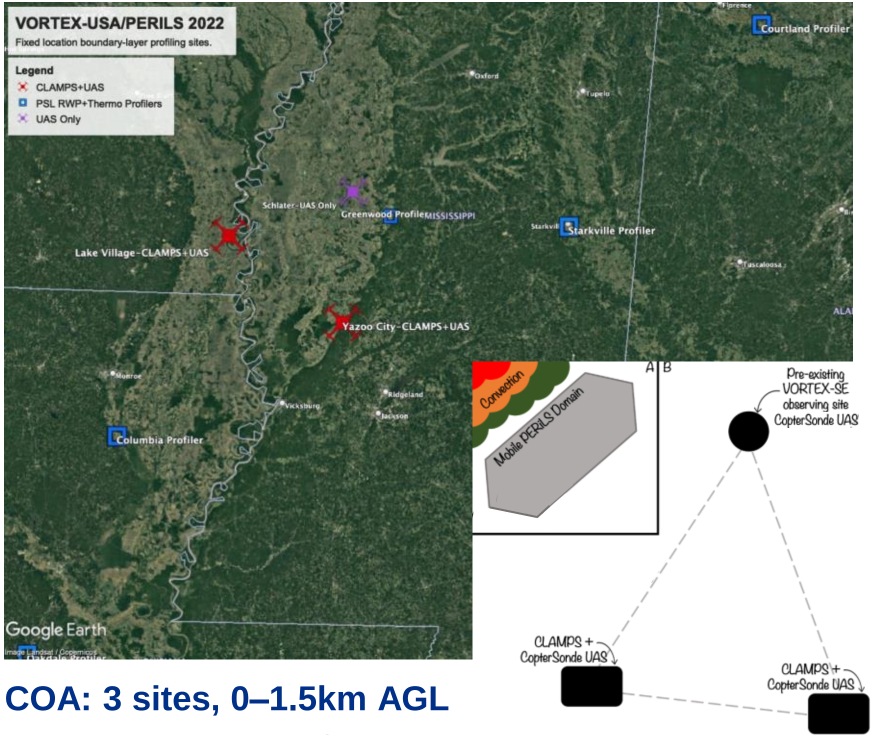
2015-2020 VORTEX-SouthEast

Cool season deployments of fixed facilities to North Alabama

Use these years of data to determine scales of motion and necessary observation spacing



Innovation as motivation for PERiLS CONOPS



COA: 3 sites, 0–1.5km AGL

0–5000 feet AGL

Need: *network* low-atmosphere observations in *challenging environment* of southeastern US

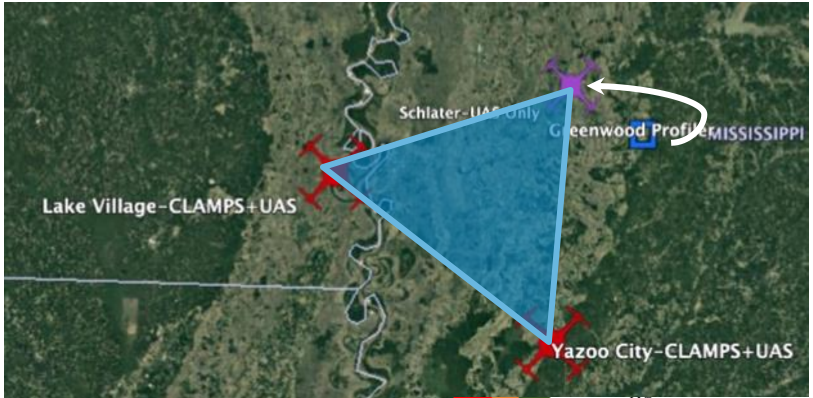
VORTEX-SE findings: above-surface variability critical, ~~2016-2019 remote sensor profiling obs suggested ~50 km min. spacing~~, 90 km spacing

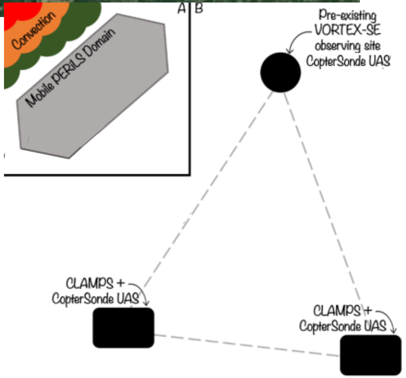
PERiLS opportunity: deploy prototype network with *network-in-network* framework

- Finer spacing within broader coarse deployment
- Mix obs types; remote sensor types and **UAS**
- Enables experiments with adaptable network concepts, testing data assimilation density needs, evaluating impacts of mixed obs networks, etc…

PERiLS as a next-generation observation network testbest

Innovation as motivation for PERiLS CONOPS





Green's Theorem

$$\oint_C P\,dx + Q\,dy = \iint \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dA$$

Need: *network* low-atmosphere observations in *challenging environment* of southeastern US

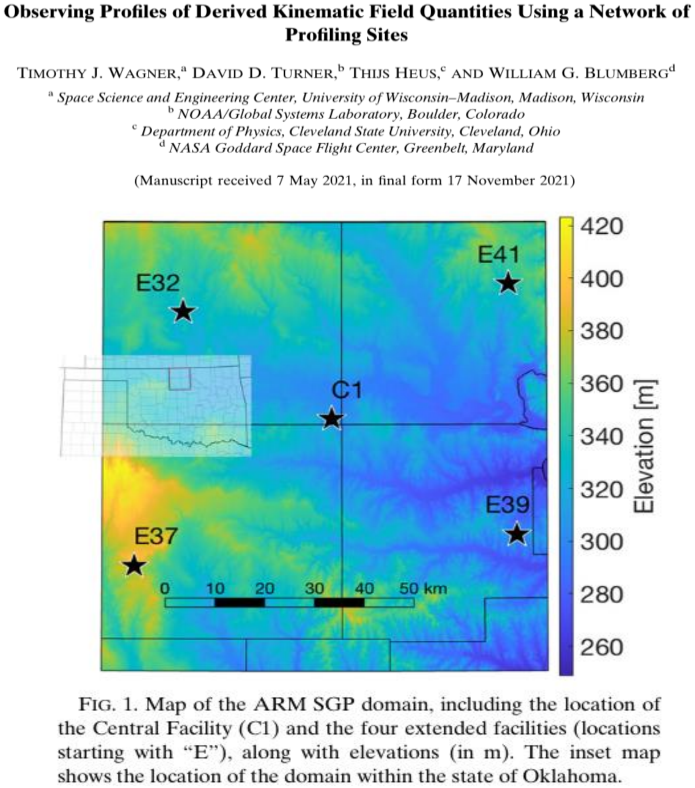
VORTEX-SE findings: above-surface variability critical

PERiLS opportunity: deploy prototype network with *network-in-network* framework

- **Networked deployment strategy enables interesting analyses**
- **Exploring development of products for future next-generation networks, *including 3D networks***

Green’s Theorem: Wagner et. al. (2022)

- Used HRRR profiles and data from remote profilers locations at the ARM SGP central and satellite facilities to evaluate the method
- Decent agreement between quantities derived from HRRR and ARM data
- Found small perturbations to the location of a vertex could impact calculations, especially if the magnitudes were small to begin with



Observing Profiles of Derived Kinematic Field Quantities Using a Network of Profiling Sites

TIMOTHY J. WAGNER,[a] DAVID D. TURNER,[b] THIJS HEUS,[c] AND WILLIAM G. BLUMBERG[d]

[a] *Space Science and Engineering Center, University of Wisconsin–Madison, Madison, Wisconsin*
[b] *NOAA/Global Systems Laboratory, Boulder, Colorado*
[c] *Department of Physics, Cleveland State University, Cleveland, Ohio*
[d] *NASA Goddard Space Flight Center, Greenbelt, Maryland*

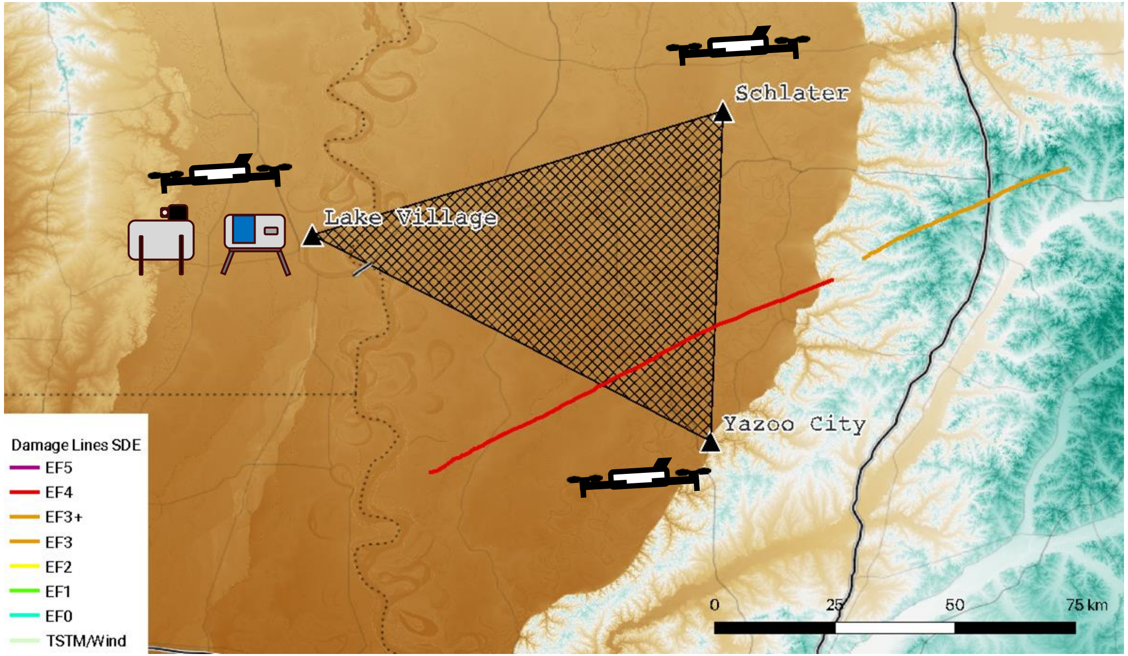
(Manuscript received 7 May 2021, in final form 17 November 2021)

FIG. 1. Map of the ARM SGP domain, including the location of the Central Facility (C1) and the four extended facilities (locations starting with “E”), along with elevations (in m). The inset map shows the location of the domain within the state of Oklahoma.

Green’s Theorem: Application

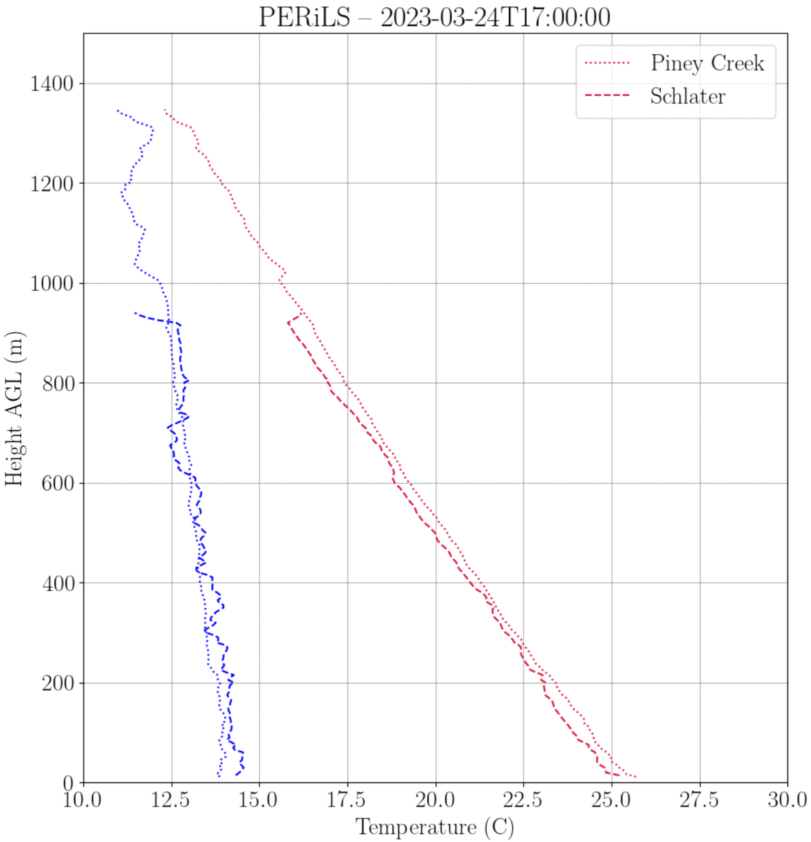
Rolling Fork Tornado

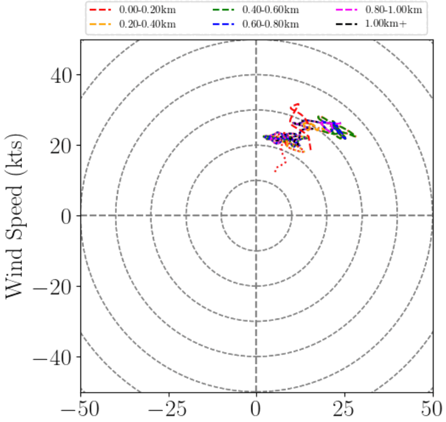
PERiLS mobile armada deployed NNW
(Lake Village area)

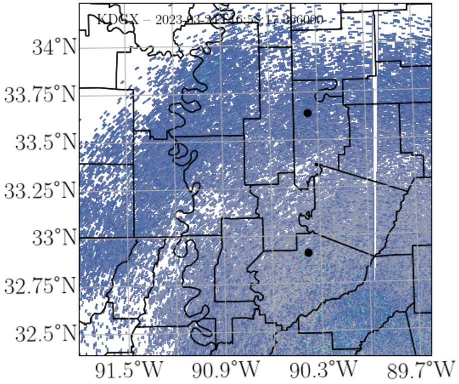


inside.nssl.noaa.gov/ensmith — elizabeth.smith@noaa.gov

Green’s Theorem: Application







Each line is one Coptersonde site.

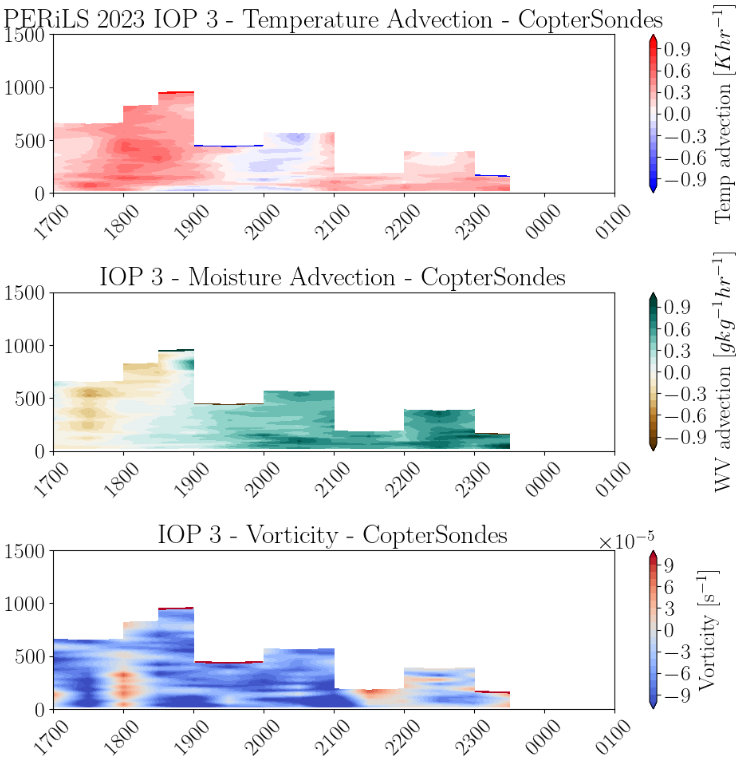
If a line is missing that site did not fly for that timestamp. Points correspondingly appear/disappear on radar plot

Different sites make it to different maximum heights due to wind tolerance and visual line of site limits (cloud base)

LV= WEST PC= SOUTH
SCH= NORTH

Green’s Theorem: Application

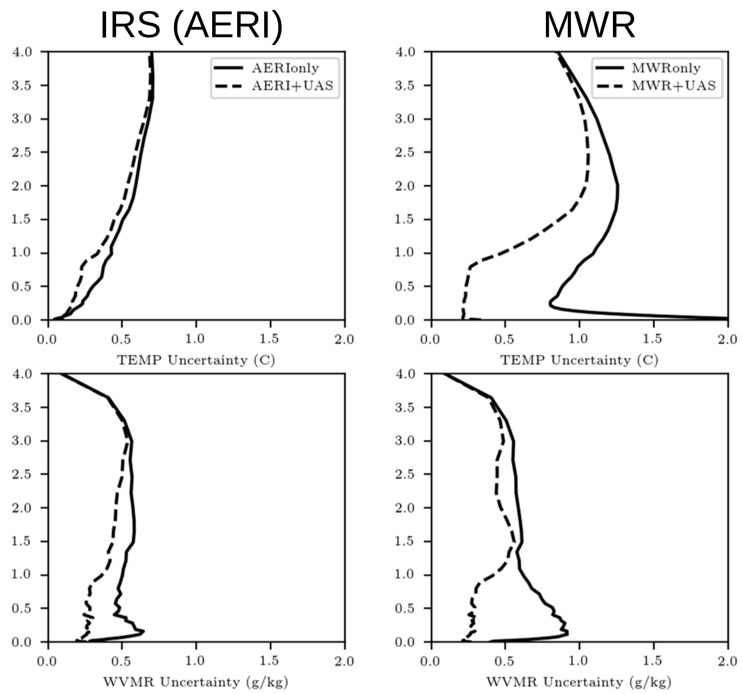
Variable profile depth/information content degrades the success of this approach for basic CopterSonde data



Southeast US complexity invites innovation to meet mission needs:

- Observation platforms
- Observation strategies
- **Observation analysis products**

TROPoe – Tropospheric Remotely Observed Profiling via optimal estimation

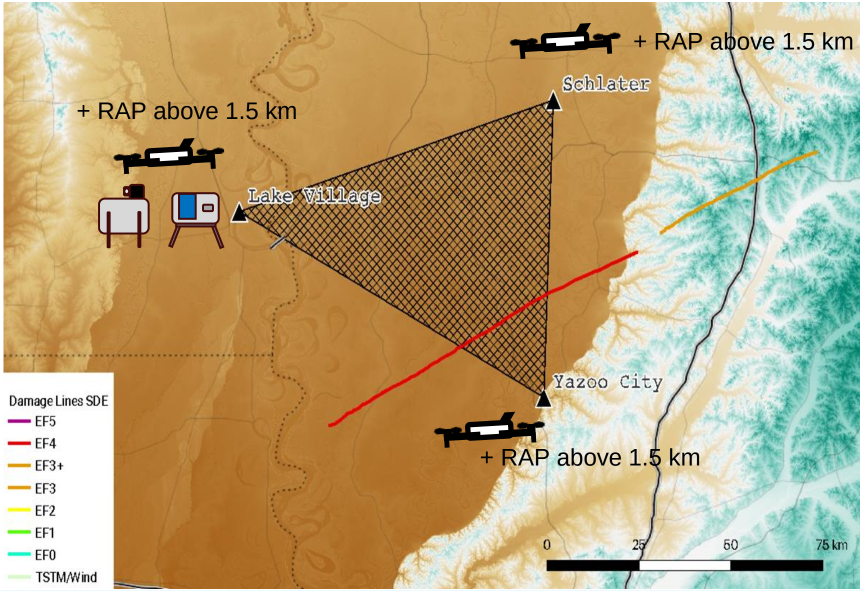


Bell, 2021

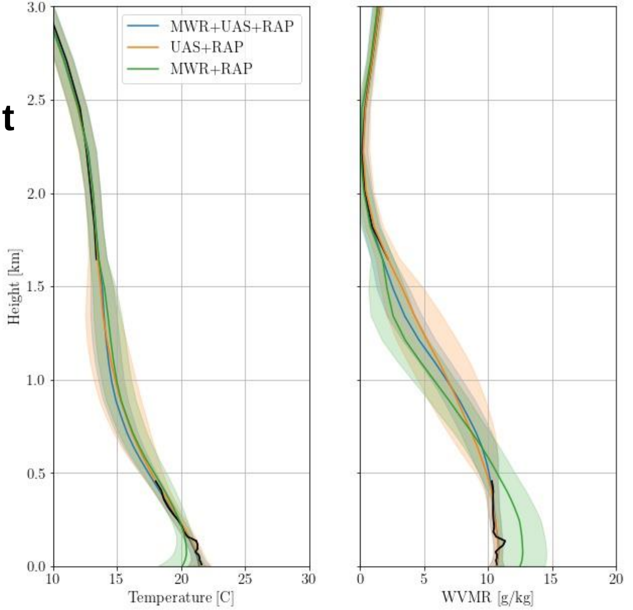
- Developed primarily for performing thermodynamic retrievals from IRS and MWRs
- Method can be generalized to take **multiple types of input**
- Provides a way to **create similar datasets from dissimilar data**, with uncertainty baked in

TROPoe – Tropospheric Remotely Observed Profiling via optimal estimation

- NOAA Rapid Refresh (RAP) Model above 1.5 km
- TROPoe can take any combination of instruments as long as a proper forward model is available

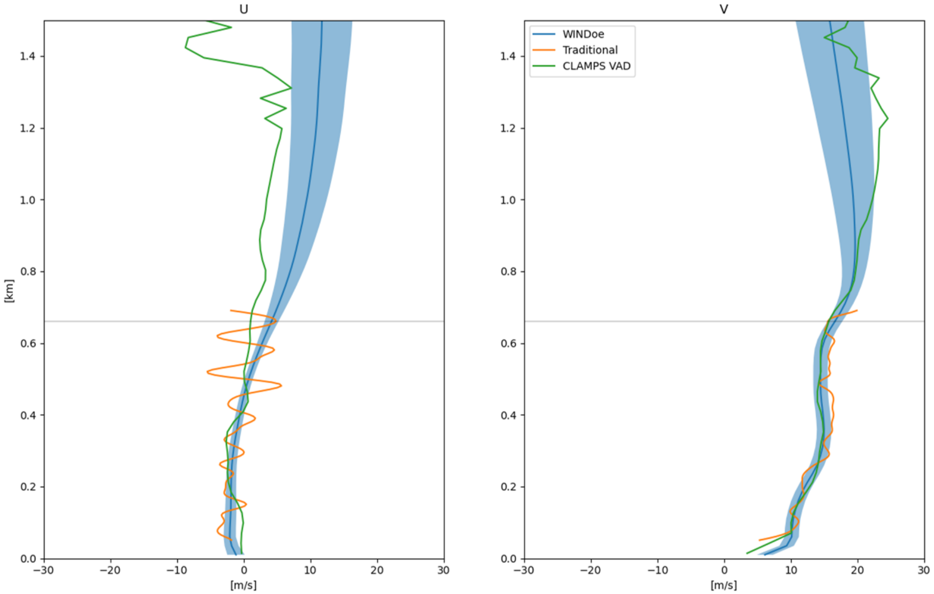


But what about the winds?



WINDoe

A ***new OE method*** developed by Dr. Josh Gebauer can retrieve wind profiles from dissimilar wind profiling platforms and data streams *(pub under review)*



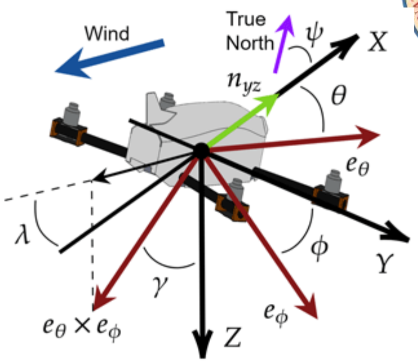
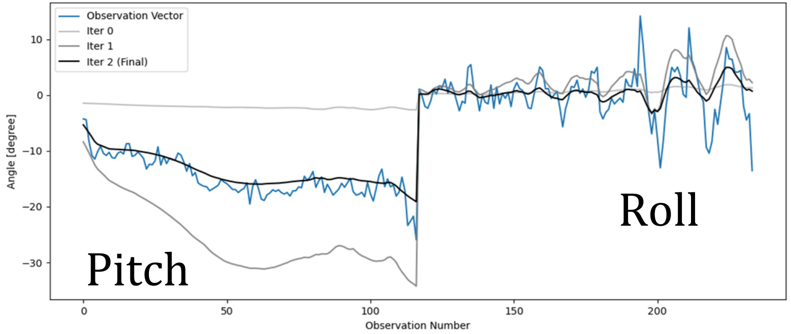
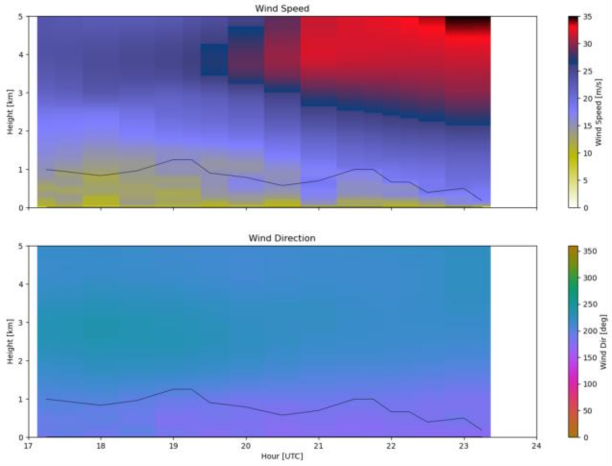


Figure from Segales et al. (2020)

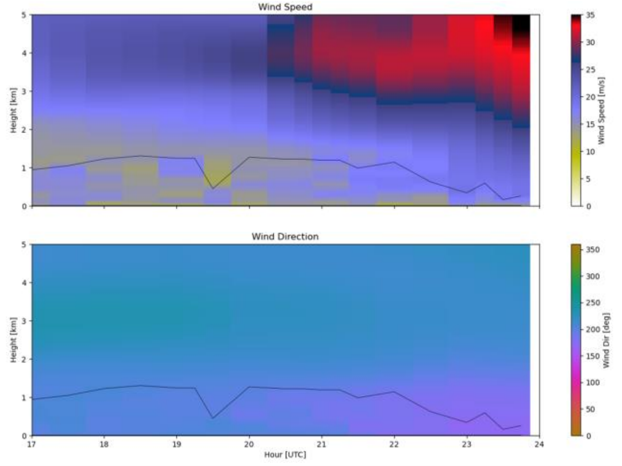


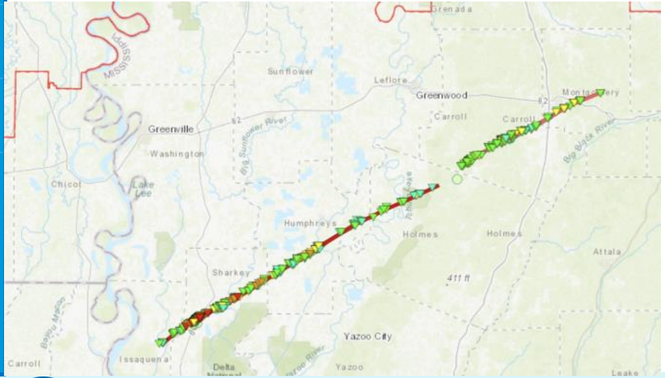
WINDoe examples

Lake Village

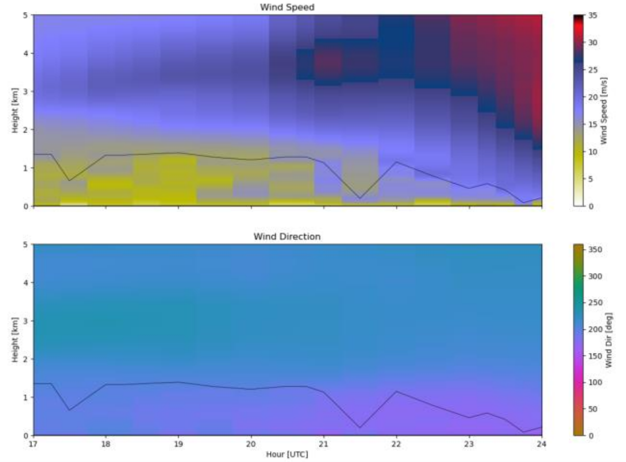


Schlater



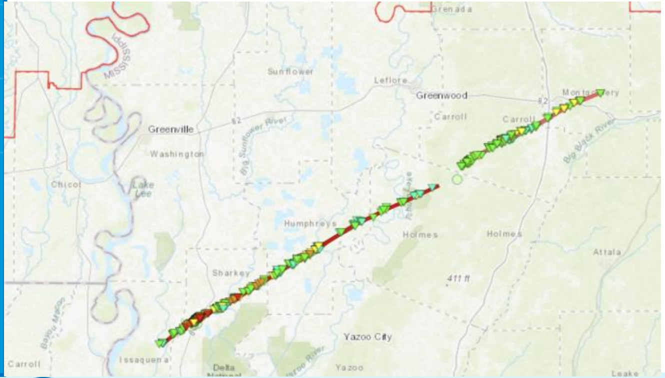


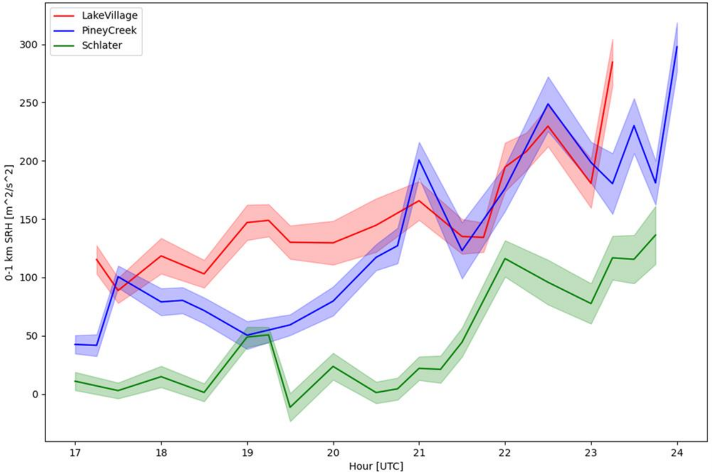
Piney Creek



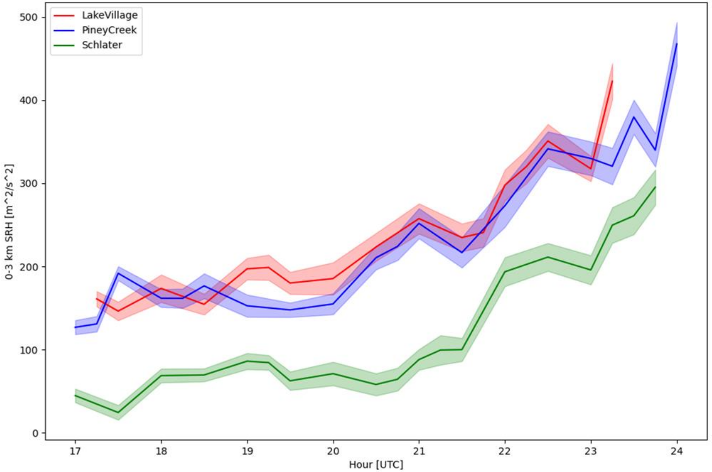
WINDoe examples

Through Monte Carlo sampling of the posterior covariance matrix, we can obtain uncertainties for derived indices using the retrieved profile





0-1 km SRH



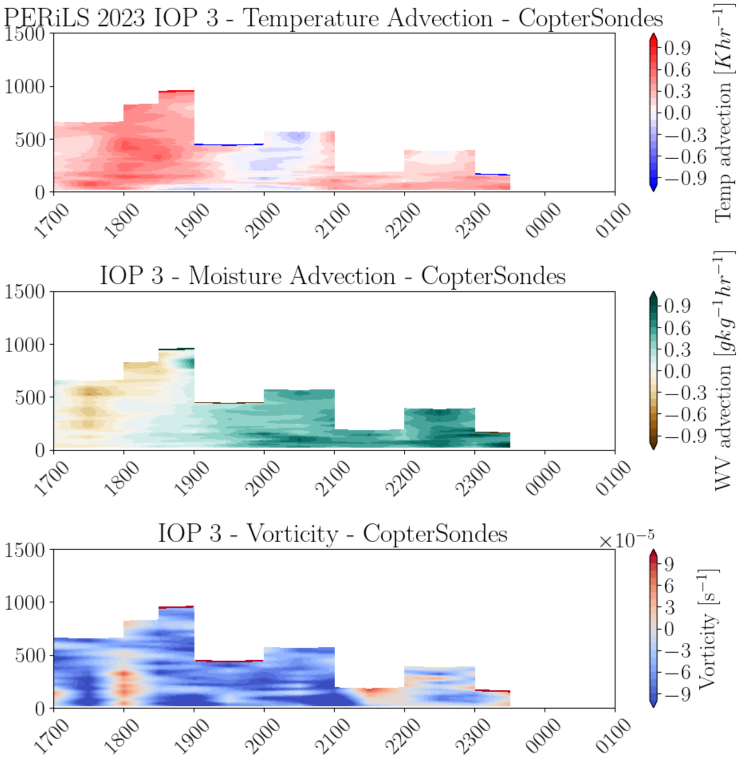
0-3 km SRH

Green’s Theorem: TROPoe + WINDoe

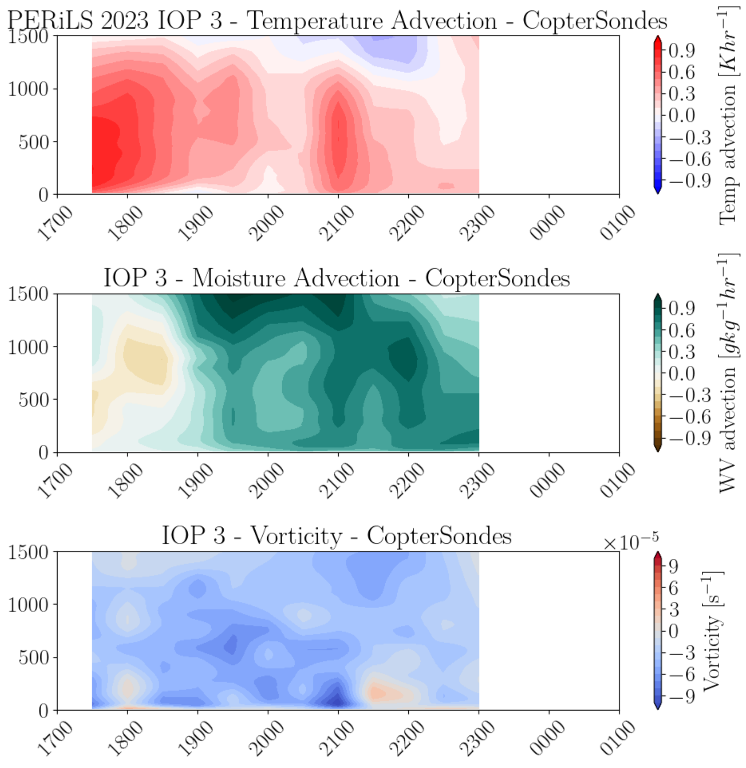
- NOAA Rapid Refresh (RAP) Model above 1.5 km

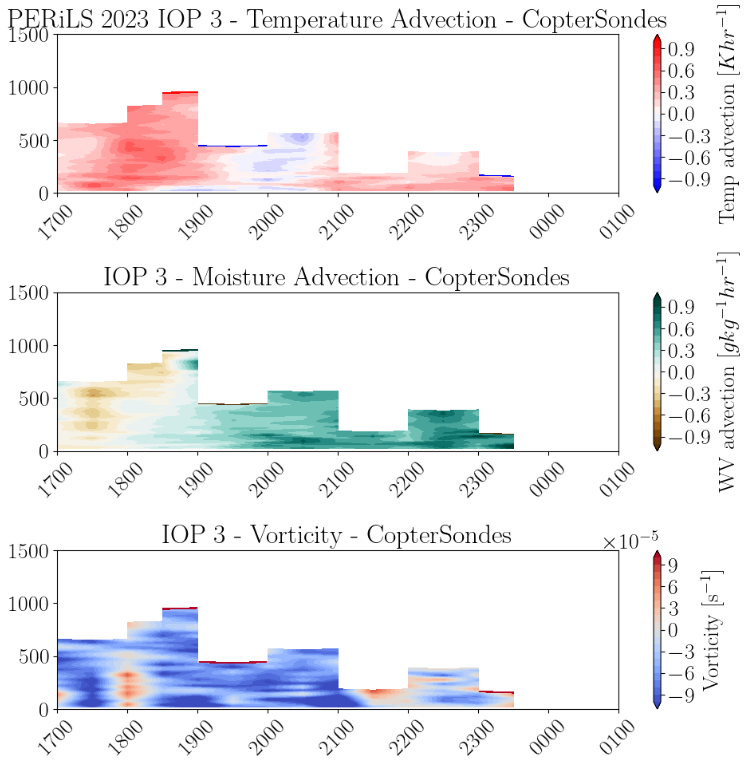
- TROPoe can take any combination of instruments as long as a proper forward model is available

- Combined with WINDoe, can rerun advection analysis on retrieved profiles



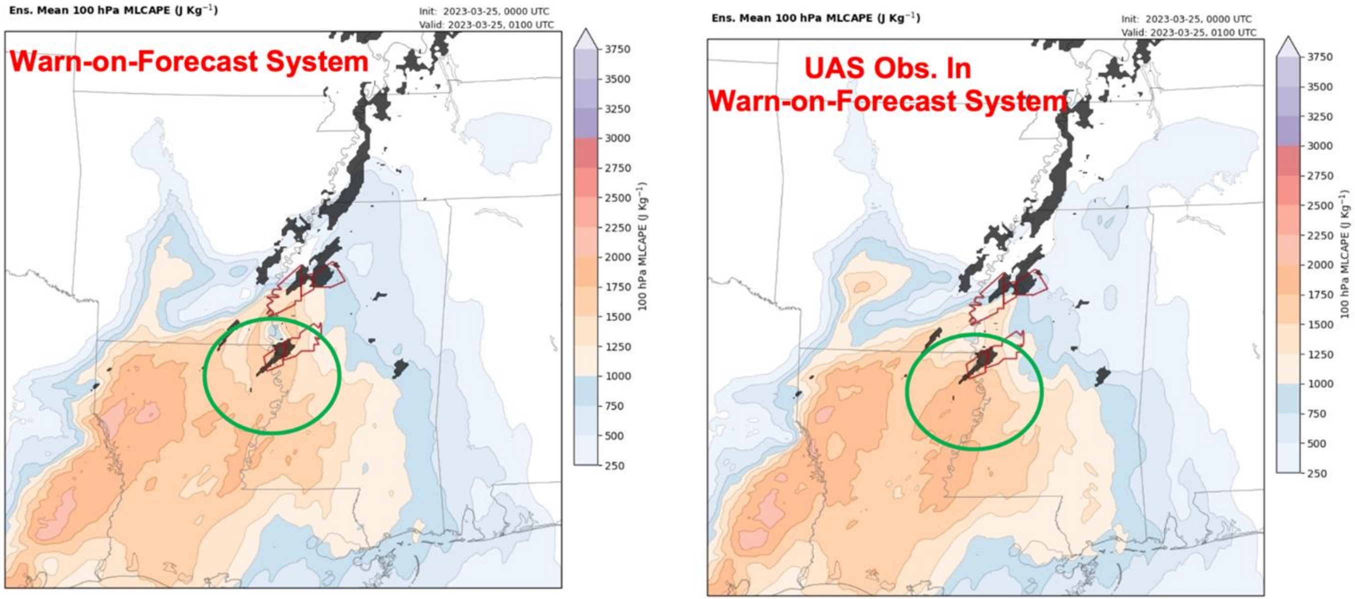
Green’s Theorem: TROPoe + WINDoe





Data Assimilation Experiments

1-hr Fcst Ensemble Mean 100 hPa MLCAPE (J Kg^{-1})



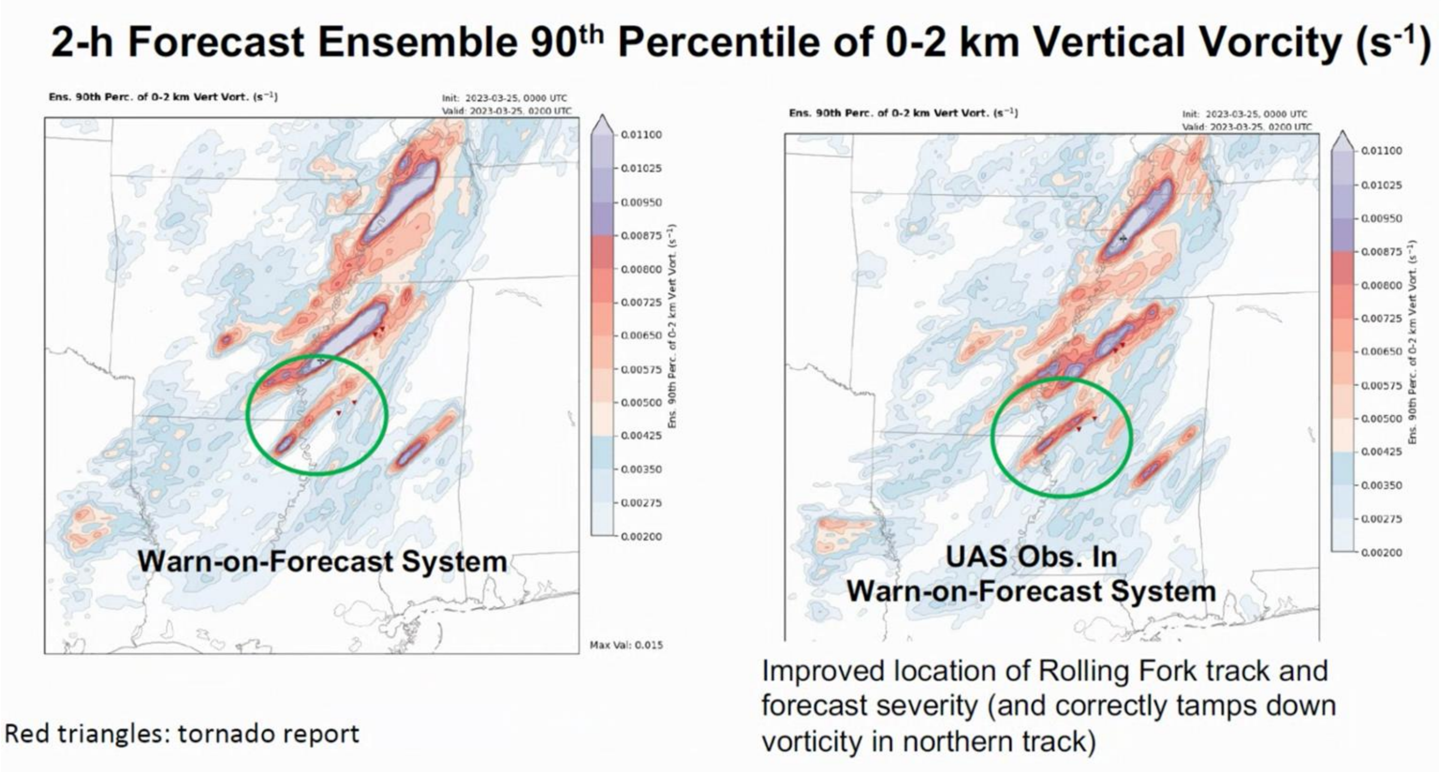
warning polygons in red

UAS experiment increases MLCAPE in inflow to Rolling Fork storm

CIWRO Scientist
Dr. Nusrat Yussouf

MS Student
Jordan Tweedie

Data Assimilation Experiments



2-h Forecast Ensemble 90th Percentile of 0-2 km Vertical Vorcity (s^{-1})

Red triangles: tornado report

Improved location of Rolling Fork track and forecast severity (and correctly tamps down vorticity in northern track)

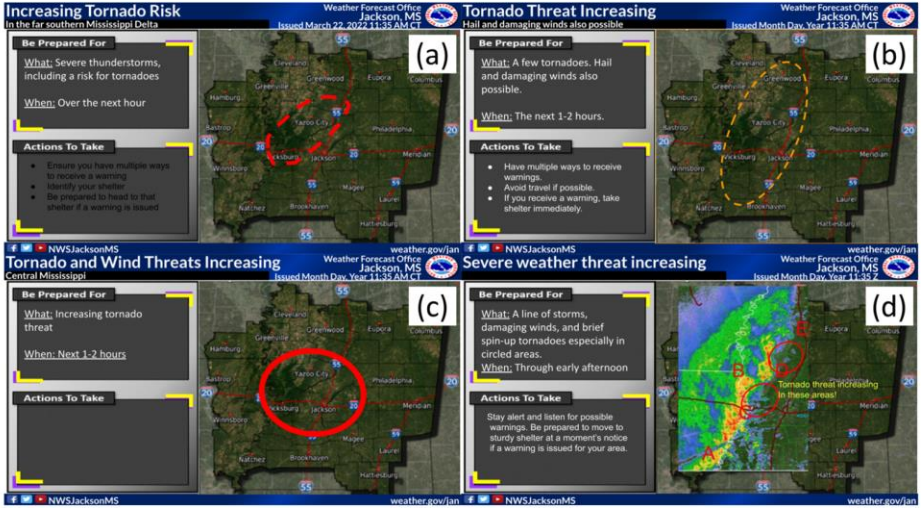
CIWRO Scientist
Dr. Nusrat Yussouf

MS Student
Jordan Tweedie

R2O – Stakeholder/End User Needs

PERiLS 2022 CopterSonde data evaluated in NWS forecast exercises

Between the second (1505 UTC) and third (1535 UTC) time steps, and then between the fourth (1605 UTC) and last (1635 UTC) time steps, only updates from the radar and CopterSonde were provided. P6 described the benefit of having observations between updates in the RAP, such that “the CopterSonde provided data that helped me determine that the environment at Point D had changed over the past 30 minutes and had become more supportive of a tornado threat.” Most of the experimental groups’ responses to the survey at this time, focused on the use of CopterSonde data.



Increasing Tornado Risk
In the far southern Mississippi Delta
Weather Forecast Office Jackson, MS
Issued March 22, 2022 11:35 AM CT

Be Prepared For
What: Severe thunderstorms, including a risk for tornadoes
When: Over the next hour

Actions To Take
- Ensure you have multiple ways to receive a warning
- Identify your shelter
- Be prepared to head to that shelter if a warning is issued

NWSJacksonMS weather.gov/jan

Tornado Threat Increasing
Hail and damaging winds also possible
Weather Forecast Office Jackson, MS
Issued Month Day, Year 11:35 AM CT

Be Prepared For
What: A few tornadoes. Hail and damaging winds also possible.
When: The next 1-2 hours.

Actions To Take
- Have multiple ways to receive warnings.
- Avoid travel if possible.
- If you receive a warning, take shelter immediately.

NWSJacksonMS weather.gov/jan

Tornado and Wind Threats Increasing
Central Mississippi
Weather Forecast Office Jackson, MS
Issued Month Day, Year 11:35 AM CT

Be Prepared For
What: Increasing tornado threat
When: Next 1-2 hours

Actions To Take

NWSJacksonMS weather.gov/jan

Severe weather threat increasing
Weather Forecast Office Jackson, MS
Issued Month Day, Year 11:35 Z

Be Prepared For
What: A line of storms, damaging winds, and brief spin-up tornadoes especially in circled areas.
When: Through early afternoon

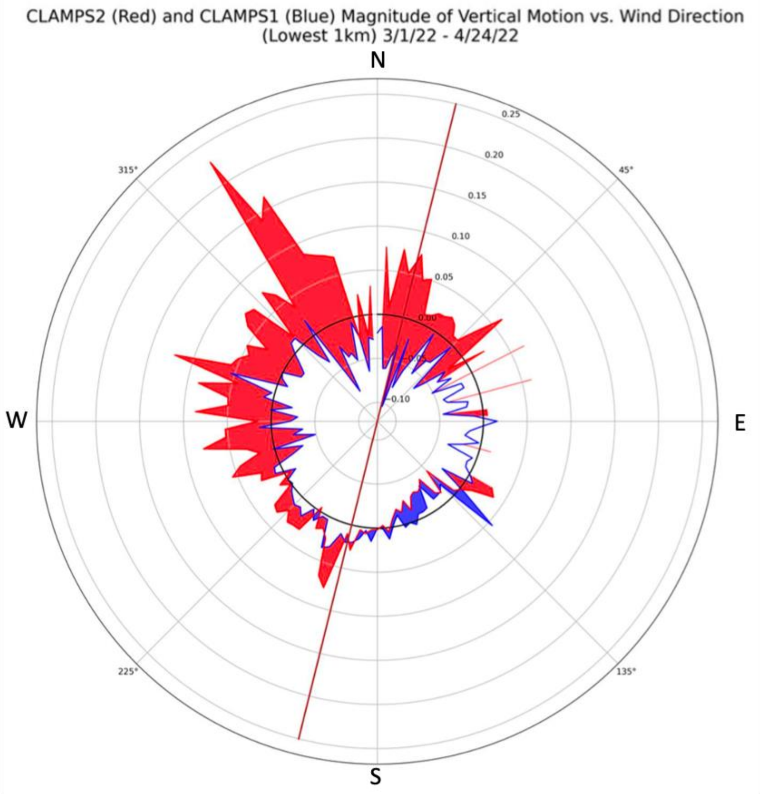
Actions To Take
Stay alert and listen for possible warnings. Be prepared to move to sturdy shelter at a moment's notice if a warning is issued for your area.

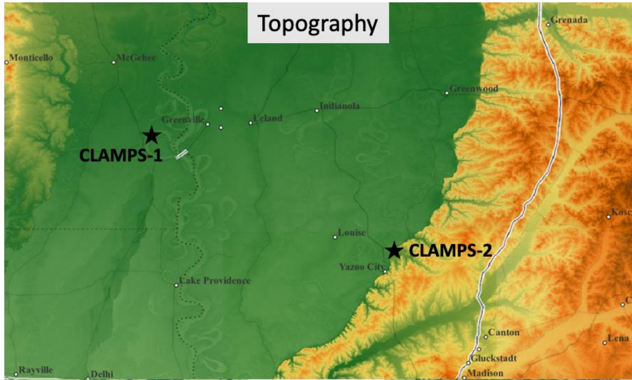
NWSJacksonMS weather.gov/jan

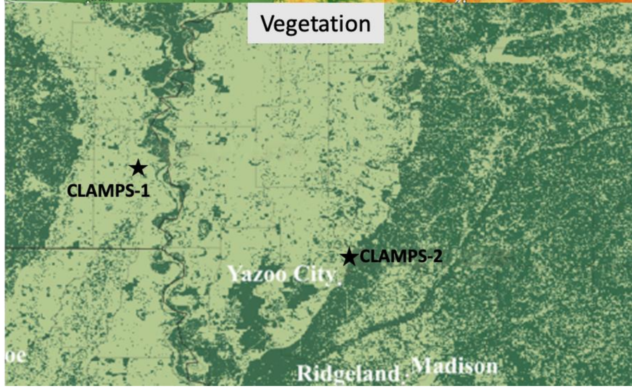
Connor Bruce, 2023: Exploring CopterSonde Use for National Weather Service Operations

OU Master Thesis

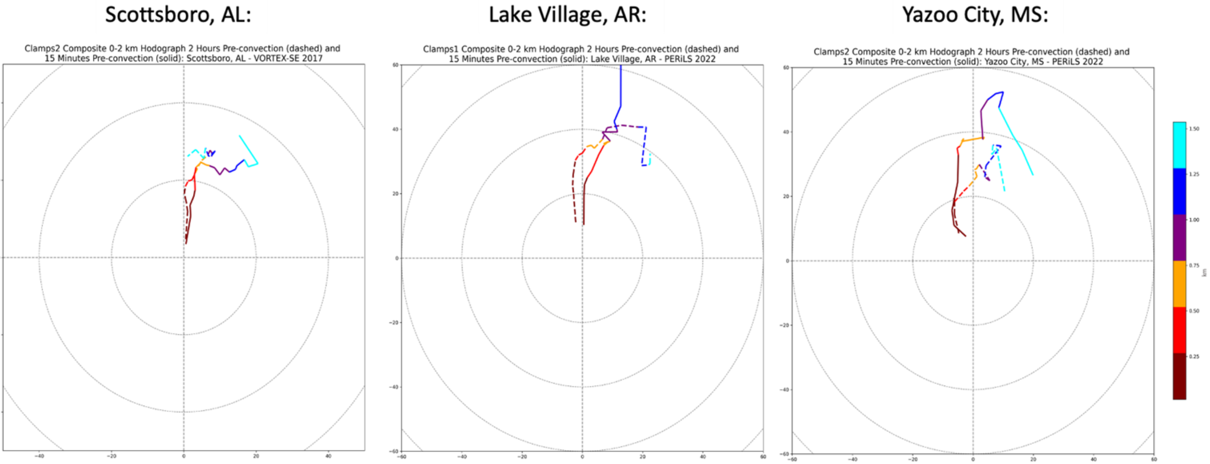
Process Understanding – Terrain Influence

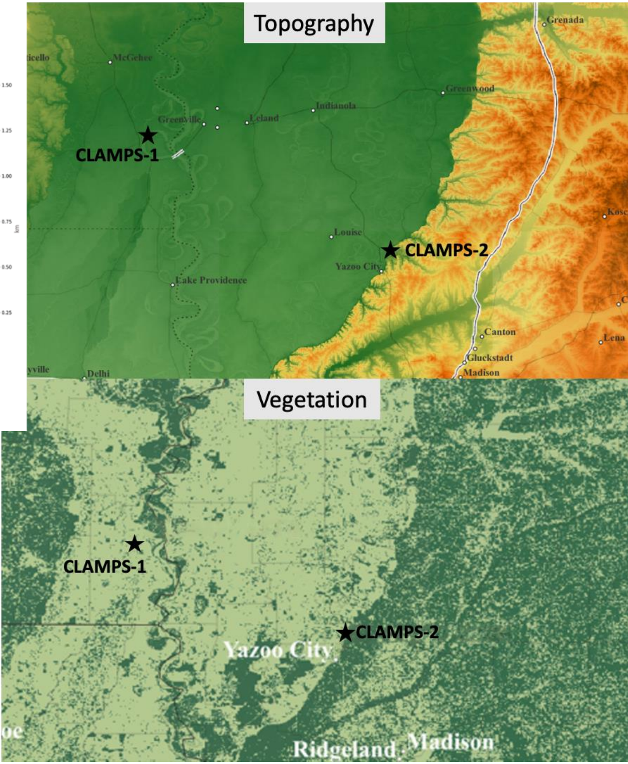

CLAMPS2 (Red) and CLAMPS1 (Blue) Magnitude of Vertical Motion vs. Wind Direction (Lowest 1km) 3/1/22 - 4/24/22


Topography


Vegetation

Process Understanding – Terrain Influence

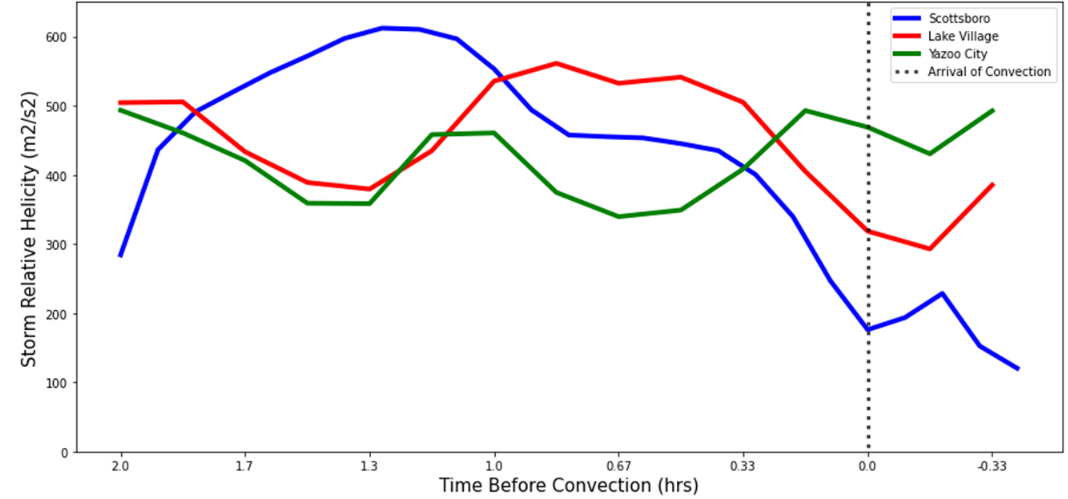


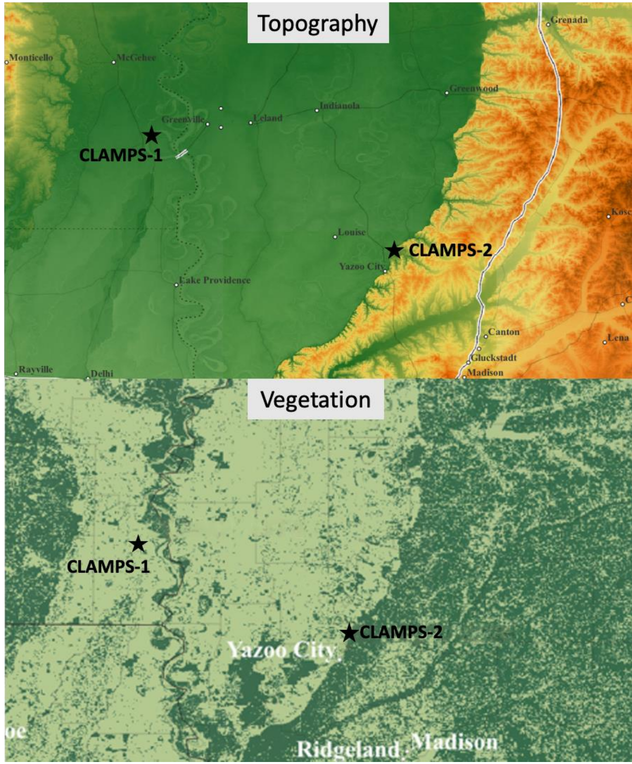


- Yazoo City composite exhibits much more **curvature** in lowest ~0.5 km due to terrain-induced backing of near-surface flow. This promotes more streamwise oriented vorticity
- There is notable **acceleration of 0-1 km shear vector** between 2 hours pre-convection, and 15 minutes pre-convection in Yazoo City composite while others reflect little change

Process Understanding – Terrain Influence

CLAMPS 0-1 km SRH 2-hr pre-convective Composites at Scottsboro, AL (blue), Lake Village, AR (red), and Yazoo City, MS (green)

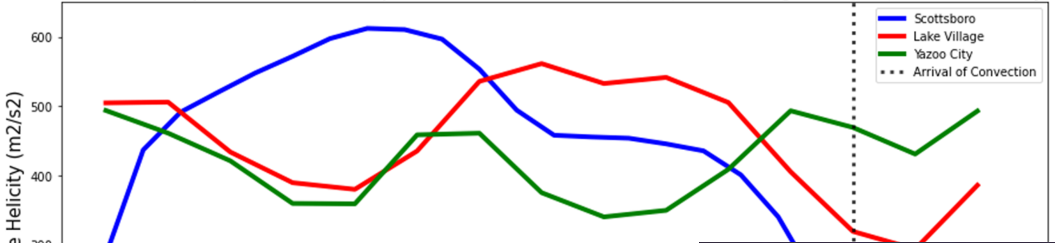


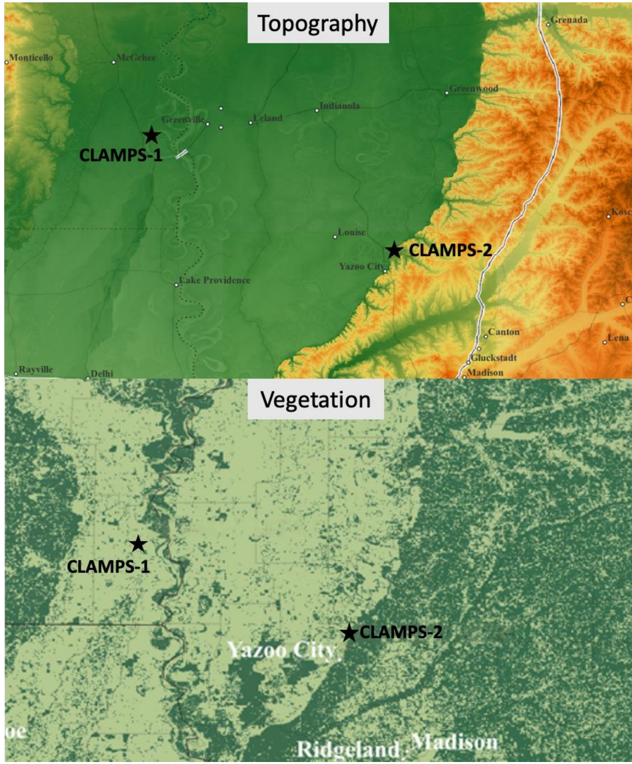


0-1 km SRH increases during the ~45 minutes leading up to the arrival of convection at the Yazoo City site while it decreases during that same period at the other sites. *This is possibly due to the interaction between the terrain gradient and the backing winds that occurs in response to the storm inflow.*

Process Understanding – Terrain Influence

CLAMPS 0-1 km SRH 2-hr pre-convective Composites at Scottsboro, AL (blue), Lake Village, AR (red), and Yazoo City, MS (green)





Recorded Seminar:

bliss.science/seminar/20230508-matthew-ammon/

PERiLS PBL Profiling:
CLAMPS and CopterSonde UAS

Dr. Elizabeth Smith Research Meteorologist–NOAA National Severe Storms Laboratory
Affiliated Assistant Professor–OU School of Meteorology
Email: elizabeth.smith@noaa.gov / Social media: @eeeeelizzzzz
Tyler Bell, Joshua Gebauer, Tony Segales – OU CIWRO

BLISS
BOUNDARY-LAYER INTEGRATED SENSING & SIMULATION

Looking ahead

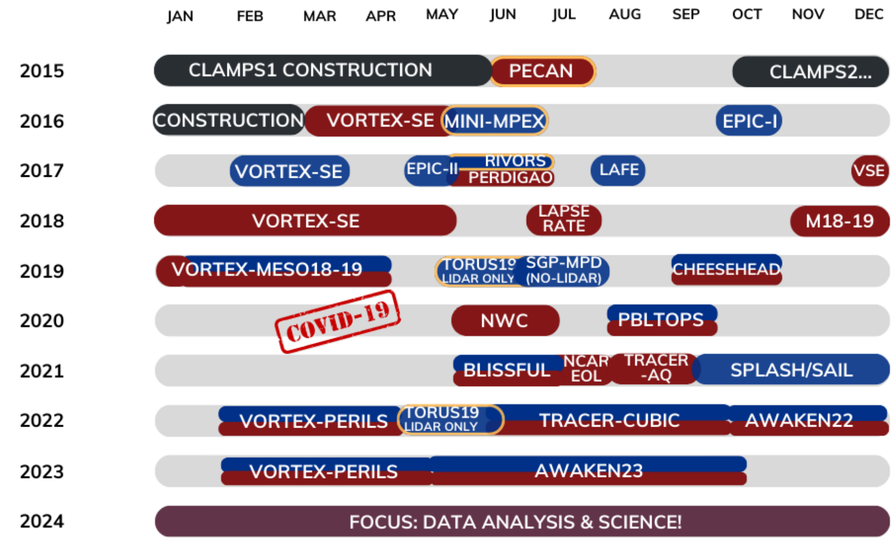
Ongoing work and what's next

CLAMPS TIMELINE

LEGEND

- CLAMPS1
- CO-DEPLOY
- CLAMPS2
- SPLIT DEPLOY
- NIMBLE

Created by OU UG Victor Alvarez



2015: CLAMPS1 CONSTRUCTION · PECAN · CLAMPS2...

2016: CONSTRUCTION · VORTEX-SE · MINI-MPEX · EPIC-I

2017: VORTEX-SE · EPIC-II · RIVORS · PERDIGAO · LAFE · VSE

2018: VORTEX-SE · LAPSE RATE · M18-19

2019: VORTEX-MESO18-19 · TORUS19 LIDAR ONLY · SGP-MPD (NO-LIDAR) · CHEESEHEAD

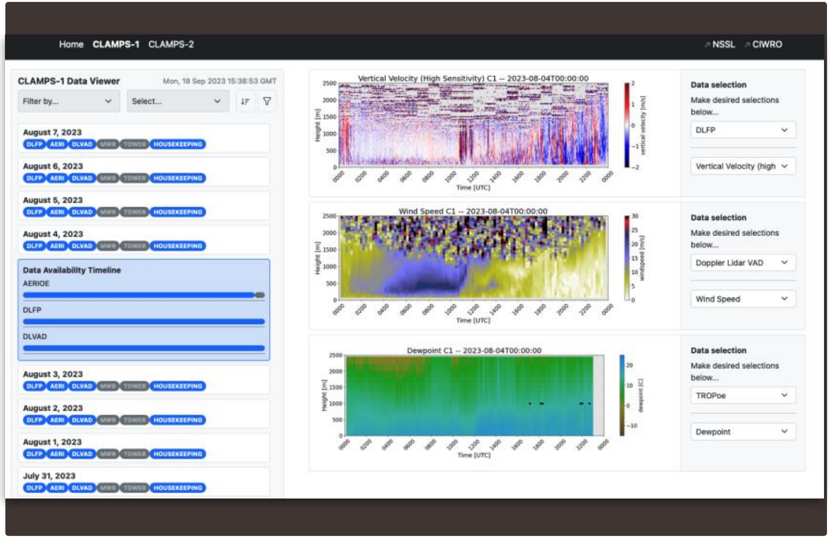
2020: COVID-19 · NWC · PBLTOPS

2021: BLISSFUL · NCAR EOL · TRACER -AQ · SPLASH/SAIL

2022: VORTEX-PERILS · TORUS19 LIDAR ONLY · TRACER-CUBIC · AWAKEN22

2023: VORTEX-PERILS · AWAKEN23

2024: FOCUS: DATA ANALYSIS & SCIENCE!



CLAMPS-1 Data Viewer Mon, 18 Sep 2023 15:38:53 GMT

August 7, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

August 6, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

August 5, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

August 4, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

Data Availability Timeline
AERIOE
DLFP
DLVAD

August 3, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

August 2, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

August 1, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

July 31, 2023
DLFP AERI DLVAD MWR TOWER HOUSEKEEPING

Data selection
Make desired selections below...
DLFP
Vertical Velocity (high

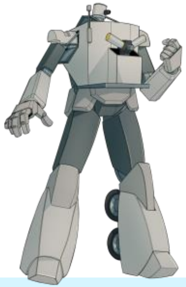
Data selection
Make desired selections below...
Doppler Lidar VAD
Wind Speed

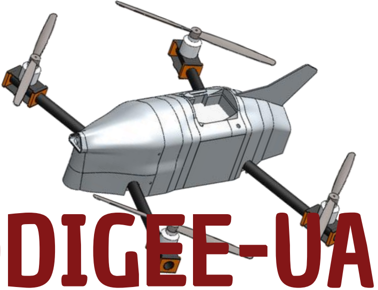
Data selection
Make desired selections below...
TROPoe
Dewpoint

Data Viewer

THREDDS Data Access

Get started using our data with tools at ***bliss.science/resources/code***





PRODIGEE-UAS

The Coptersonde UAS collects meteorological profiling observations on multiple projects at NSSL and CIWRO/University of Oklahoma. Since 2020, it has conducted **approximately 1,500 research flights**. Science & engineering staff at NSSL and CIWRO are leading a project supported by NOAA's UxSRTO called **PRODIGEE** to advance Coptersonde capabilities.

CURRENT		TARGET
WIND TOLERANCE: 22 M/S (50 MPH)	->	WIND TOLERANCE: 35 M/S (78 MPH)
MAX FLIGHT CEILING: 1.5 KM AGL	->	MAX FLIGHT CEILING: 3 KM AGL
VISUAL LINE OF SIGHT OPERATIONS	->	BEYOND VISUAL LINE OF SIGHT OPERATIONS

bliss.science/resources/sensing/coptersonde

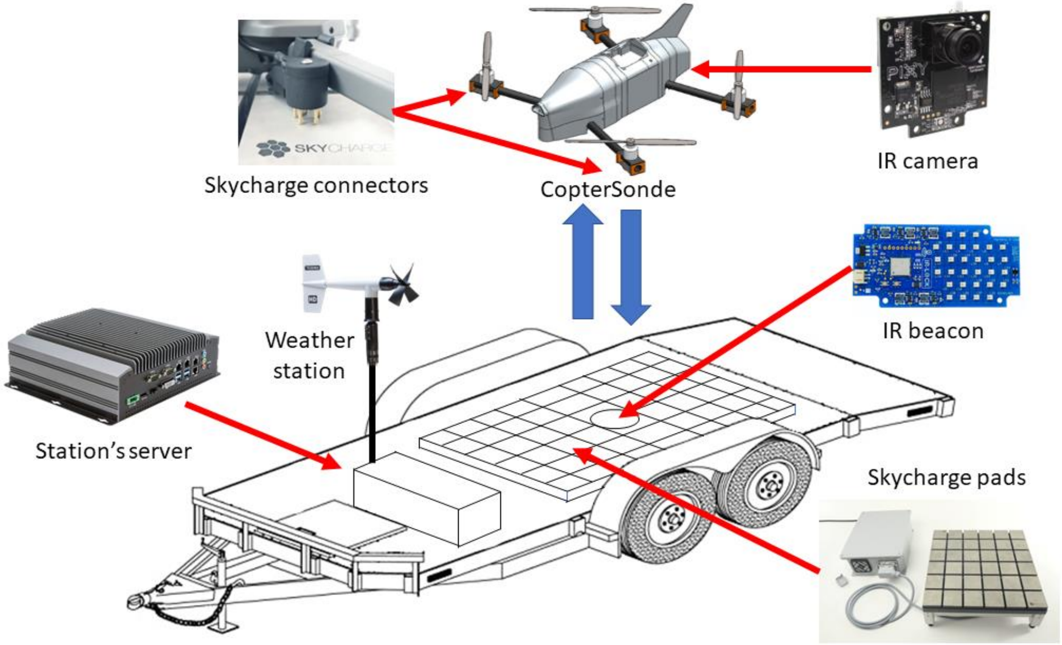
CopterSonde flights are enabling rapid, in-situ, low-level profiling of thermodynamic and kinematic conditions in the atmosphere. Many research directions are being explored.

- R&D of UAS platform and supporting software and hardware to increase flight capability and autonomy
- similarities, differences, and possible synergies between UAS-based and ground-based profiling techniques
- impacts and network needs for low-level, rapid profiles in data assimilation contexts
- basic science (e.g., knowledge development based on the new types of obs these platforms enable such as parcel residence times, convection initiation processes, etc.)

CIWRO – Precision Landing and Auto-Charging for Weather-Sensing UAS

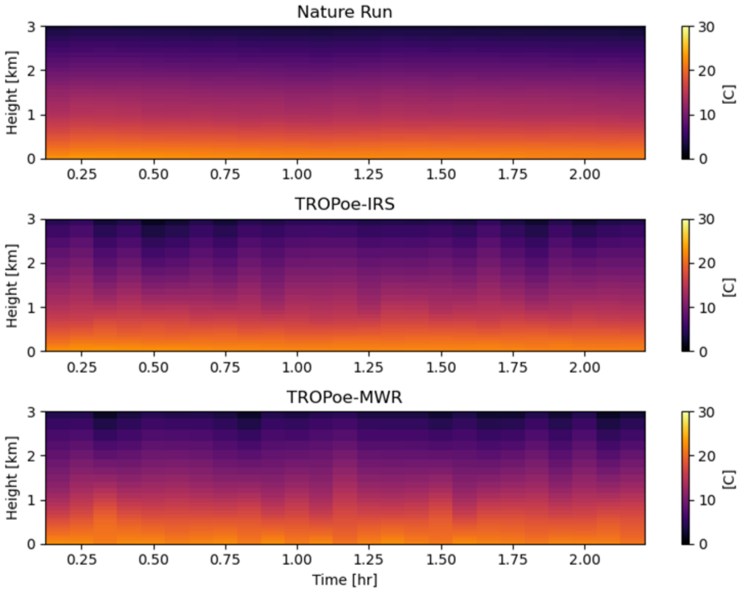
Key research goals:

1. Create a proof-of-concept platform for the future development of many supporting requirements (e.g. detect and avoid capabilities, surface station integration, fully remote launch and recovery, etc.) necessary to realize fully autonomous operations (i.e. the 3D Mesonet)
2. Continue to develop the cloud-infrastructure necessary to operate and monitor remote operations



WPO: Venturing into the Vertical–OSSES

This study proposes to conduct research that will facilitate the development of a vital boundary layer profiling mesonet, often referred to as a 3D mesonet, that could fill the boundary layer data gap in current observation networks. Remote *and* in situ platforms such as infrared spectrometers, microwave radiometers, Doppler lidars, and weather-sensing uncrewed aircraft systems (UAS) can provide boundary layer observation profiles, but the **optimal design of such a network venturing into the vertical remains unknown**.

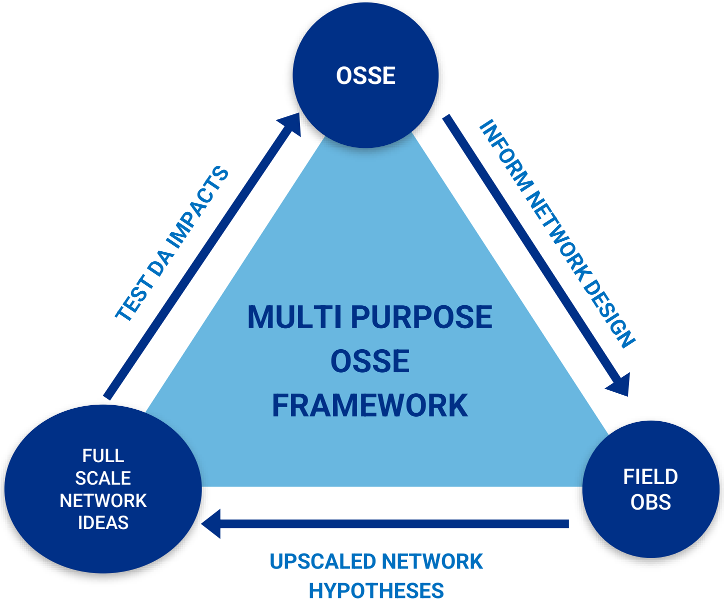


Key research goals:

1. **Observing system simulation experiments (OSSEs) with high-quality observation *simulators*** to replicate directly observed variables from remote profilers, UAS.
2. Field deployments with **up to 12 weather UAS** to replicate operational boundary layer profiling mesonet in high-impact weather environments.
3. Use OSSEs and field deployments to test analysis and retrieval techniques that could be performed in near-real time.
4. Leverage high-resolution flow-simulations and data from past and current CopterSonde deployments to improve upon the CopterSonde design for operational profiling.

WPO: Venturing into the Vertical–OSSES

This study proposes to conduct research that will facilitate the development of a vital boundary layer profiling mesonet, often referred to as a 3D mesonet, that could fill the boundary layer data gap in current observation networks. Remote *and* in situ platforms such as infrared spectrometers, microwave radiometers, Doppler lidars, and weather-sensing uncrewed aircraft systems (UAS) can provide boundary layer observation profiles, but the **optimal design of such a network venturing into the vertical remains unknown**.



OSSE

INFORM NETWORK DESIGN

FIELD OBS

UPSCALED NETWORK HYPOTHESES

FULL SCALE NETWORK IDEAS

TEST DA IMPACTS

MULTI PURPOSE OSSE FRAMEWORK

Key research goals:

1. **Observing system simulation experiments (OSSEs) with high-quality observation *simulators*** to replicate directly observed variables from remote profilers, UAS.
2. Field deployments with **up to 12 weather UAS** to replicate operational boundary layer profiling mesonet in high-impact weather environments.
3. Use OSSEs and field deployments to test analysis and retrieval techniques that could be performed in near-real time.
4. Leverage high-resolution flow-simulations and data from past and current CopterSonde deployments to improve upon the CopterSonde design for operational profiling.

PERiLS Meeting — November 2023

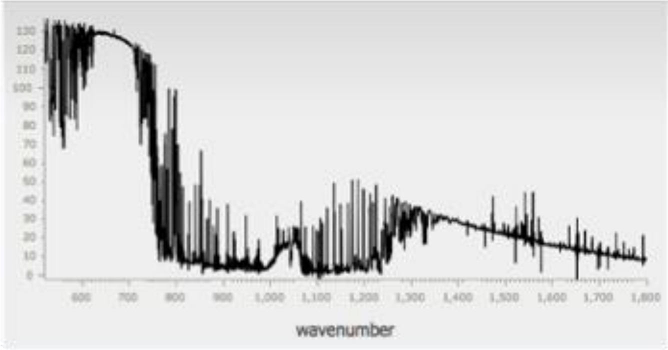
inside.nssl.noaa.gov/ensmith — elizabeth.smith@noaa.gov

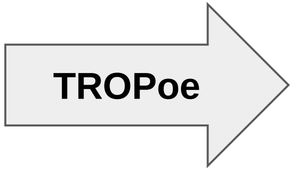
PERiLS PBL Profiling:
CLAMPS and CopterSonde UAS

Dr. Elizabeth Smith Research Meteorologist–NOAA National Severe Storms Laboratory
Affiliated Assistant Professor–OU School of Meteorology
Email: elizabeth.smith@noaa.gov / Social media: @eeeeelizzzzz
Tyler Bell, Joshua Gebauer, Tony Segales – OU CIWRO

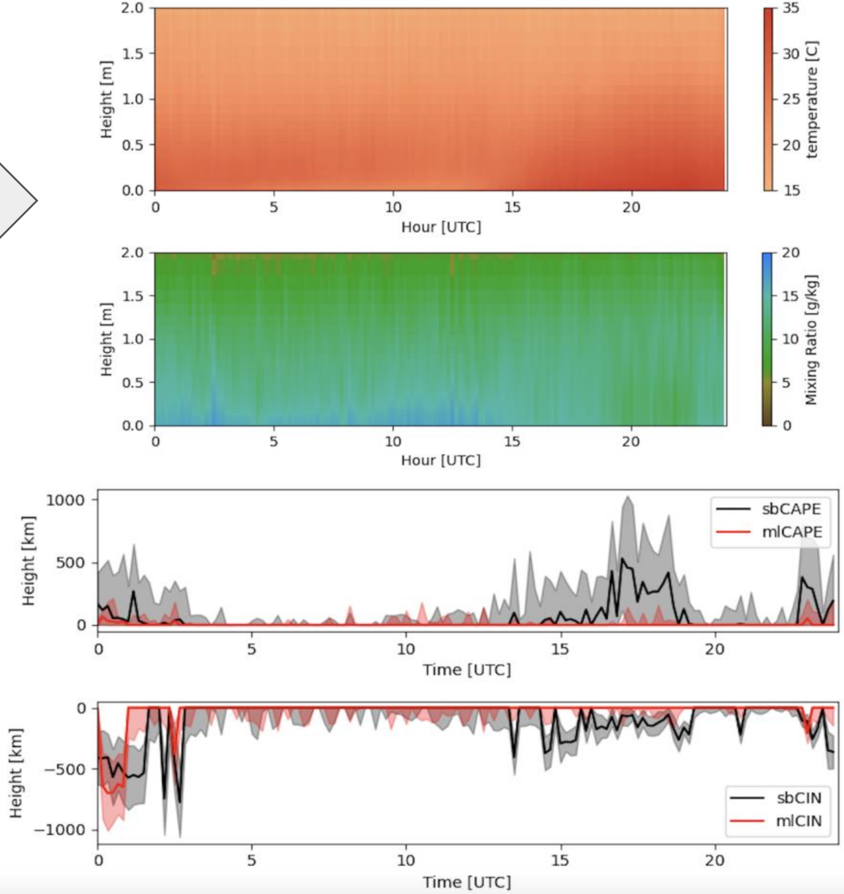
BLISS
BOUNDARY-LAYER INTEGRATED SENSING & SIMULATION

TROPoe: Tropospheric Remotely Observed Profiling via Optimal Estimation





TROPoe



Thermodynamic optimal estimation retrieval developed and maintained in collaboration with Global Systems Laboratory.

Very flexible retrieval system that works with:

- Infrared spectrometers
- Microwave radiometers
- Micropulse differential absorption lidar
- Radio acoustic sounding systems
- CopterSondes
- Radiosondes
- Numerical weather prediction

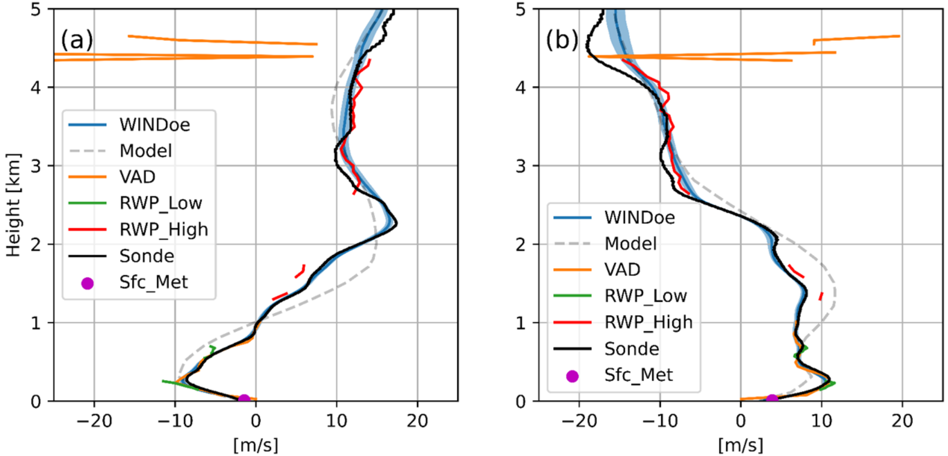
WINDoe: Wind via Optimal Estimation

Newly developed wind profile optimal estimation retrieval designed to be a complement to TROPoe. Developed by CIWRO/NSSL staff.

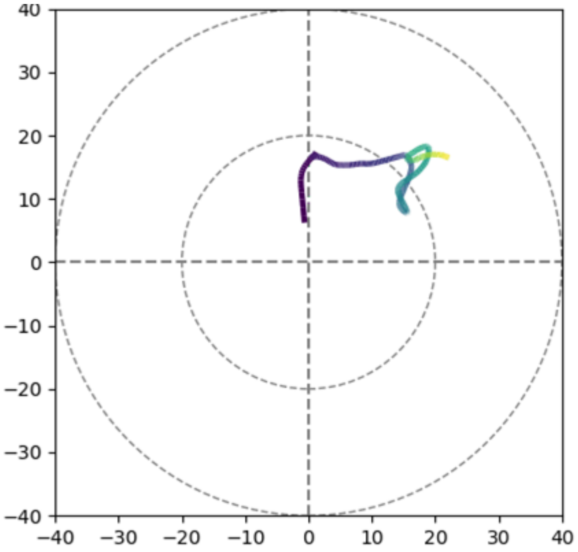
The technique allows for information content from wind profiling instrument to be used to the fullest extent and enables combined data products from:

- Doppler lidar
- Radar wind profiler
- CopterSondes
- Soundings
- Models

Example Combined WINDoe Retrieval at ARM-SGP Site



WINDoe retrievals on 19 April 2023

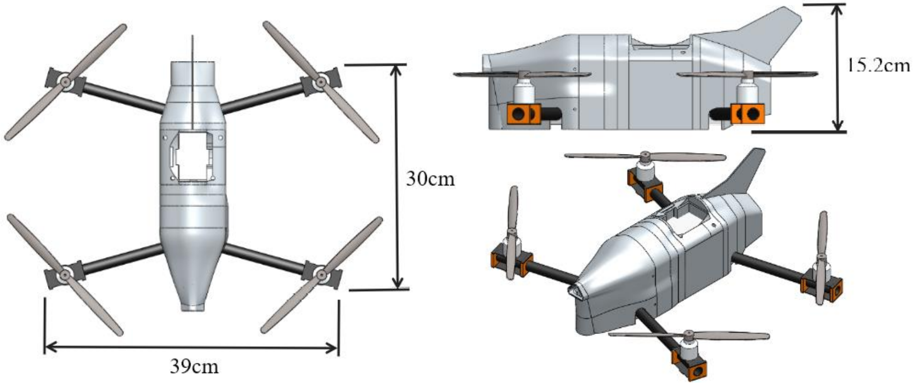


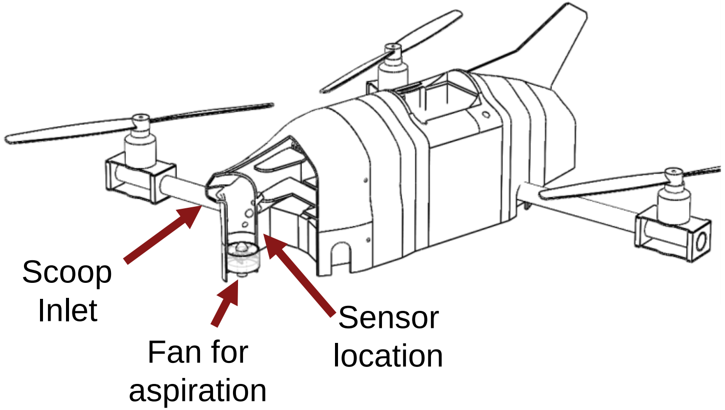
Code available for OAR at: https://github.com/OAR-atmospheric-observations/WINDoe

CopterSonde UAS

Technical Specs

All-up weight:	2 kg
Hover time:	18 min
Max. mean wind:	22 m/s
Max. wind gust:	26 m/s
Max. altitude (AGL):	1500m
Max. const. current:	61.5 A



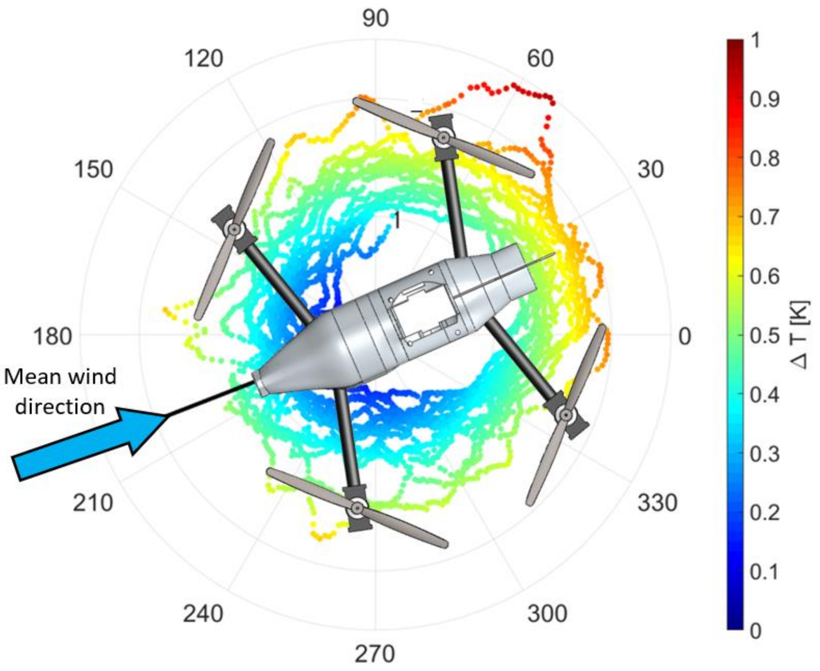


CopterSonde Comparisons

CS3D vs. Radiosonde	RMSE	R
Temperature	0.430 K	0.995
Relative humidity	2.548 %	0.907

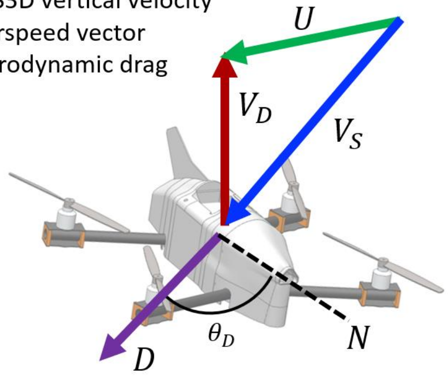
CopterSonde Thermodynamics

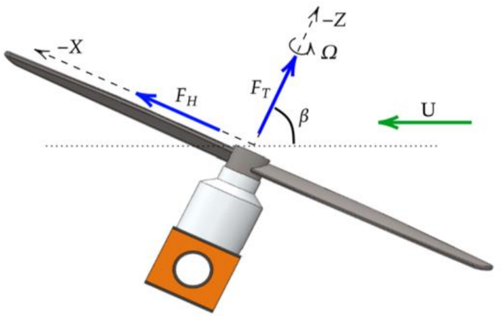
Wind vane function significantly helps mitigating sources of measurement errors

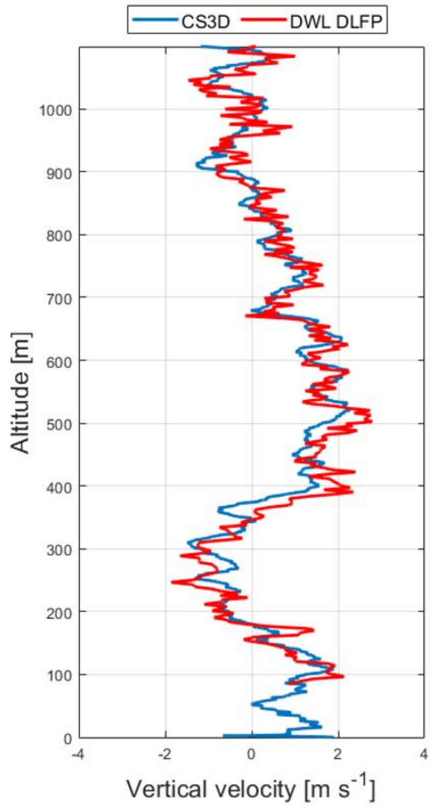


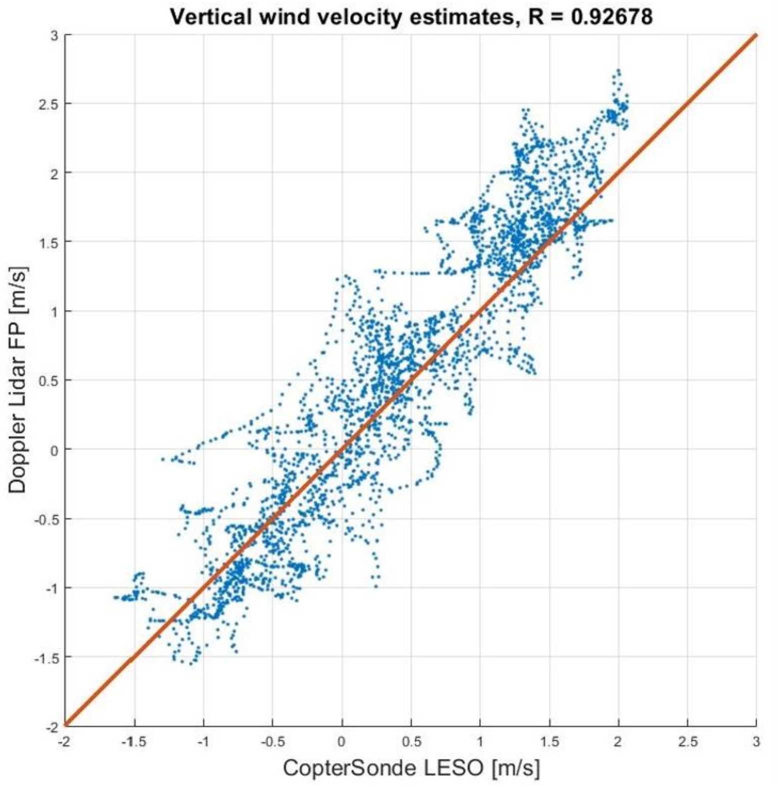
CopterSonde Vertical wind estimation

U: Wind velocity
V_D: CS3D vertical velocity
V_S: Airspeed vector
D: Aerodynamic drag









PERiLS 2022–2023 Operations

Variable	**All Sites**	**Yazoo City**	**Schlater**	**Lake Village**
Max altitude (m)	1380	1380	1300	1247
Avg altitude (m)	491	572	514	393
Total flight count	347	119	111	103
Total operations time	44:15:19			

The Incidents…

Green’s Theorem Approach

$$\oint_C P\,dx + Q\,dy = \int\int\left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right)dA$$

$$\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \approx \frac{\sum\left(\overline{P}\Delta x + \overline{Q}\Delta y\right)}{A}$$

$$-\mathbf{V}\cdot\nabla\alpha = -\left(u\,\frac{\partial\alpha}{\partial x} + v\,\frac{\partial\alpha}{\partial y}\right)$$

$$-\mathbf{V}\cdot\nabla T = -\left(u\,\frac{\partial T'}{\partial x} + v\,\frac{\partial T'}{\partial y}\right) \approx \frac{-\sum\overline{T'}\left(\overline{u}\Delta y - \overline{v}\Delta x\right)}{A}$$

$$-\mathbf{V}\cdot\nabla q = -\left(u\,\frac{\partial q'}{\partial x} + v\,\frac{\partial q'}{\partial y}\right) \approx \frac{-\sum\overline{q'}\left(\overline{u}\Delta y - \overline{v}\Delta x\right)}{A}$$

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \approx \frac{\sum\left(\overline{u}\Delta x + \overline{v}\Delta y\right)}{A}$$

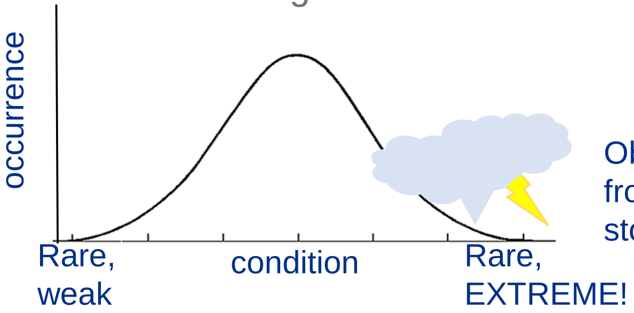
Per Wagner et. al. (2022), since the calculation depend on the scalar magnitude, the mean scalar value of the vertices needs to be removed prior to calculating advection to be properly scaled

Innovation as motivation for PERILS CONOPS

Colocated with CLAMPS remote sensing boundary layer profiler (or near other profiler site)

+

1. CopterSondes begin profiling 8 hours prior to expected storm arrival
2. Coordinated flights occur every 30 minutes, unless the cadence is changed by the mission commander
3. Cadence may increase (at all sites) to 15-minute if a site is near-storm or another interesting weather feature is thought to be observable



Observe the continuum from quiescent BL up to storm arrival!

VORTEX-USA/PERiLS

PhD student
Tyler Pardun

2015-2020 VORTEX-SoutheEast

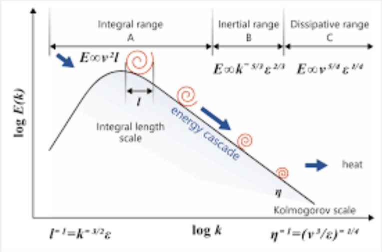
Cool season deployments of fixed facilities to North Alabama

Use these years of data to determine scales of motion and necessary observation spacing

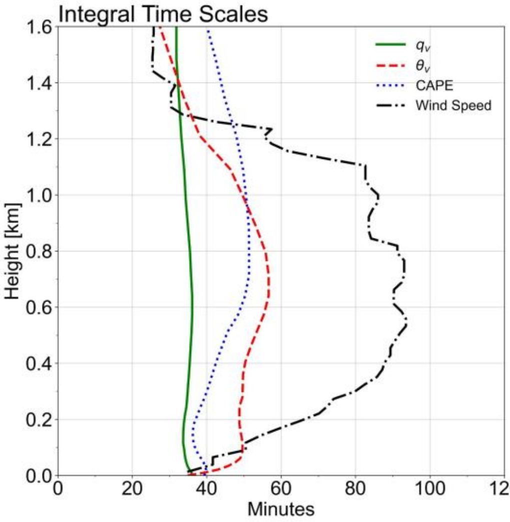
Time-to-space (Taylor's Frozen)

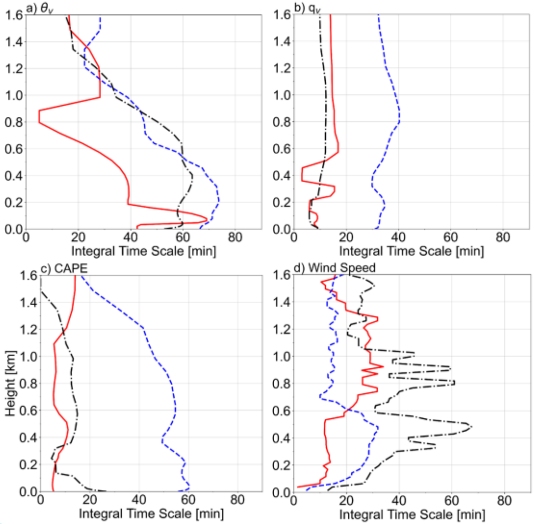
D = ITS x U

D=distance, ITS= integral time scale,
U= mean wind speed



Note water vapor mixing ratio smallest time scale





VORTEX-USA/PERiLS

PhD student
Tyler Pardun

2015-2020 VORTEX-SouthEast

Cool season deployments of fixed facilities to North Alabama

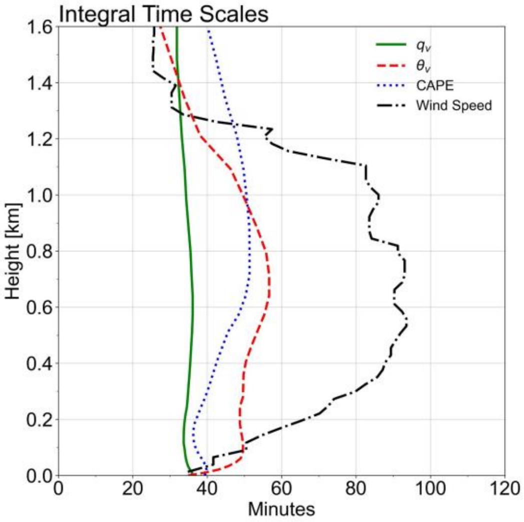
Use these years of data to determine scales of motion and necessary observation spacing

Time-to-space (Taylor’s Frozen)

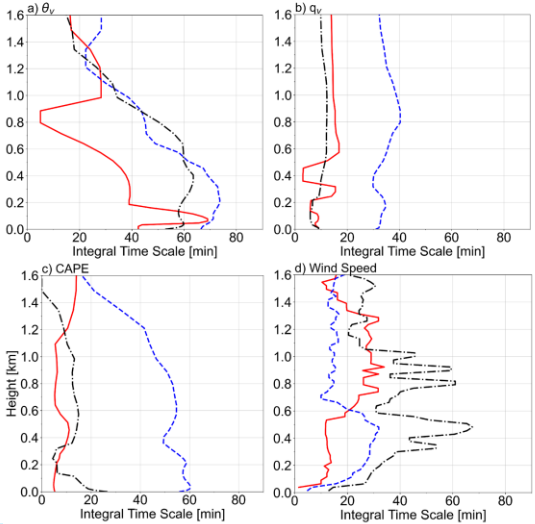
D = ITS x U

D=distance, ITS= integral time scale,
U= mean wind speed

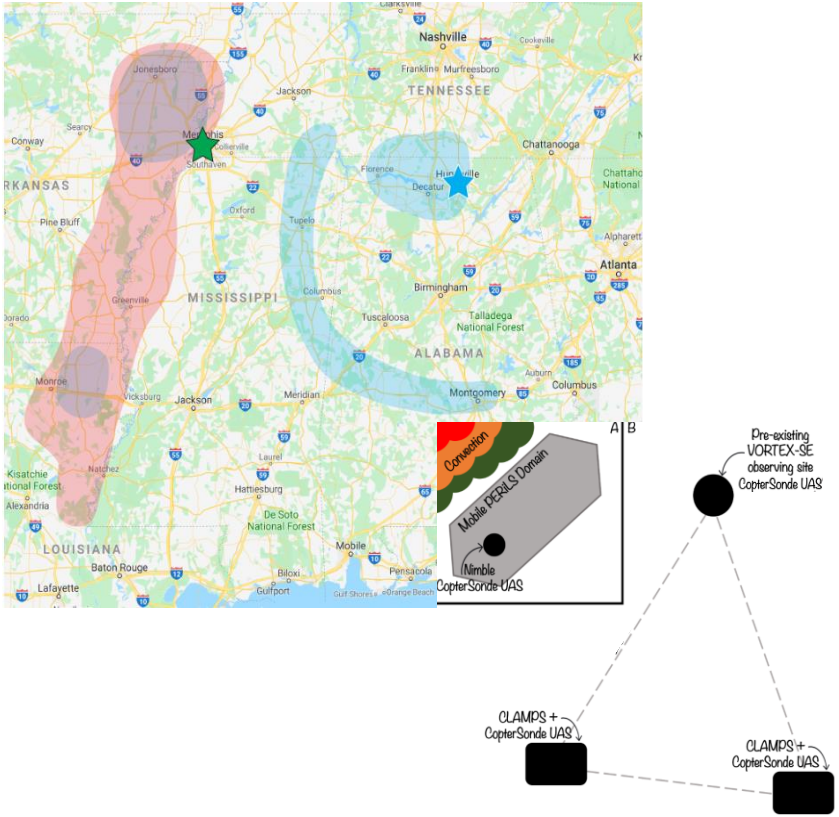
Convective cases:
ITS ~ 40 min
U ~15-20 m/s
D = 36 – 48 km



Note water vapor mixing ratio smallest time scale



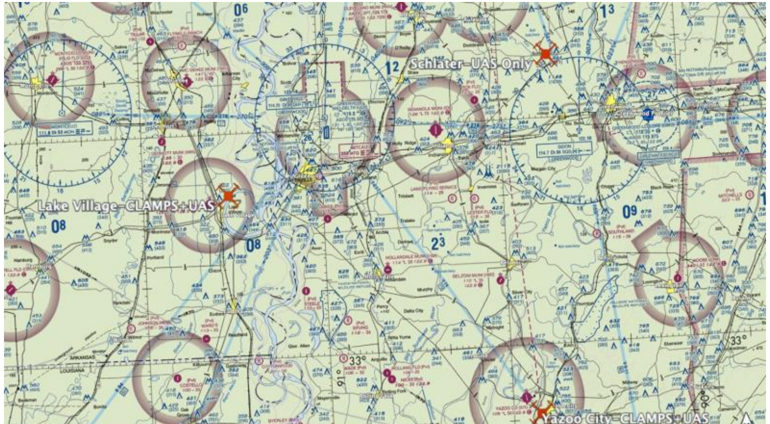
Innovation as motivation for PERiLS CONOPS



Need: *network* low-atmosphere observations in *challenging environment* of southeastern US

VORTEX-SE findings: above-surface variability critical

Innovation as motivation for PERiLS CONOPS

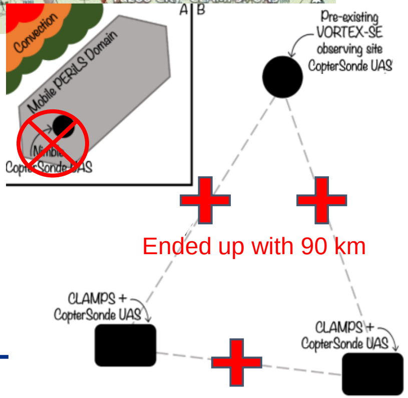


Iterations with NOAA UASD

- *defined ultimate location of inner network*
- *led to elimination of nimble + fixed approach*
- *walk before you can run!*

COA: 3 sites, 0–1.5km AGL

0–5000 feet AGL



Ended up with 90 km

Need: *network* low-atmosphere observations in *challenging environment* of southeastern US

VORTEX-SE findings: above-surface variability critical, 2016-2019 remote sensor profiling obs suggested ~50 km min. spacing

PERiLS opportunity: deploy prototype network with *network-in-network* framework

- Network-in-network concept further enhanced by PERiLS mobile armada (esp. adaptable obs)
- Deploys only when high-impact weather is imminent