# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

$$LCoE = \frac{\sum_{n=1}^{i}(CAPEX_n + O\&M_n)/(1+r)^n}{\sum_{n=1}^{i} AEP/(1+r)^n}$$

LCoE = Levelized Cost of Energy

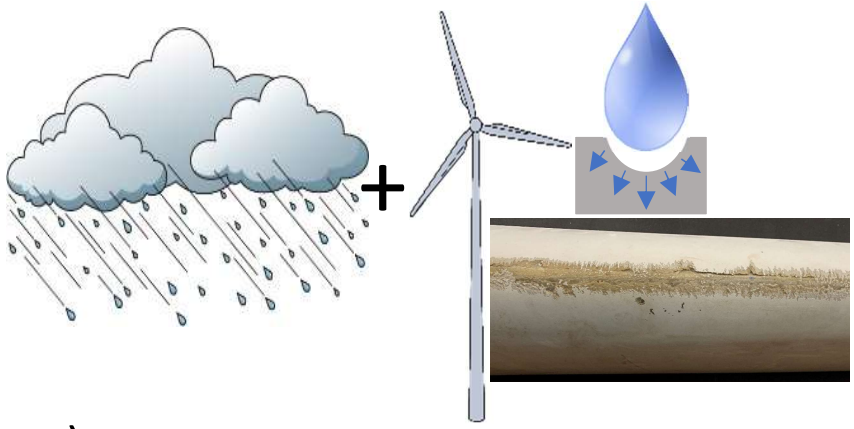
CAPEX = CAPital EXpenditures

O&M = Operations and Maintenance costs ⬆

AEP = Annual Electricity Production ⬇

r = discounting rate

year n = 1 to i, where i =lifetime



3 options to mitigate LEE (extend blade coating lifetimes):

1) Redesign of blades – ⬆ CAPEX
2) Use LEP – ⬆ CAPEX and/or O&M and ⬇ AEP
3) Use of 'erosion-safe-mode' – ⬇ AEP

Cost-benefit analyses of different options require:

- Assess amount of material stress (coating lifetime)
- PDF of material stress (conc. in time/occurrence of stress).



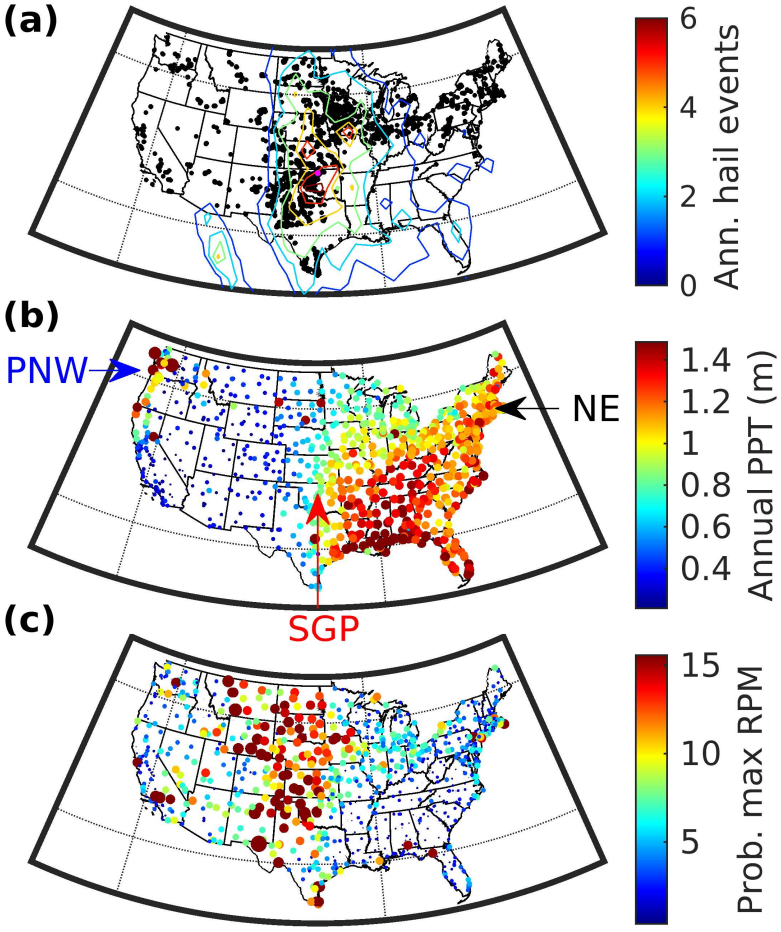
NSF Sandia National Laboratories U.S. DEPARTMENT OF ENERGY Office of Science

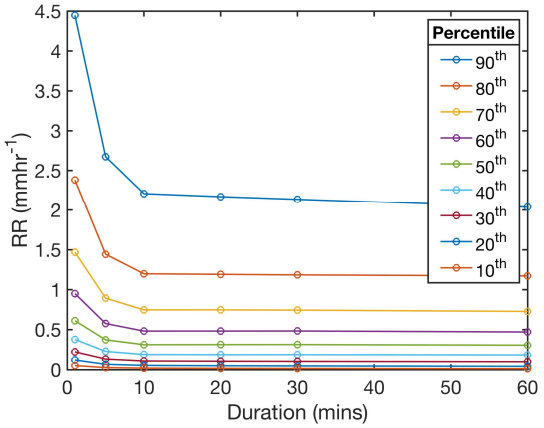
# Translating atmospheric measurements to wind turbine blade coating lifetimes

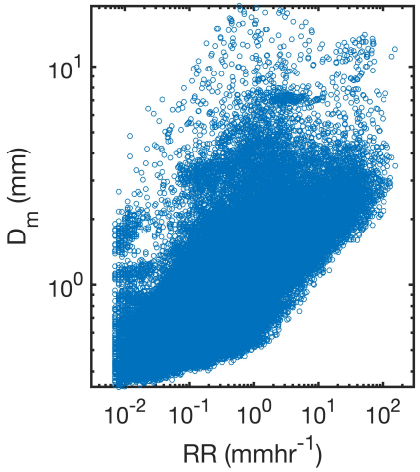
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

Blade coating lifetime TO 1st ORDER $f$(kinetic energy transfer) btwn falling hydrometeors & rotating blades:

- Closing velocity:
  - Hydrometeor fall velocity: $f$(diameter)
  - Blade RPM: $f$(wind speed)
- # & mass of collisions:
  - Precipitation intensity (Rainfall rate)
- Hydrometeor phase (freq hail)




Pryor et al. (2022): *Energies*. ***15***, 8553; doi: 10.3390/en15228553

CENER, 2025

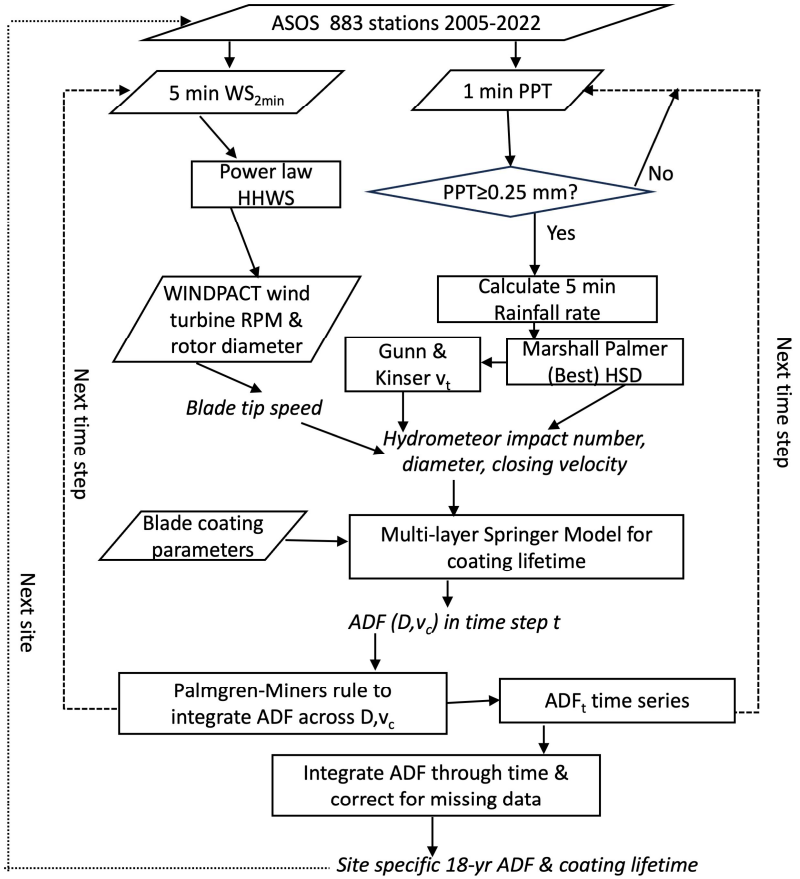
Pryor et al. (2025): *Energies* **18**, 425; doi: 10.3390/en18020425

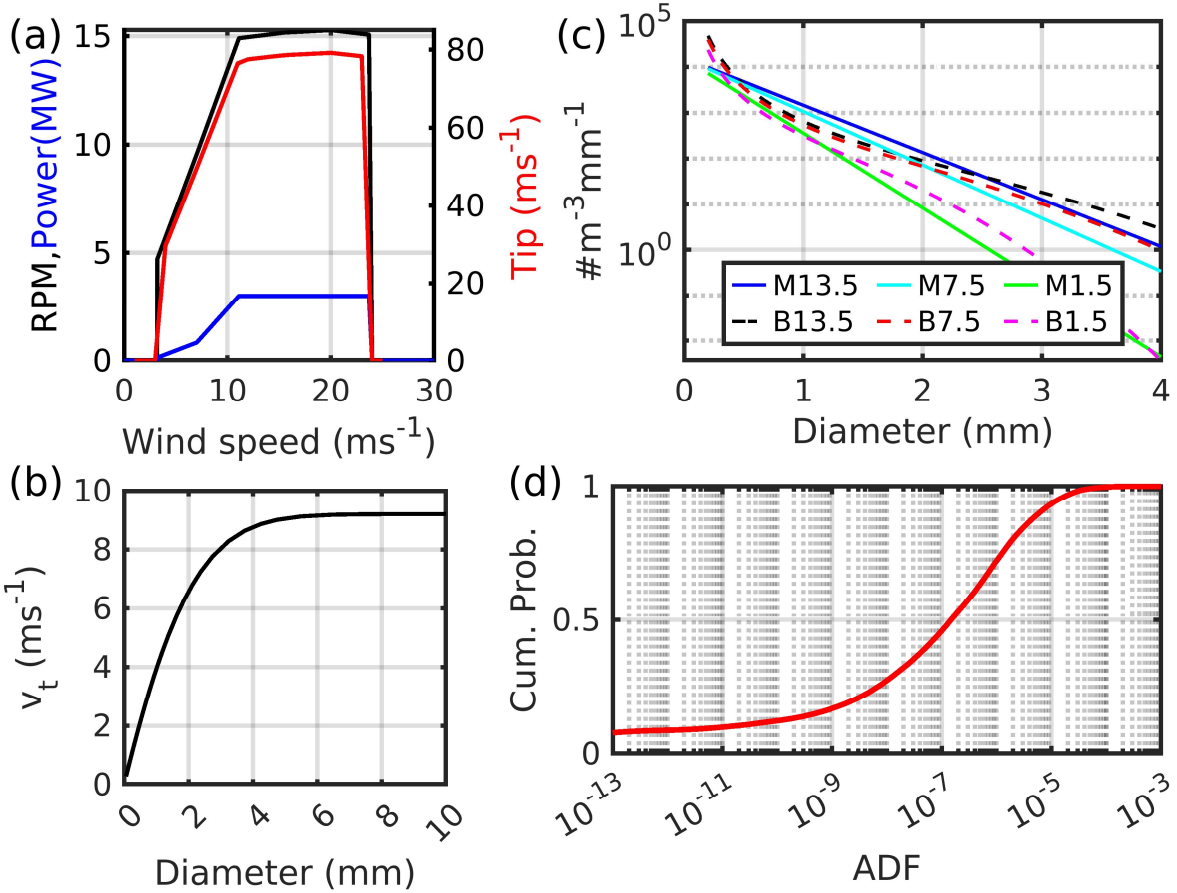
NSF
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY
Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

## Part 1: Method & results for a geospatial & temporal assessment of blade coating lifetime




Pryor et al. (2025): *Energies* **18**, 425;
doi: 10.3390/en18020425

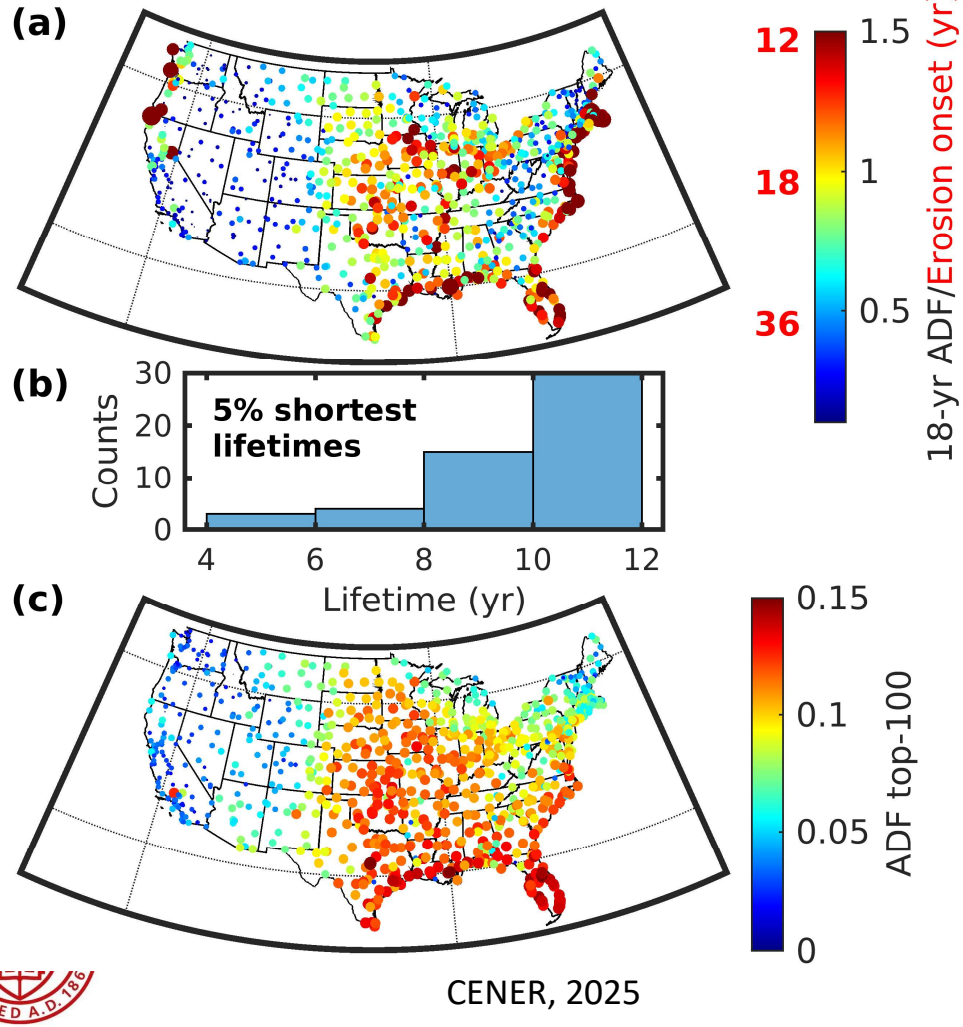
CENER, 2025

NSF
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY
Office of Science

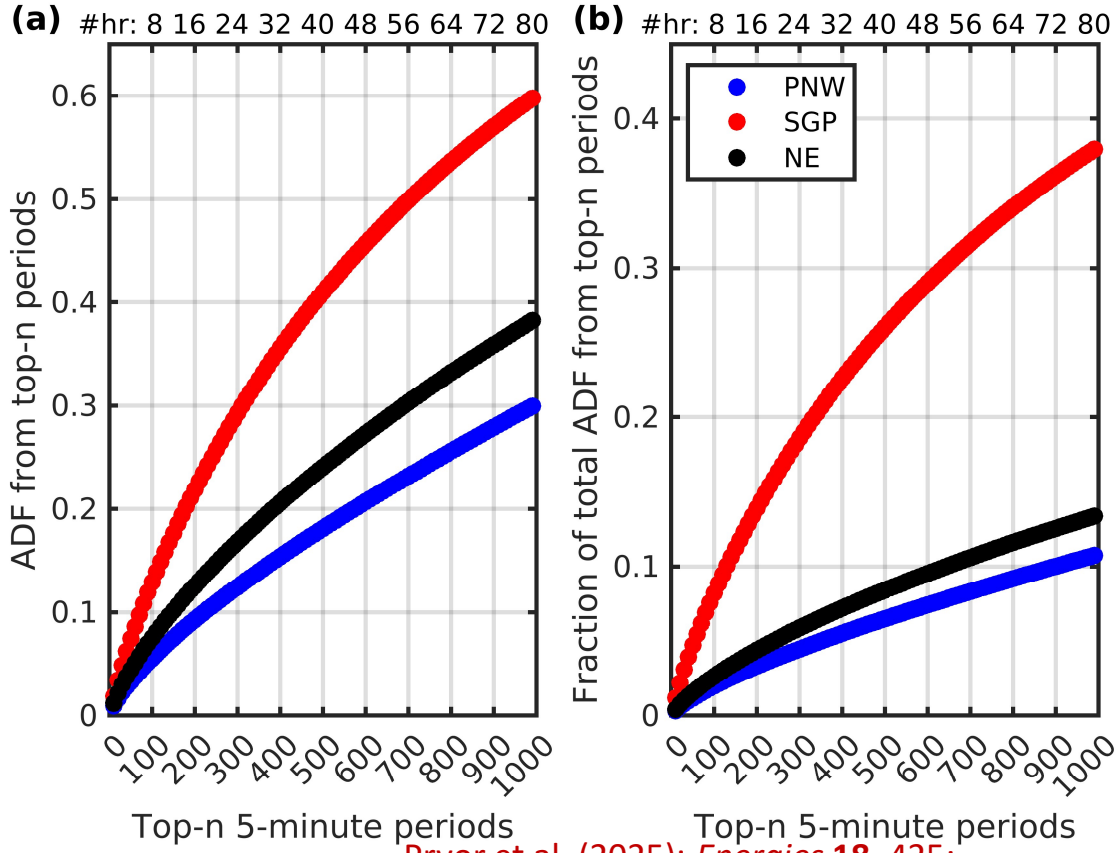
# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University**

Part 1: Method & results for a geospatial & temporal assessment of blade coating lifetime




CENER, 2025




Pryor et al. (2025): *Energies* **18**, 425;
doi: 10.3390/en18020425

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY | Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

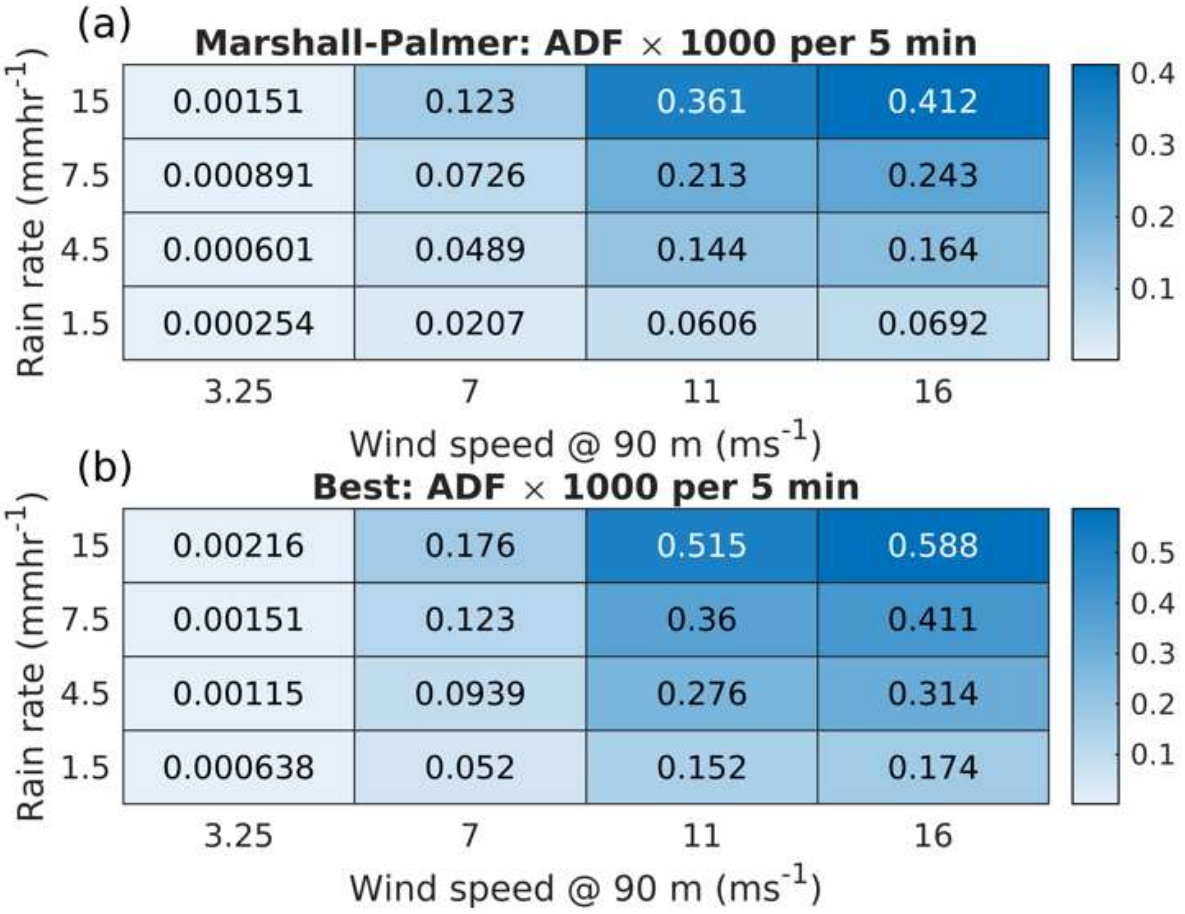
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

Part 1: Method & results for a geospatial & temporal assessment of blade coating lifetime

Uncertainties

1) Springer model parameters (material properties)
2) Wind speed vertical extrap.
3) Impingement prob.
   - DNV: $\beta = 1 - e^{-15D}$
   - β > 0.99 for D > 0.3 mm
   - ΔADF < 0.3%.
4) HSD/phase (**freq. hail**) – need measurements!
5) Un-sampled locations – need modeling!

Solutions to 4+5 also for 'short-term forecasting for dynamic operation'




Pryor et al. (2025): *Energies* **18**, 425;
doi: 10.3390/en18020425

CENER, 2025

NSF · Sandia National Laboratories · U.S. DEPARTMENT OF ENERGY · Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

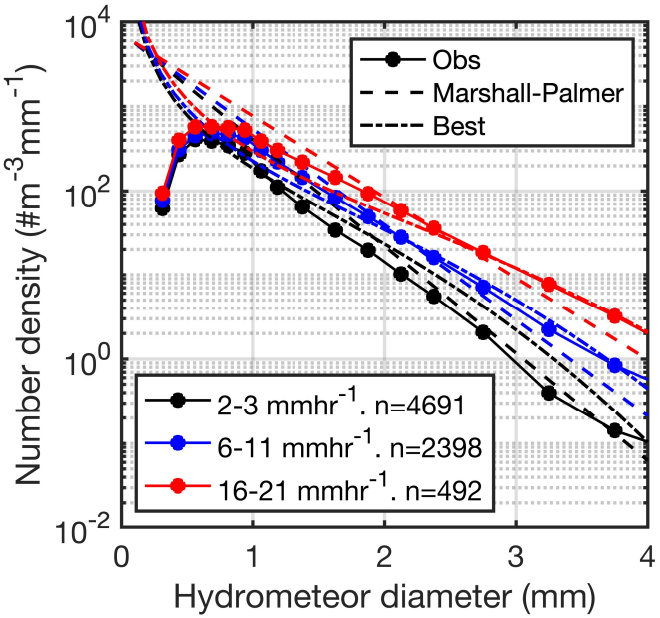
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

## Part 2: Measurements of HSD/phase

### Hydroclimate definitions

- Rainfall Rate (RR) – depth of liquid water that would accumulate if precip. continued for 1 hr.
- Phase: Solid (ice): Snow, graupel, hail v. Liquid: Rain, drizzle.
- Hydrometeor size distribution (HSD): Number counts in diameter classes.
- Hydrometeor asymmetry: Axis ratio:
  - $AR = \frac{D_{Vert}}{D_{Horiz}}$
  - Rain droplets deform due to drag AR < 1
  - Hail = solid so does NOT deform (AR ≈ 1)
- Options for measurements:
  - RADAR
  - Disdrometers

Pryor et al. (2022): *Energies*. ***15***, 8553; doi: 10.3390/en15228553



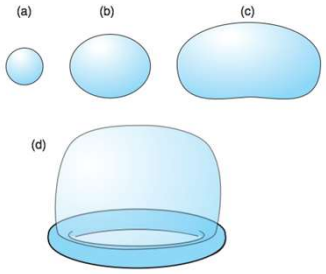




**Figure 8.41**
*Enlargement of raindrop shapes vs. diameter D (approximate). (a) D < 1 mm; (b) 1 mm < D < 3 mm ; (c) 3 mm < D; (d) large (D = 4 mm) jellyfish-like shape just before drop breaks up..*

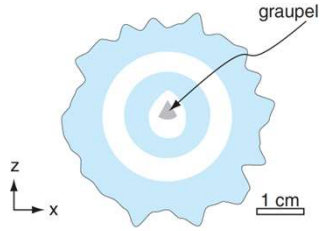



**Figure 15.6**
*Illustration of slice through a hailstone, showing a graupel embryo surrounded by 4 layers of alternating clear ice (indicated with blue shading) and porous (white) ice.*

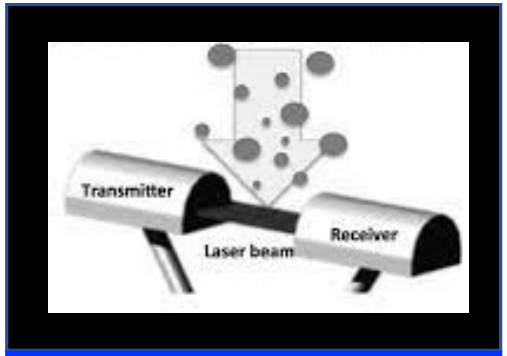
CENER, 2025

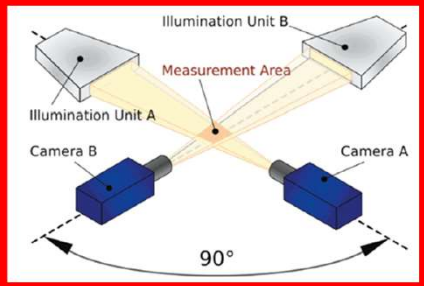
# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

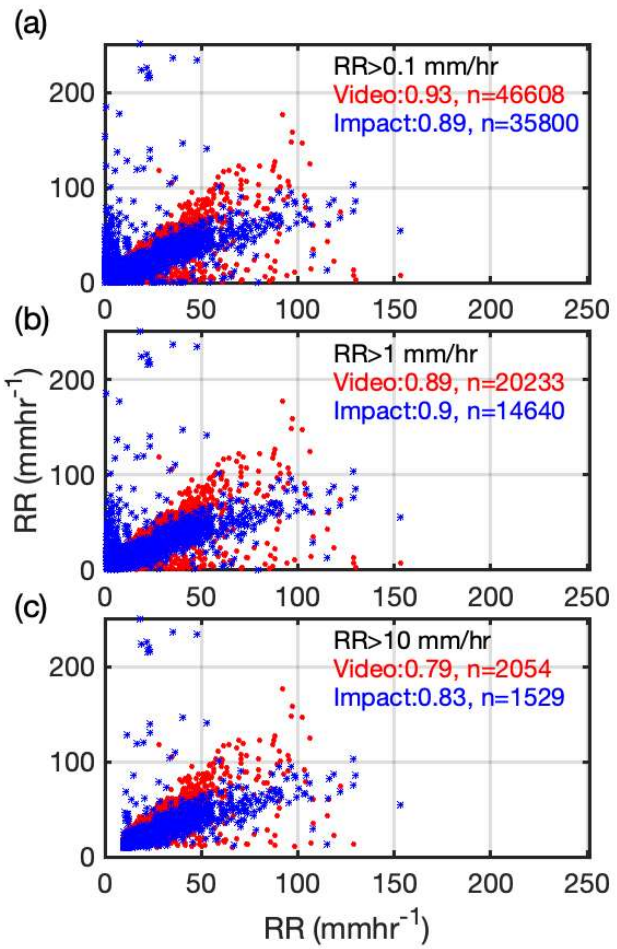
Part 2:
Measurements of HSD/phase:

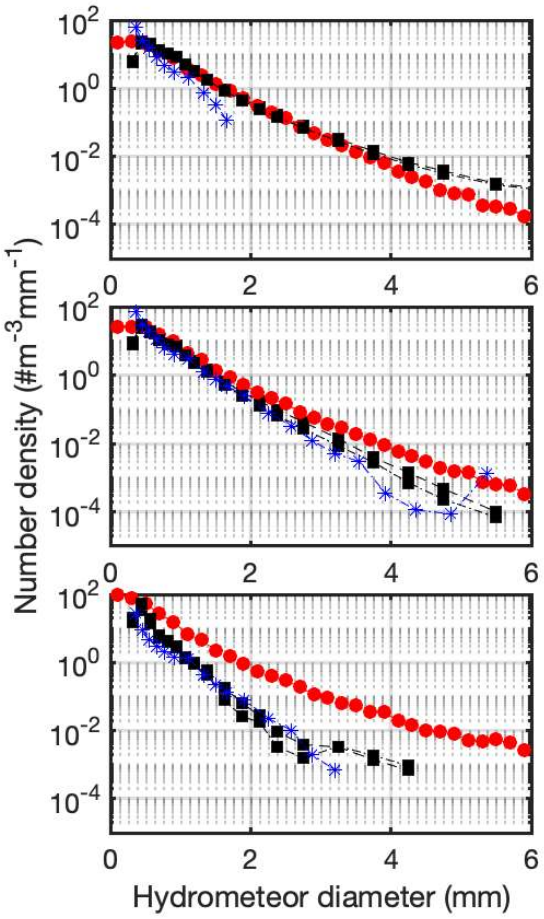
- Closure between disdrometers = imperfect




CENER, 2025




Pryor et al. (2022): *Energies*. ***15***, 8553; doi: 10.3390/en15228553

Sandia National Laboratories

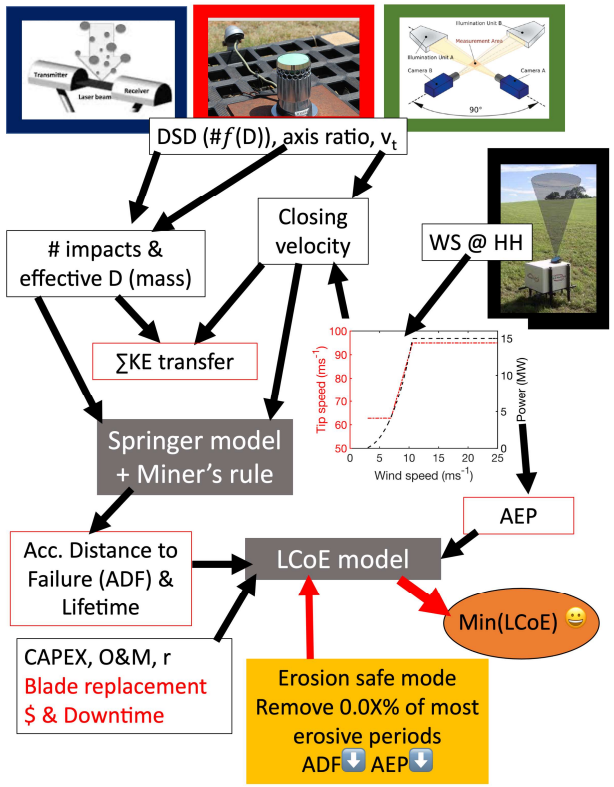
U.S. DEPARTMENT OF ENERGY | Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

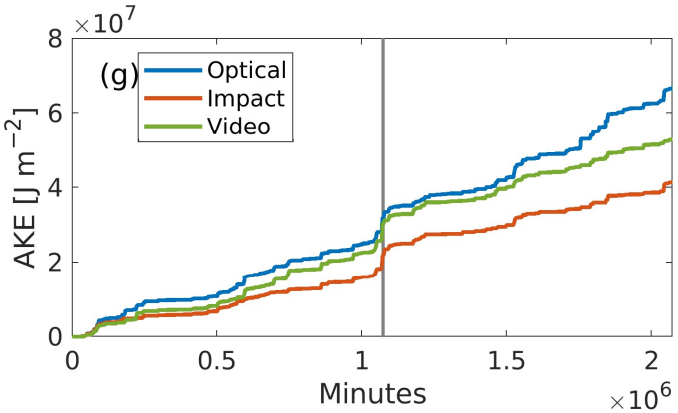
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

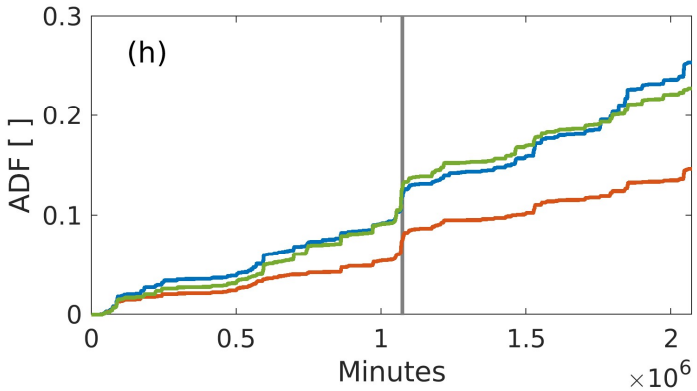
## Part 2: Measurements of HSD/phase:

- Closure between disdrometers is imperfect & matters for coating lifetime!




| 4-years of 1-min obs | Impact | Video | Optical | Optical - Hail |
|---|---|---|---|---|
| Total KE ($Jm^{-2}$) | $3.85\times10^{7}$ | $5.92\times10^{7}$ | $6.66\times10^{7}$ | $6.33\times10^{6}$ |
| Springer ADF/yr | 0.0368 | 0.0572 | 0.0638 | |
| Springer lifetime (yr) | 27.2 | 17.5 | 15.7 | |




Letson & Pryor (2023): *Energies* ***16*** 3906 doi: 10.3390/en16093906

CENER, 2025

NSF
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY
Office of Science

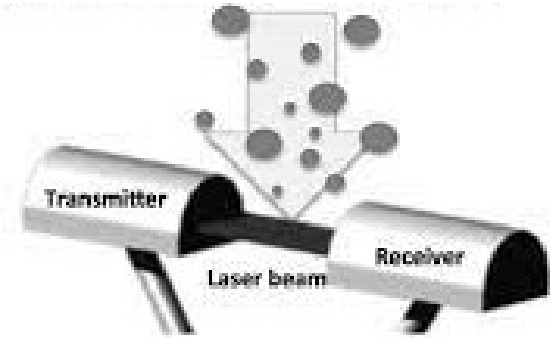
# Translating atmospheric measurements to wind turbine blade coating lifetimes

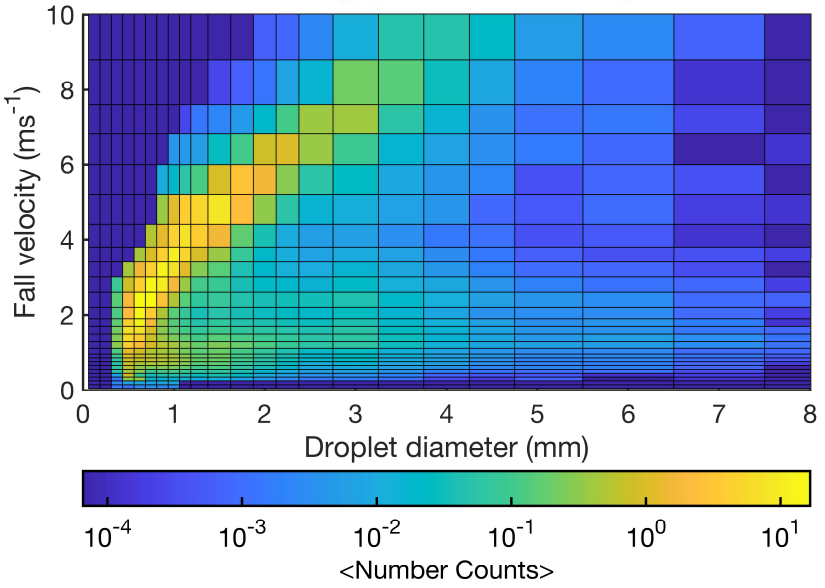
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

Part 2: Measurements of HSD/phase:

Exploring sources of lack-of-closure

- Disdrometers measure 'counts' ($n_{i,j}$) of hydrometeors of diameter D-bin i falling in j, $v_f$ bins.
  - Convert to # concentrations (#m$^{-3}$/mm):
  - $N(D_i) = \sum_{j=1}^{32} \frac{n_{i,j}}{Ft \; f(j)(D_i)\Delta D_i}$
  - Convert to precipitation intensity (mmhr$^{-1}$)
  - $RR = \frac{\pi}{6} \frac{3.6}{10^3} \frac{1}{Ft} \sum_{i=1}^{32} n_i D_i^3$
  - Optical disdrometer: (t=time, F = instrument 'field of view')
- Implications:
  - Small errors in D yield BIG errors in RR
  - Small errors in D and/or $v_f$ yield BIG errors in N($D_i$)




Pryor et al. (2022): *Energies.* ***15***, 8553; doi: 10.3390/en15228553

Pryor et al. (2024): *Energies* ***17***, 6285 doi: 10.3390/en17246285

# Translating atmospheric measurements to wind turbine blade coating lifetimes

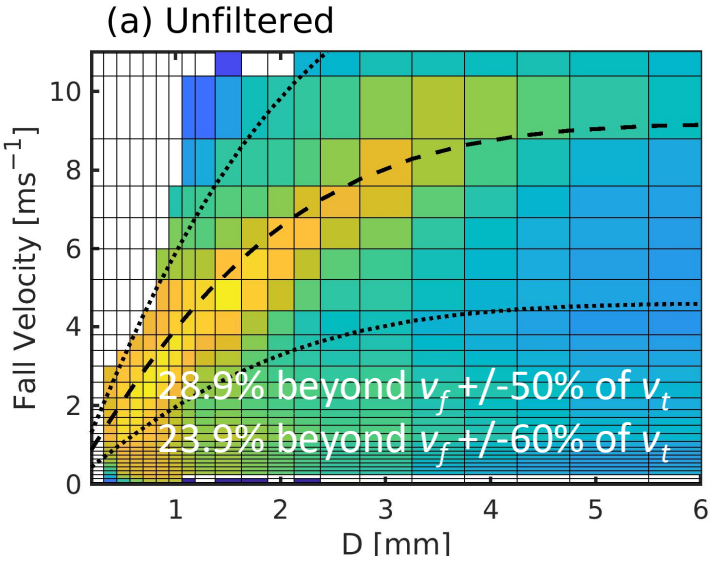
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

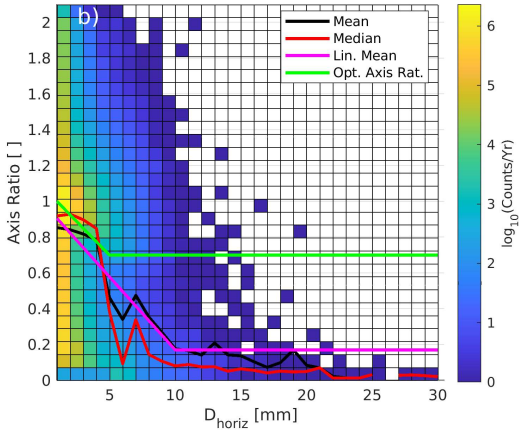
Part 2: Measurements of HSD/phase:

- Why occurrence of high D low $v_f$?
  - Lateral advection?
  - Droplets NOT spherical, AR assumptions invalid?
  - 'Splash' from instrument casing?
  - Mis-alignment of lasers?

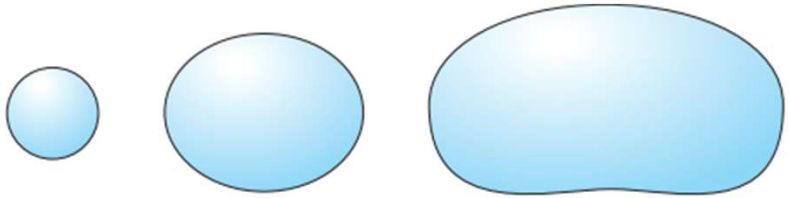
*Disdrometers report RR 'directly' settings are proprietary*

- What are we doing to quantify/reduce these uncertainties?
  1. Disdrometer closure experiments (incl. detailed calibrations & examining WHEN disdrometers disagree)
  2. Improved disdrometer deployment strategy
  3. Exploring possible sources of 'anomalous' measurements




Letson & Pryor (2023): *Energies.* **16,** 3906 doi: 10.3390/en16093906



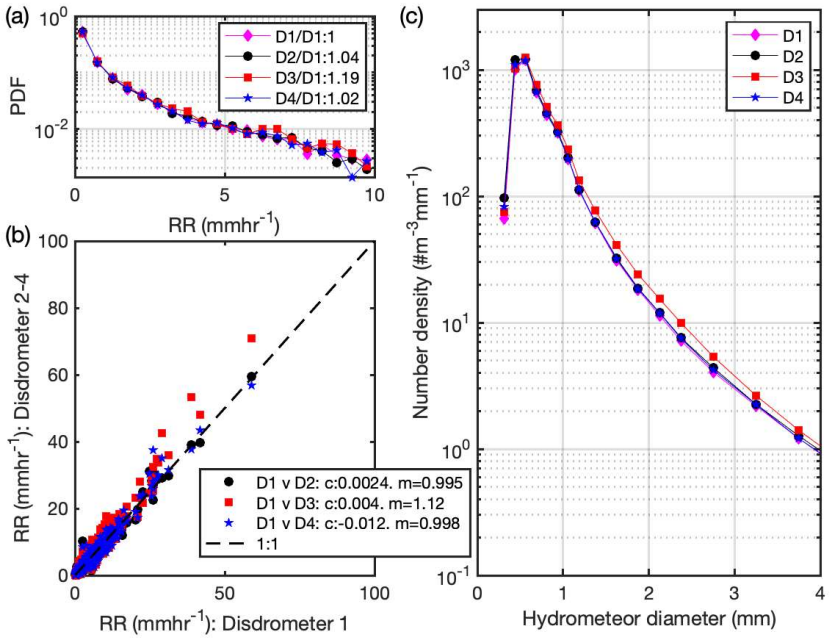
CENER, 2025

NSF
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY | Office of Science

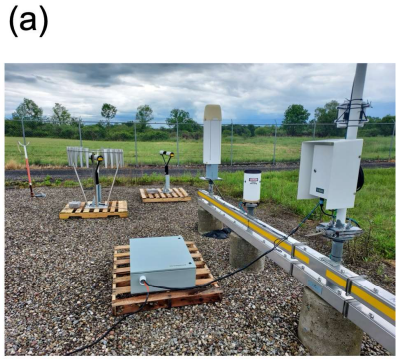
# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University**

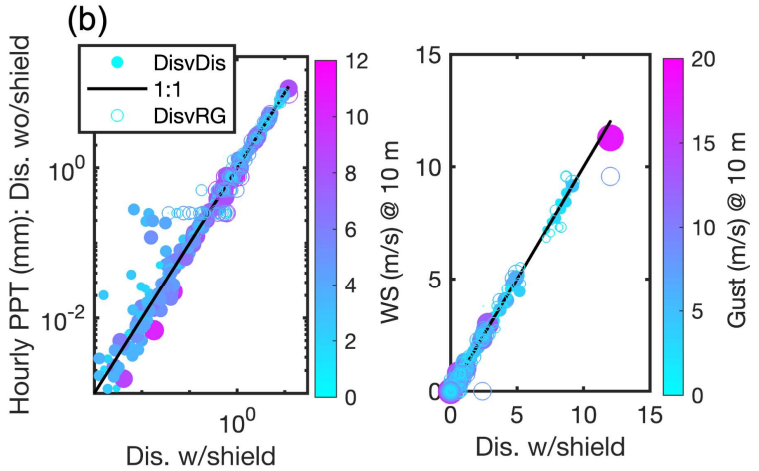
## Part 2: Measurements of HSD/phase:

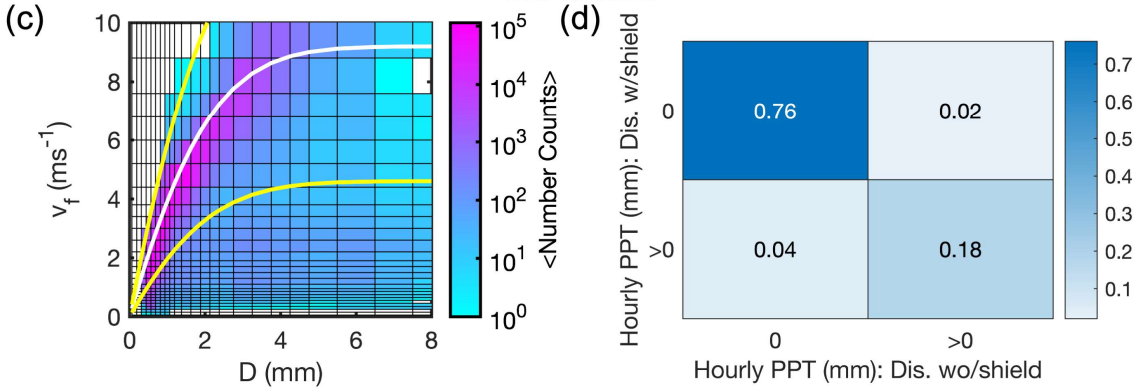



Pryor et al. (2022): *Energies* ***15***, 8553 doi: 10.3390/en15228553




Pryor et al. (2024): *Energies* ***17***, 6285 doi: 10.3390/en17246285




Laser disdrometer – misalignment/miscalibration! ➔ need intercomparison BEFORE network deployment.

Windshielding not 'solution' for moderate WS

CENER, 2025

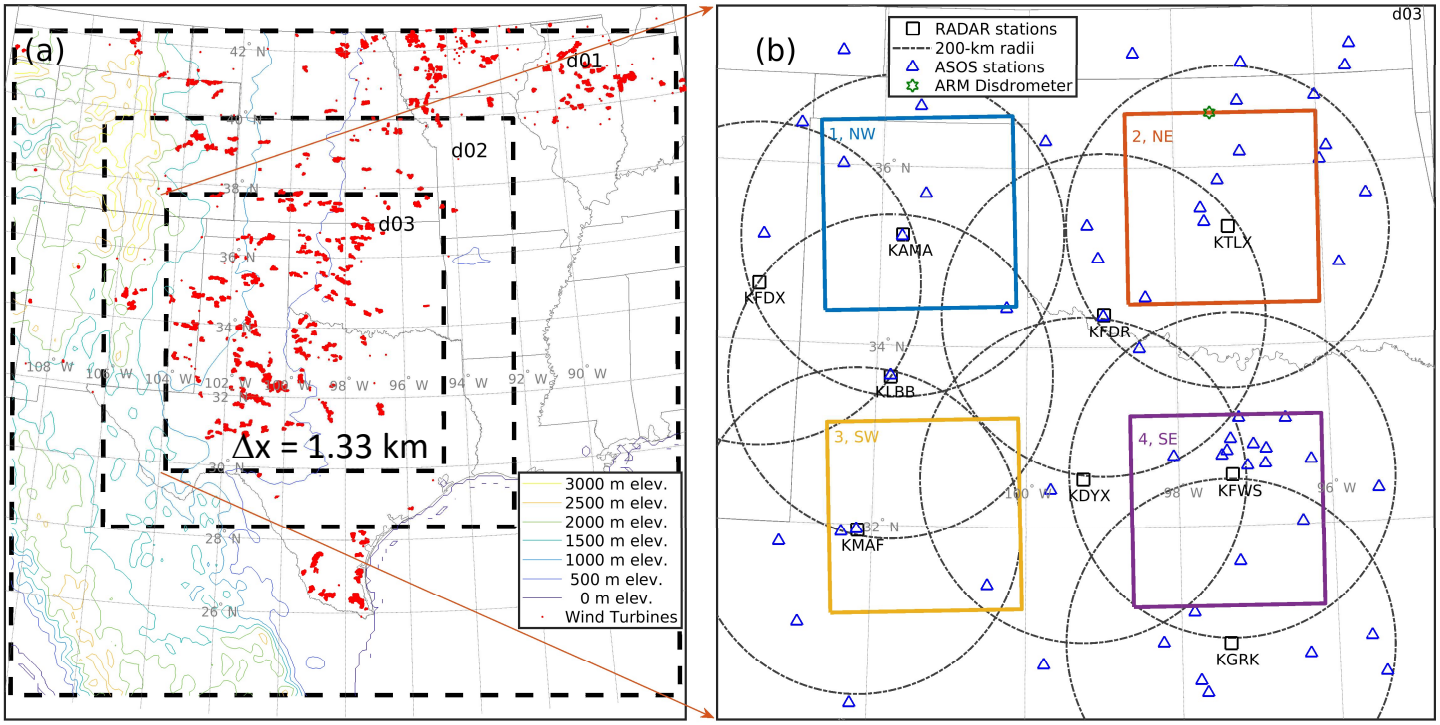
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY | Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University**

Part 3: Numerical modeling of RR + phase (*HSD applied later*) + WS:

- Weather Research and Forecasting (WRF) model simulations: Jan-Sep 2017.




Pryor et al. (2023): JAMC **62** 41-62

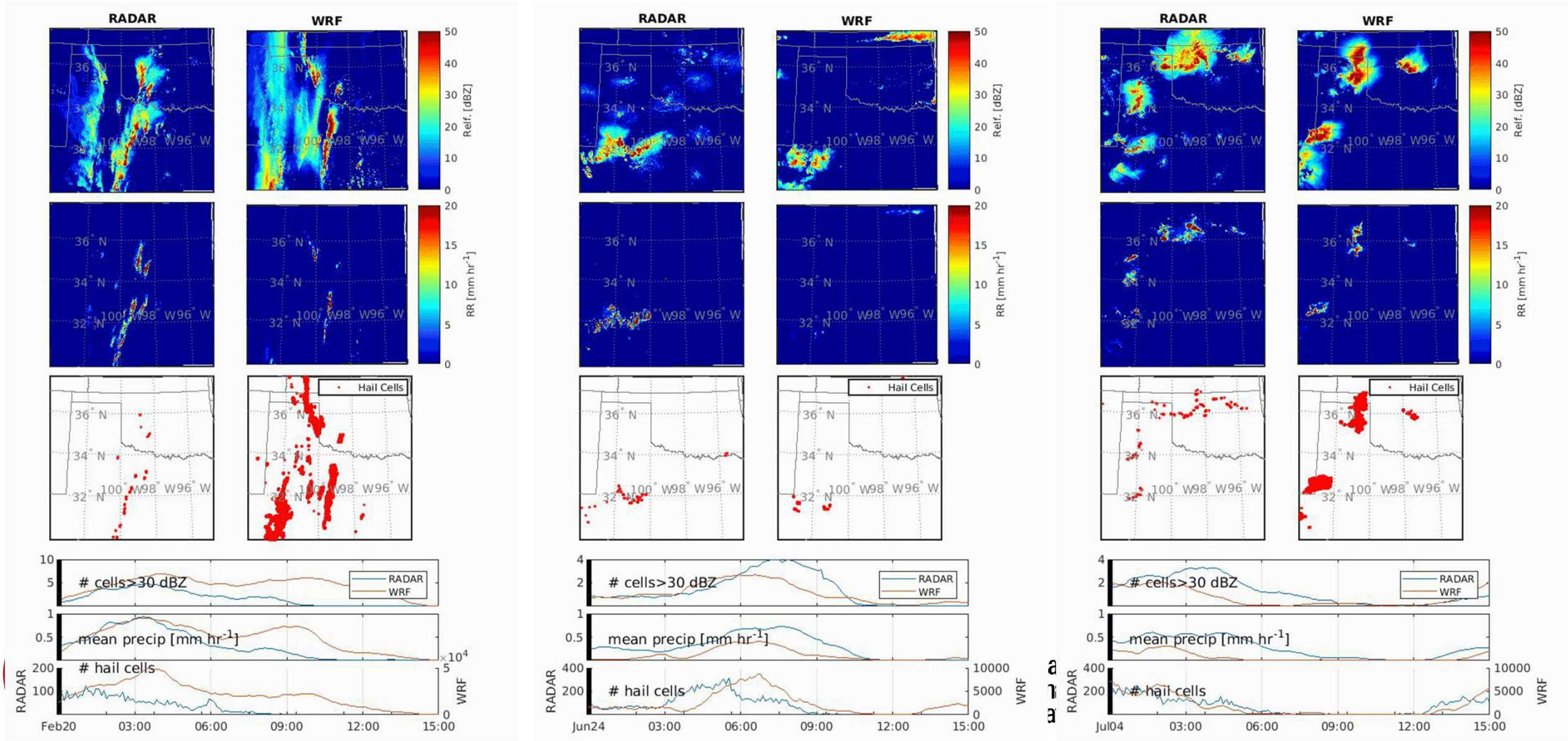
CENER, 2025

# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University**

Pryor et al. (2023): JAMC **62** 41-62

Part 3: Numerical modeling of RR + phase (*HSD applied later*) + WS: 3 example events

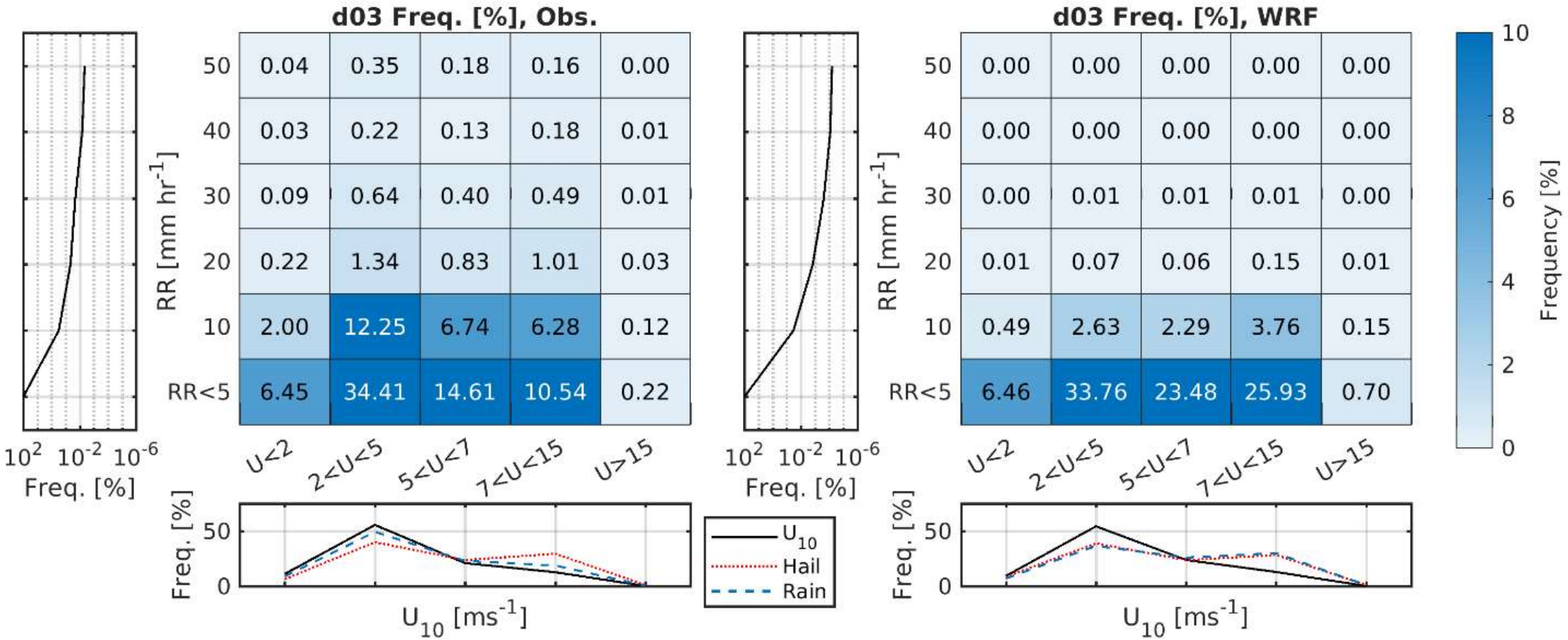


# Translating atmospheric measurements to wind turbine blade coating lifetimes

**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

Part 3: Numerical modeling of RR + phase (*HSD applied later*) + WS:

- WRF: Jan-Sep 2017: At ARM




Pryor et al. (2023): JAMC **62** 41-62

CENER, 2025

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY | Office of Science

# Translating atmospheric measurements to wind turbine blade coating lifetimes

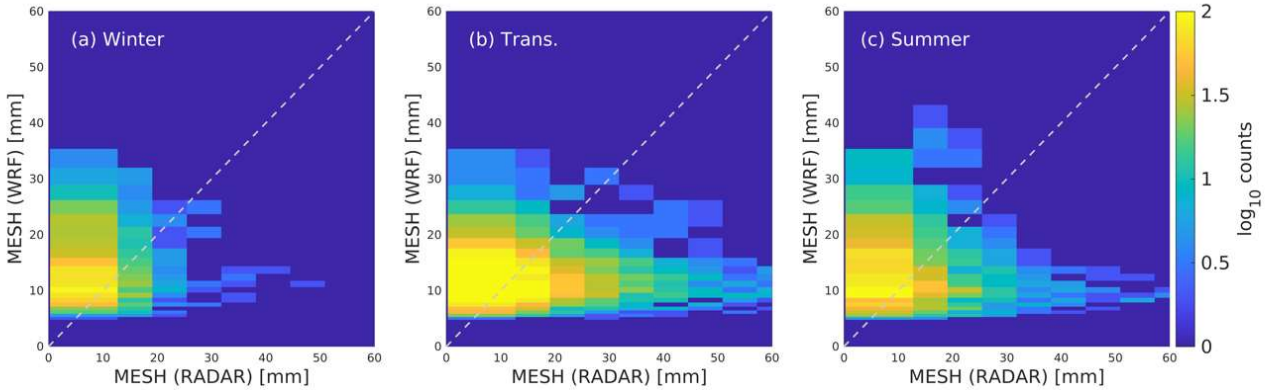
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). Cornell University

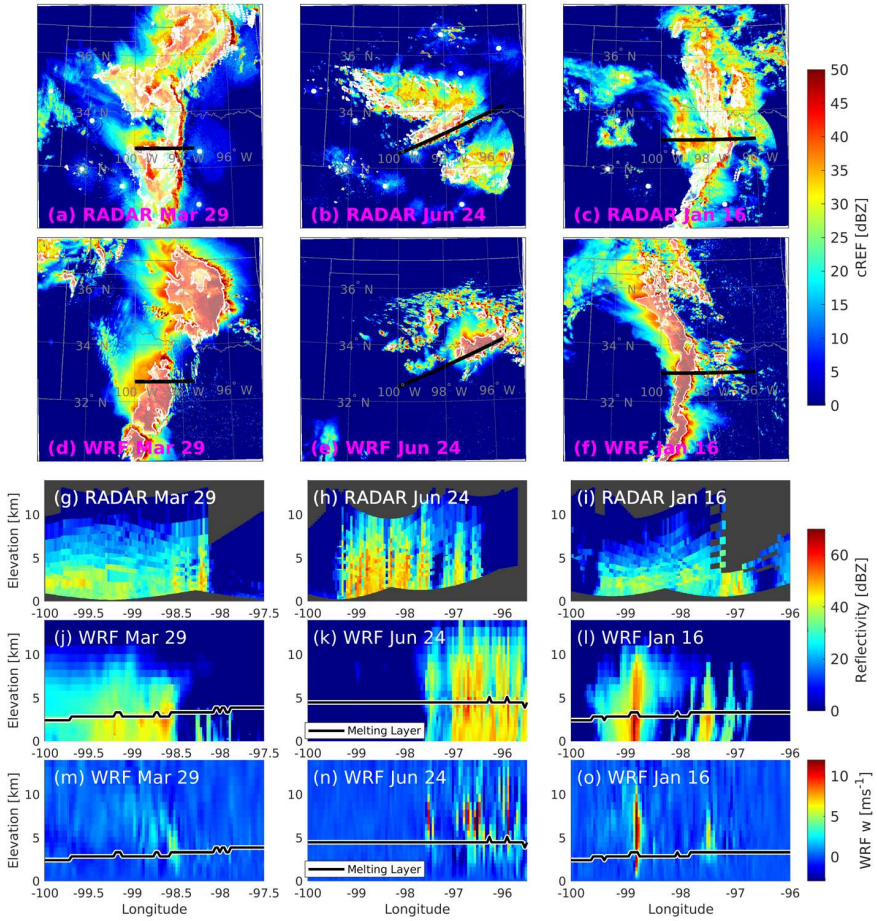
Part 3: Numerical modeling of RR + phase (*HSD applied later*) + WS:

WRF: Jan-Sep 2017: (single configuration) fidelity

- Wind speeds (at 10-m – many stations, at 90-m single site)
- For intense, hail 'rich' events
- For joint probabilities Pr{RR|U} and Pr{Hail|U}

BUT frequency of high RR underestimated & MESH variability underestimated




Pryor et al. (2023): JAMC **62** 41-62

CENER, 2025

# Translating atmospheric measurements to wind turbine blade coating lifetimes

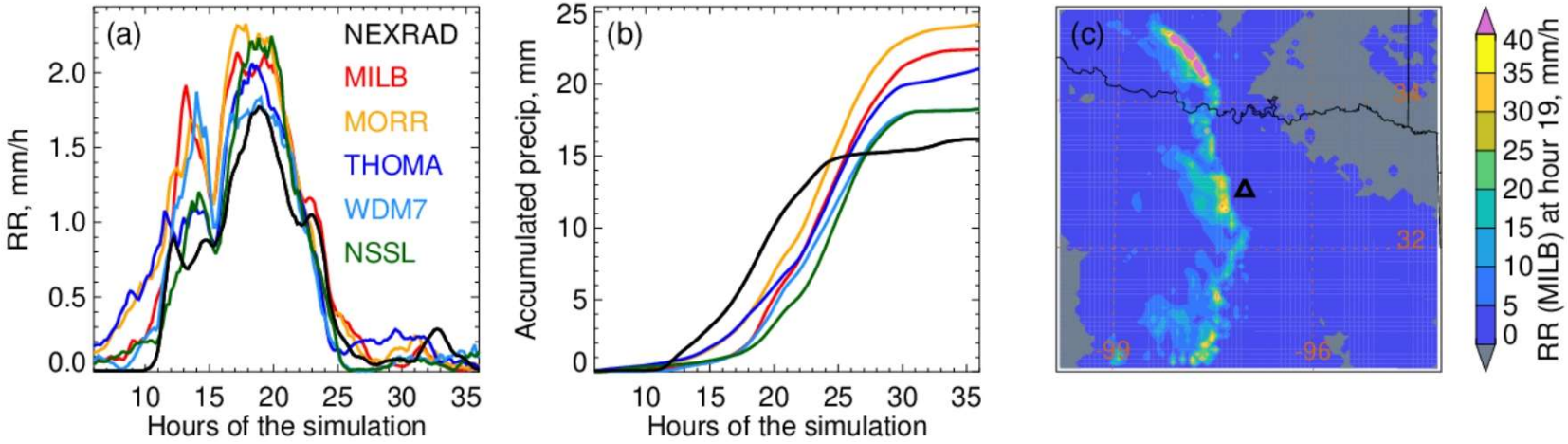
**Sara C. Pryor + Rebecca J Barthelmie**, Jacob J Coburn & Xin Zhou (+ Letson & Shepherd). **Cornell University**

Part 3: Numerical modeling of RR + phase (*HSD applied later*) + WS:

- WRF 'storyline' events w/ multiple microphysics schemes

Pryor et al. (2024): *Energies* ***17***, 6285 doi: 10.3390/en17246285

  - High dependence on model physics settings (domain-wide acc. precip varies by factor of 1.5!) Location specific acc.precip varies by > factor of 2! & RR(t,x,y) >> 2!




- What are we doing to quantify/reduce these uncertainties?
  1. Build a coalition to undertake comprehensive assessment & advance 'optimal config.'
  2. Build comprehensive & robust V&V framework

**We face a big challenge!**

**Collaborations & Questions WELCOME!**