Deep Convective Cold Pools: Potential Impacts on Wind Energy from Observations and Numerical Modelling

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Forschungspark Windenergie Krummendeich WiValdi

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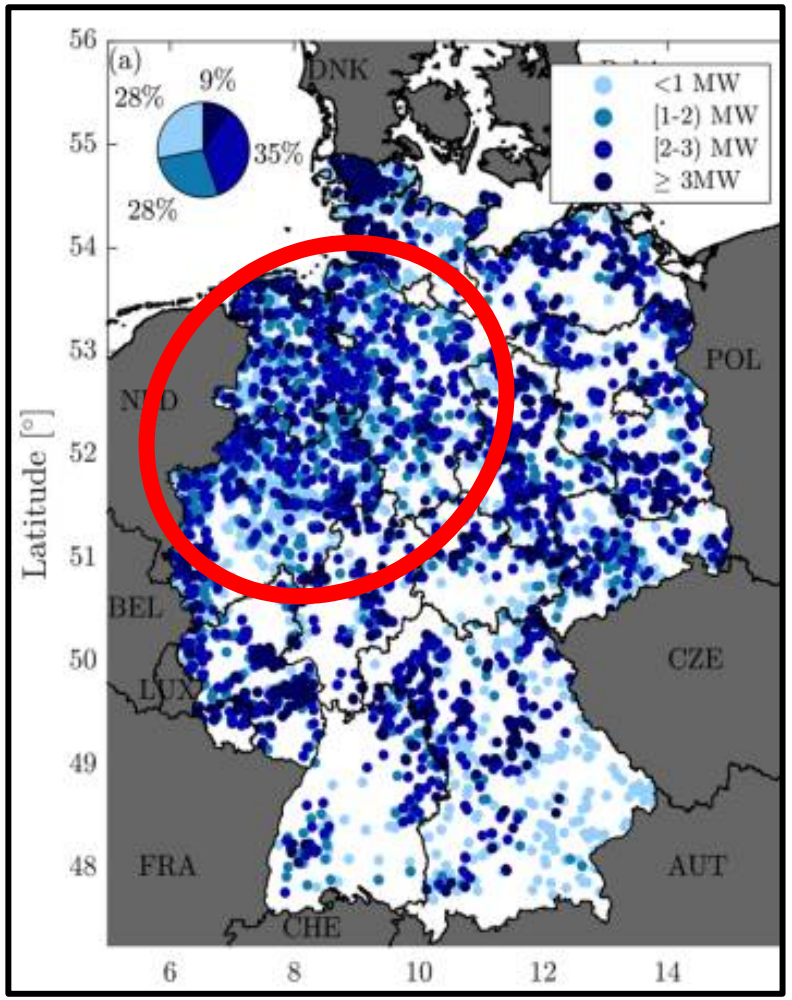
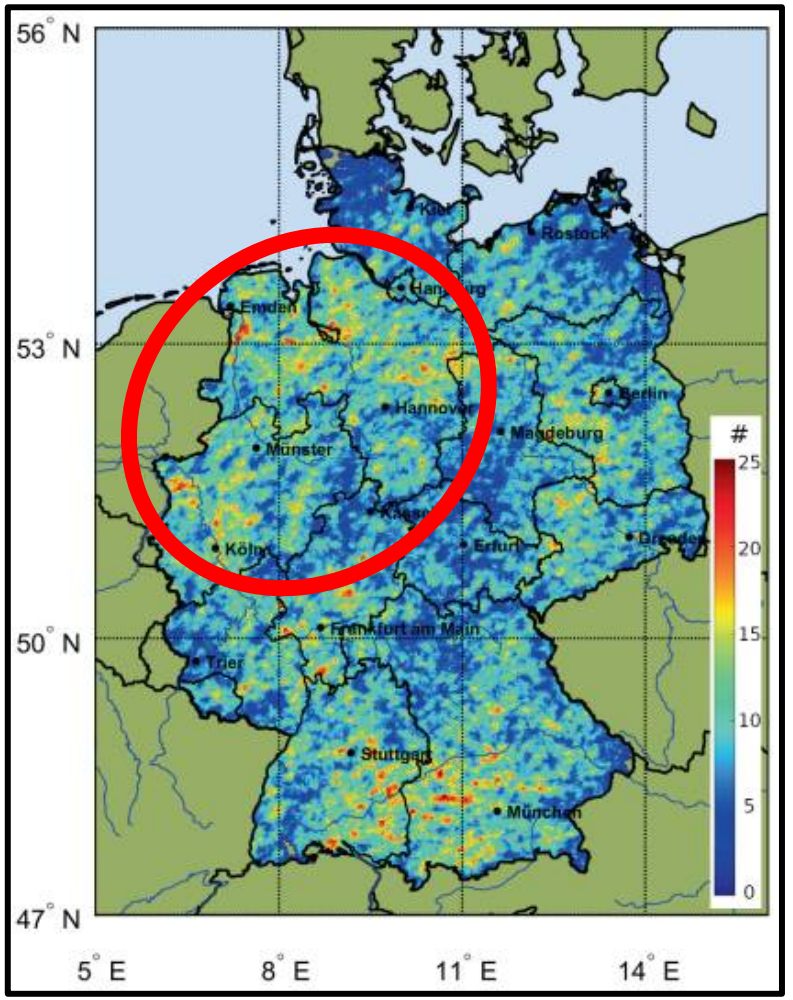
Wind Turbines



Bouchard and Romanic (2023)

Convective cell frequency



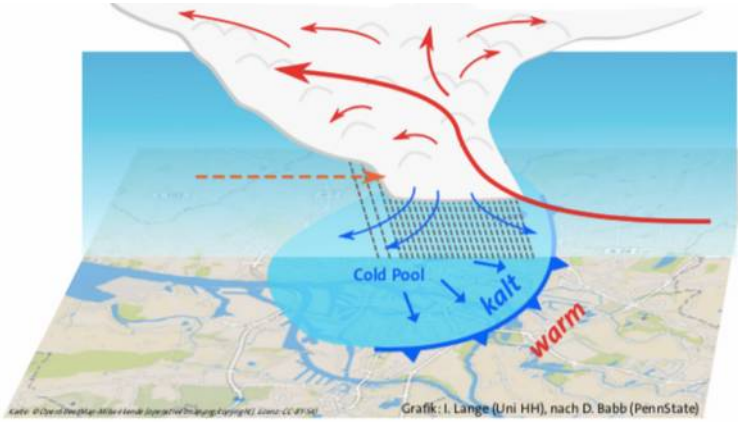
Wilhelm et al. (2023)

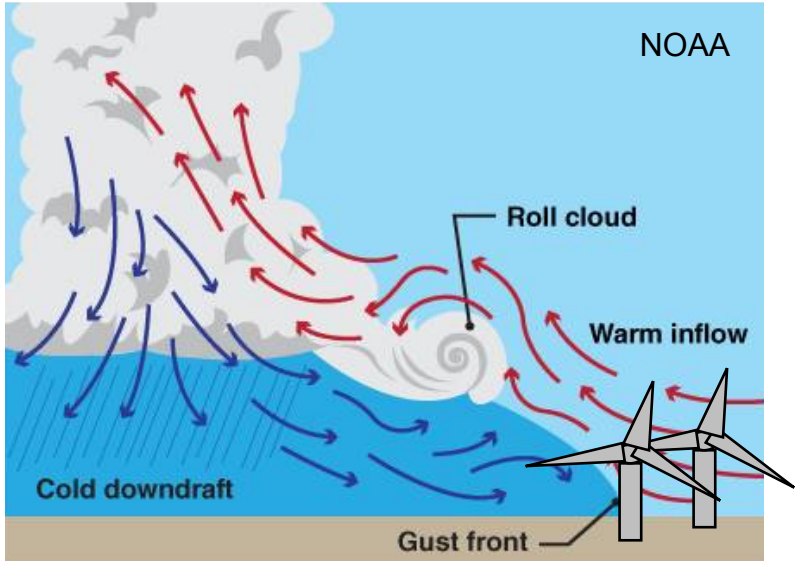
Convective cells regularly occur throughout Germany, including over *northwest Germany* where wind turbines are particularly concentrated (Bouchard and Romanic, 2023; Wilhelm et al., 2023)

Motivation

- Wind energy contribution increased in the German energy grid (from 1.7% in 2000 to 34%; 2024) - becoming increasingly important to attain a more complete understanding of meteorological phenomena that impact wind energy production.
- Larger-scale events (cold fronts, mesoscale storms or low-level jets) are relatively easy to forecast.
- Events that occur over **shorter time scales and smaller spatial scales** are much harder to predict.
- Wind ramps associated with deep convection are particularly difficult to predict due to the intrinsically stochastic nature of deep convection

Thunderstorms involve lightning, abrupt darkening, heavy precipitation, and rapid changes in wind speed and direction → play an important role in producing minute-scale fluctuations in wind energy output





WIVALDI

HTTPS://WINDENERGY-RESEARCHFARM.COM/

Gefördert durch:

Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages

DLR Deutsches Zentrum für Luft- und Raumfahrt

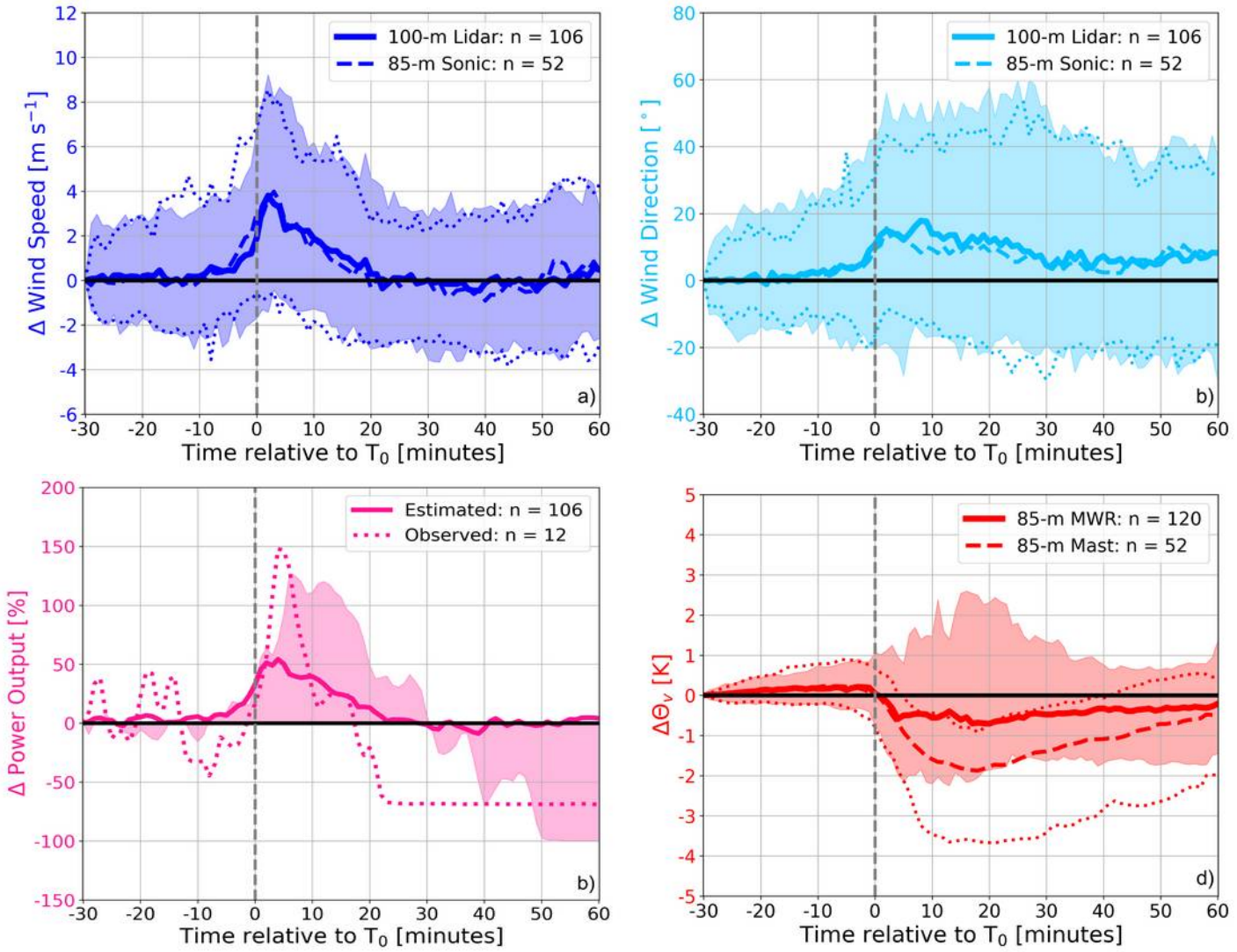
ForWind Zentrum für Windenergieforschung

ENERCON ENERGIE FÜR DIE WELT

Niedersächsisches Ministerium für Wissenschaft und Kultur

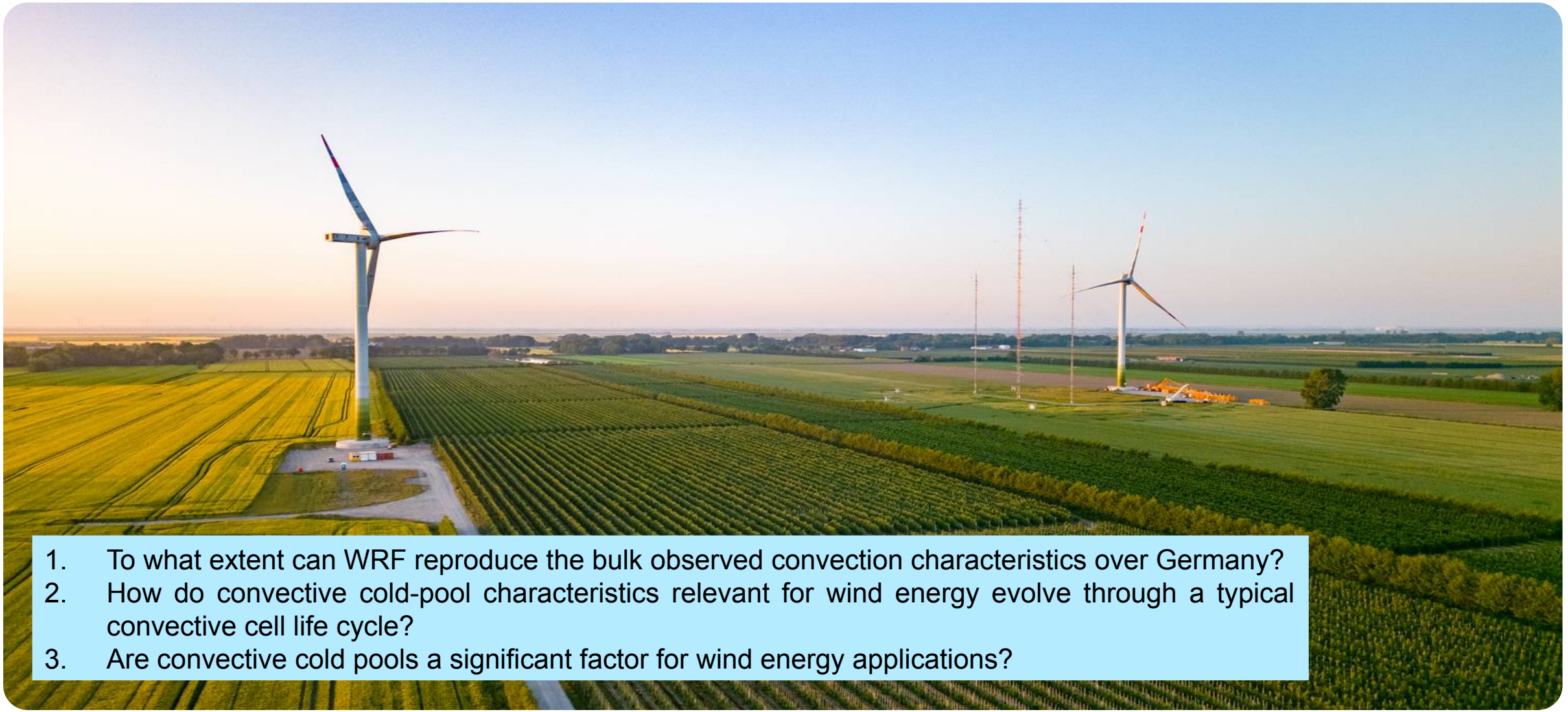
Observed median hub-height winds typically increase by 4 ms^{-1} for ~30 mins, with increased **estimated wind power generation** of up to 50%

Wivaldi Wind Park



Thayer, Kilroy and Wildmann (2025)

Research Questions



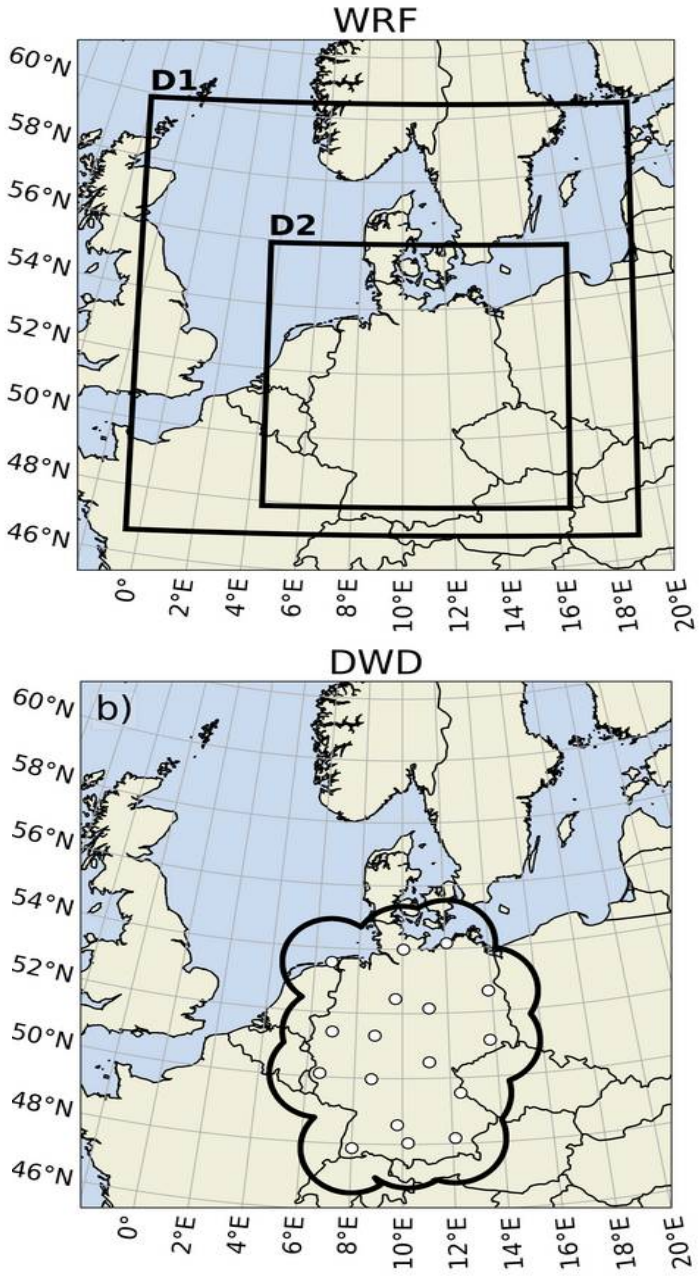
1. To what extent can WRF reproduce the bulk observed convection characteristics over Germany?
2. How do convective cold-pool characteristics relevant for wind energy evolve through a typical convective cell life cycle?
3. Are convective cold pools a significant factor for wind energy applications?

WRF Setup

- WRF V4.4.1
- 2 Domains (dx,dy = 5 km, 1 km)
- Initial/Boundary Conditions: ECMWF Op Analyses (6h)
- Model top: 50hPa (ca. 20km)
- CORINE Land Use Data (250 m) for D2
- Output every 5 min (comparison to radar)
- 1-month simulation (**July 2023**)
- Cumulus parameterization only in D1
- WDM 6-class scheme (better representation of ice species in deep convective clouds – Anisimov *et. al.,* 2023, Wise *et. al.,* 2024)
- **TATHU** Python package for detecting, tracking and analyzing the life cycle of Convective Systems

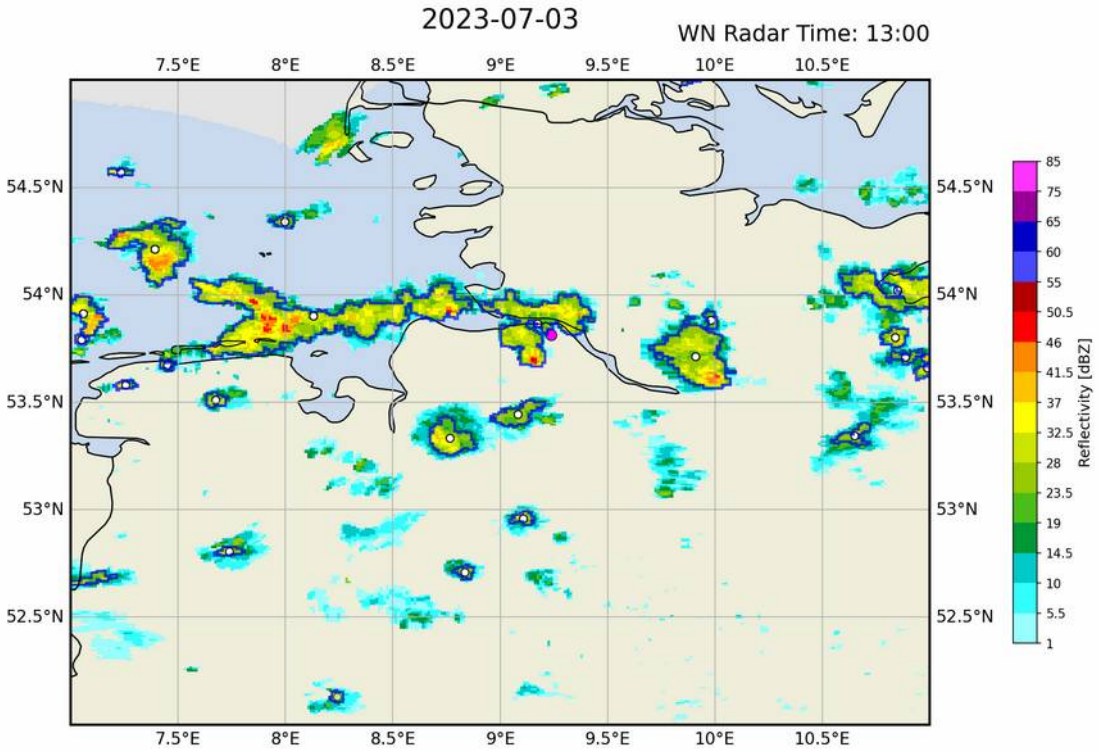
Domain	Grid Spacing	Vertical Levels	nx,ny
D1	5 km	36	301 x 301
D2	1 km	57	901 x 901

~ 7 grid points below 1 km height

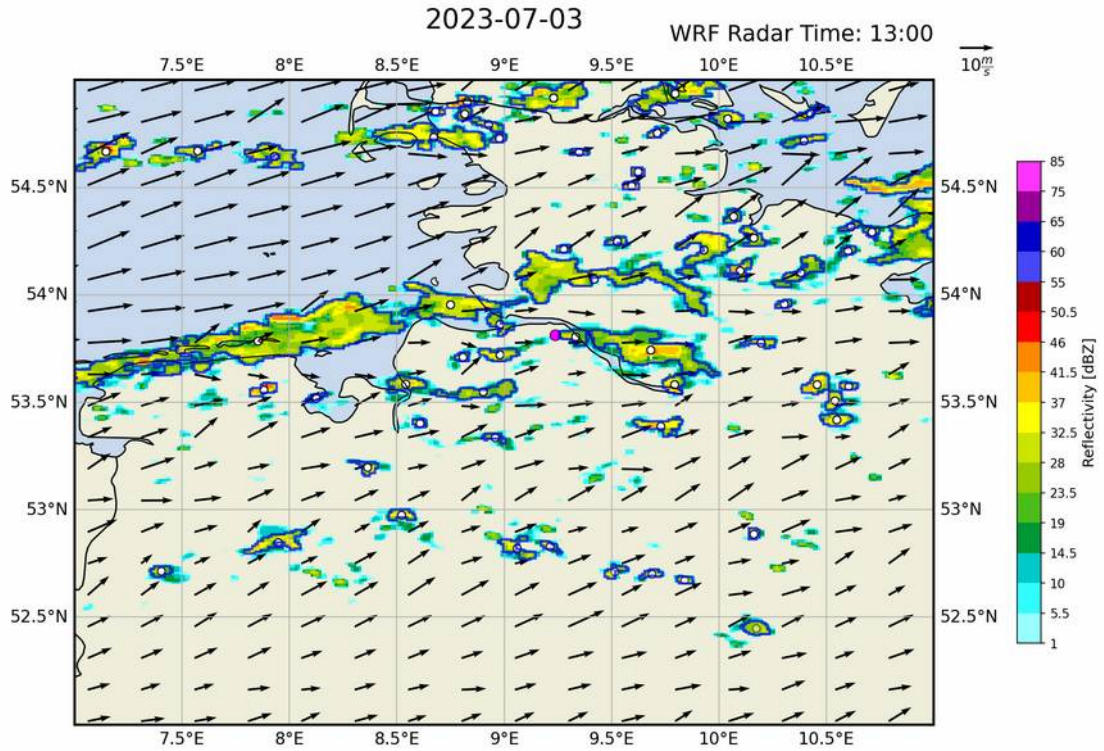


Comparison of Observed and Simulated Convection

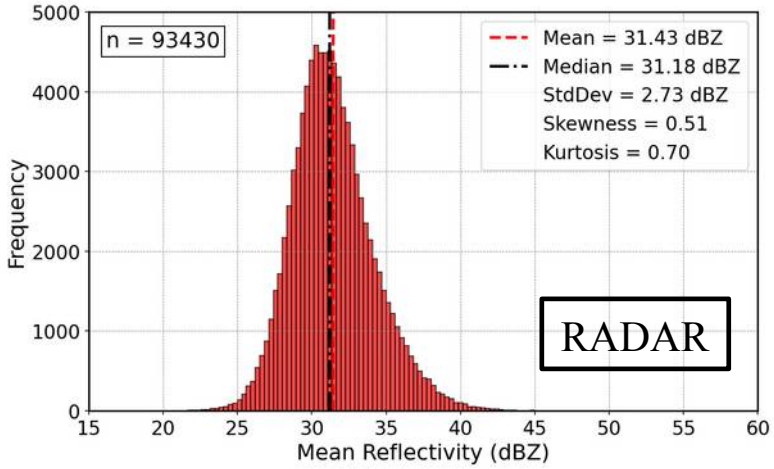
DWD RADAR

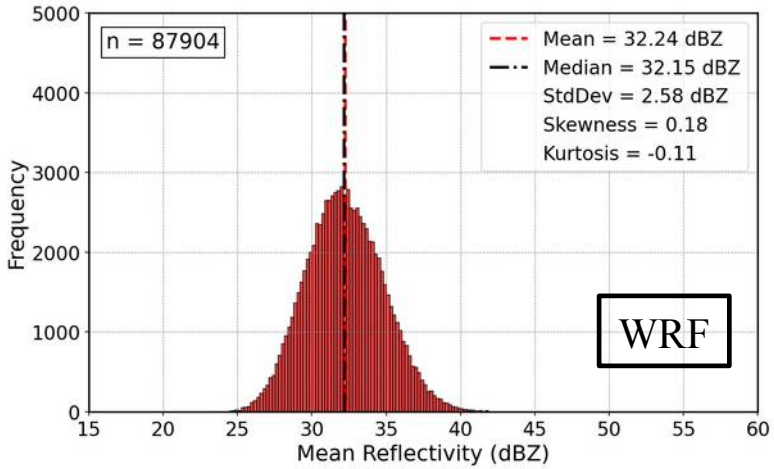


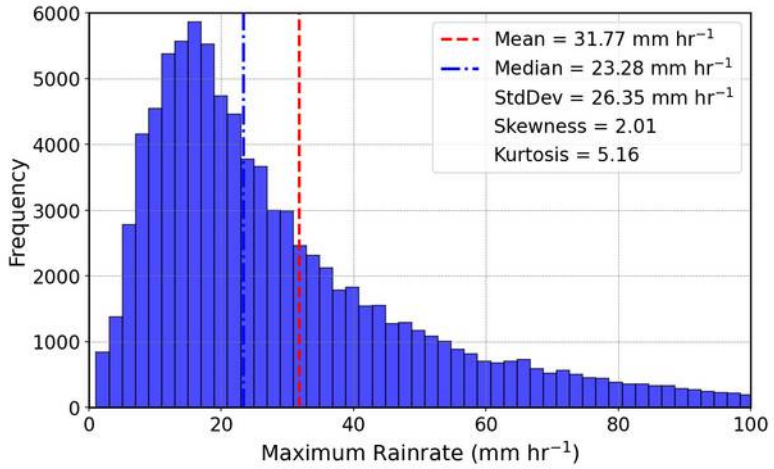
WRF

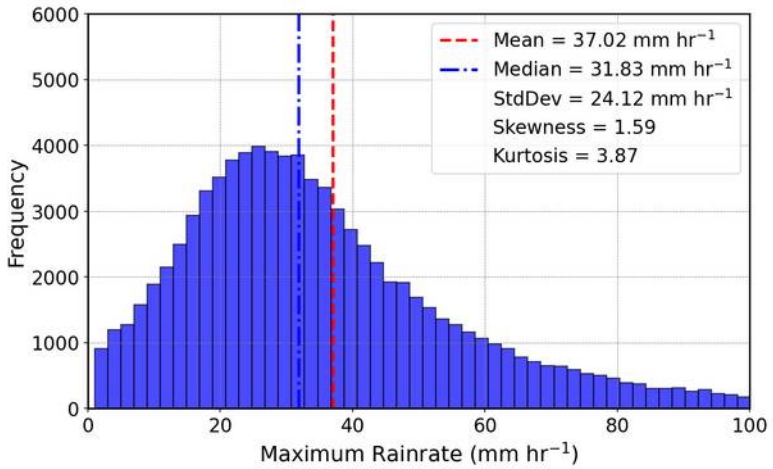


WRF tends to produce stronger mean reflectivity and rainfall on average, but reasonably captures the observed distribution (cells attaining > 46 dBZ)







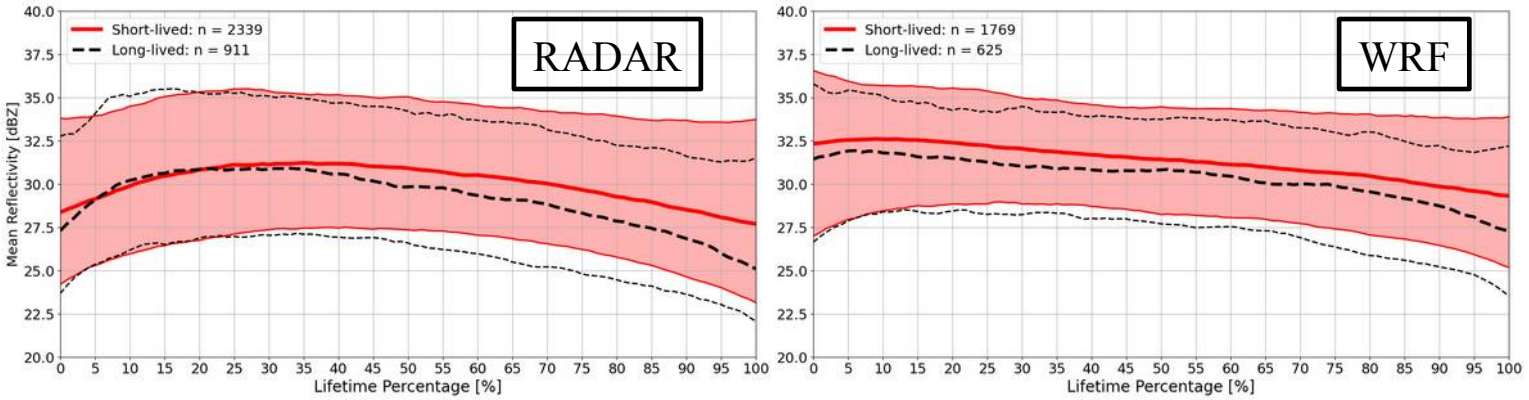


`WRF exhibits a positive bias in terms of very high RR` (Pryor *et. al.*, 2023)

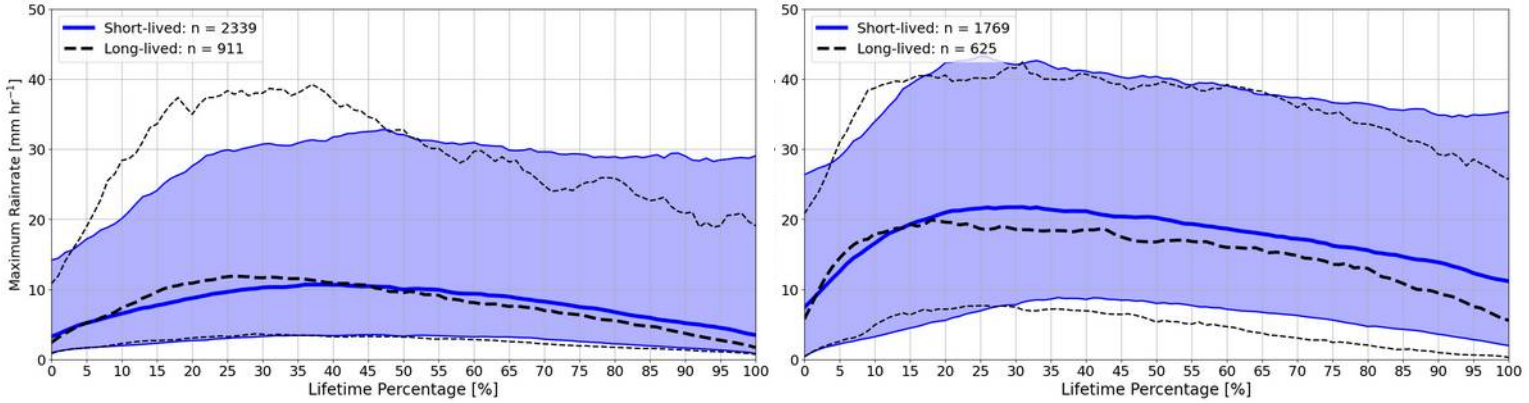
Convective Life Cycle (> 46 dBZ, < -1.5K, no splitting/merging)

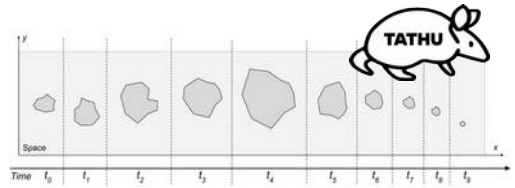
Shorter < 1 hr —
Longer > 1 hr ---

Reflectivity



Rain rate





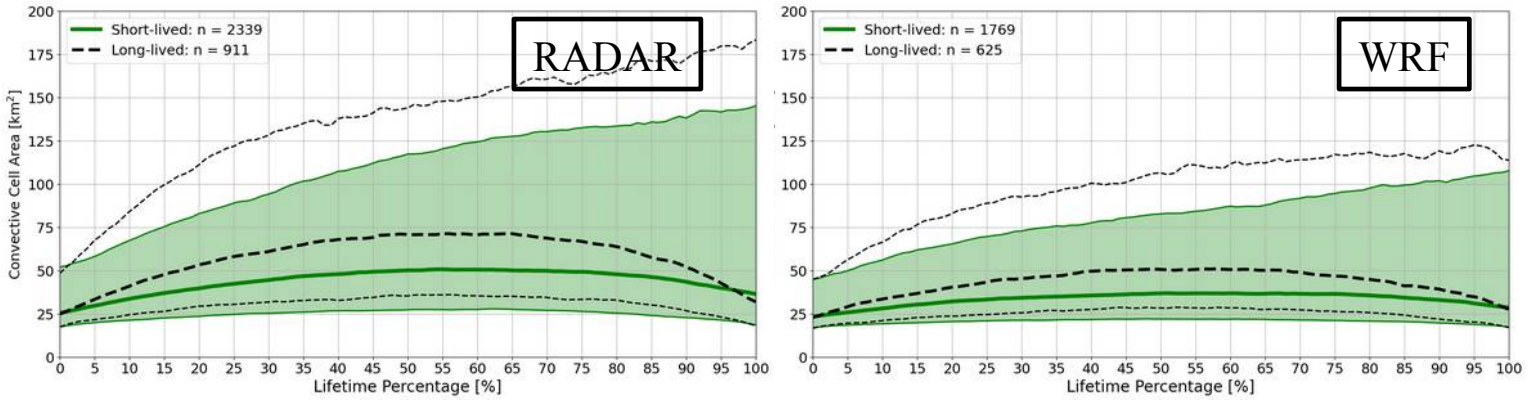
Simulated convective cells tend to **peak earlier in intensity** and attain a higher maximum intensity

The life-cycle rain rates confirm the **high rain-rate bias** in WRF

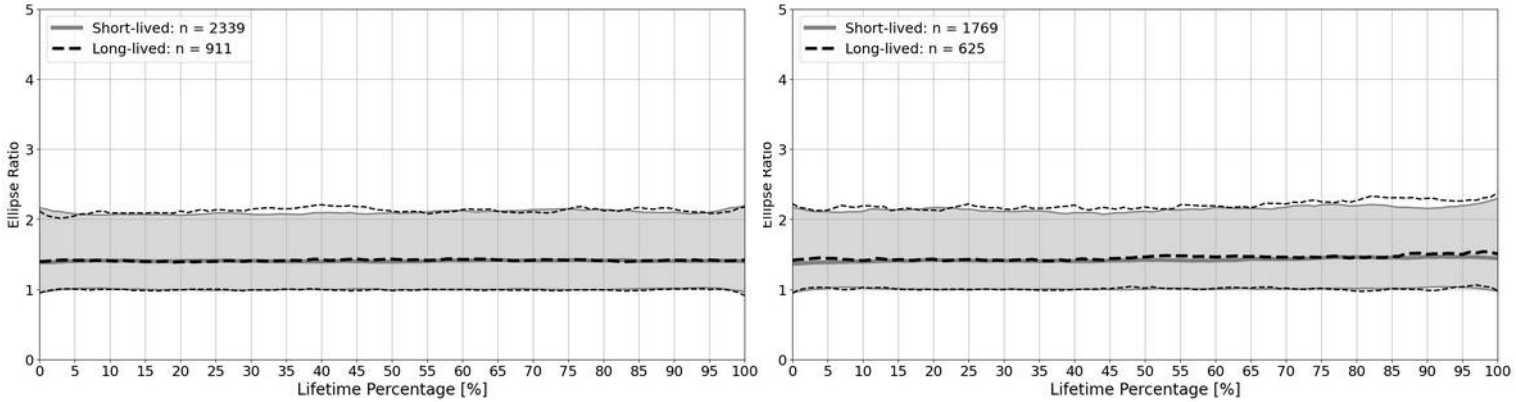
Convective Life Cycle (> 46 dBZ, < -1.5K, no splitting/merging)

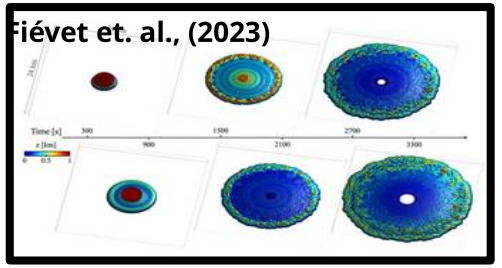
Shorter < 1 hr —
Longer > 1 hr ---

Convective Area



Shape





Mast Data: 1.56 median
Kirsch *et. al.*, (2024)

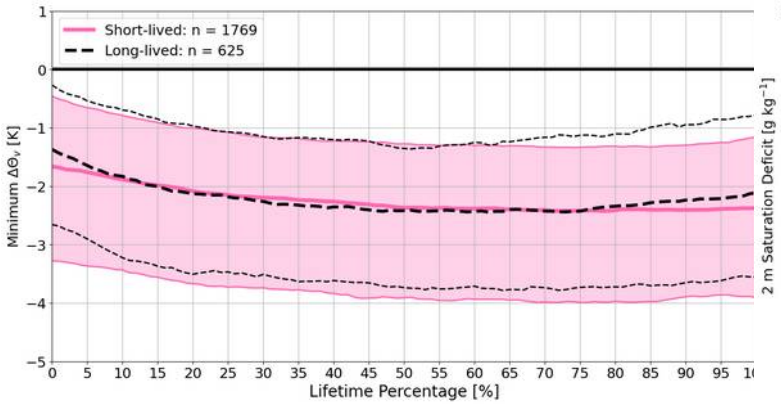
Simulated cells tend to be smaller in size, peaking halfway through their lifetimes - as in observation - symmetric **upside-down parabola archetype** described by Wapler (2021) and Wilhelm *et al.*, (2023).

WRF Convective Life Cycle (> 46 dBZ, < -1.5K, no splitting/merging)

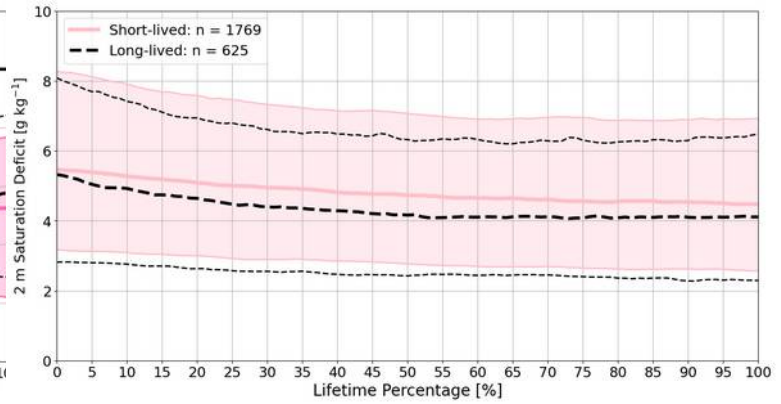
Shorter < 1 hr —
Longer > 1 hr - - -

WRF

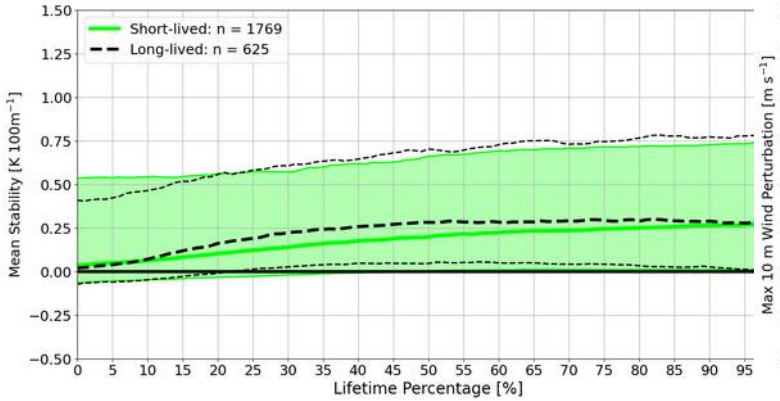
2-m $\Delta\theta_v$



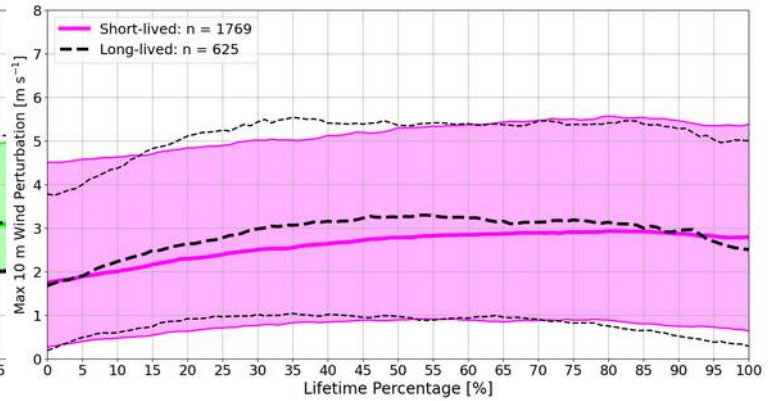
2-m Saturation Deficit



Static Stability



10-m Wind Speed Anomaly



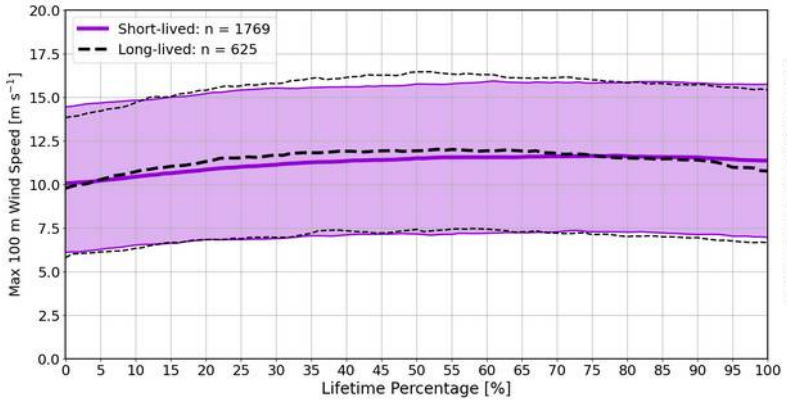
Cold-pool strength and 10 m wind speed perturbation **peak about halfway through** the cell lifetime,
While **saturation deficit decreases** and **stability increases** as cells evolve in time

Convective Life Cycle (> 46 dBZ, < -1.5K, no splitting/merging)

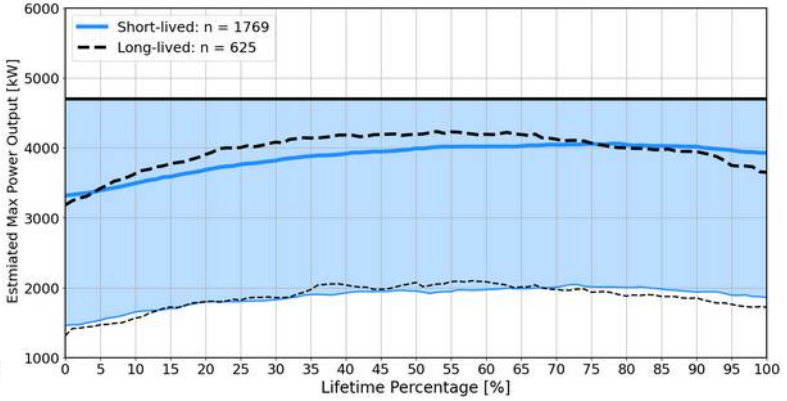
WRF

Shorter < 1 hr —
Longer > 1 hr ---

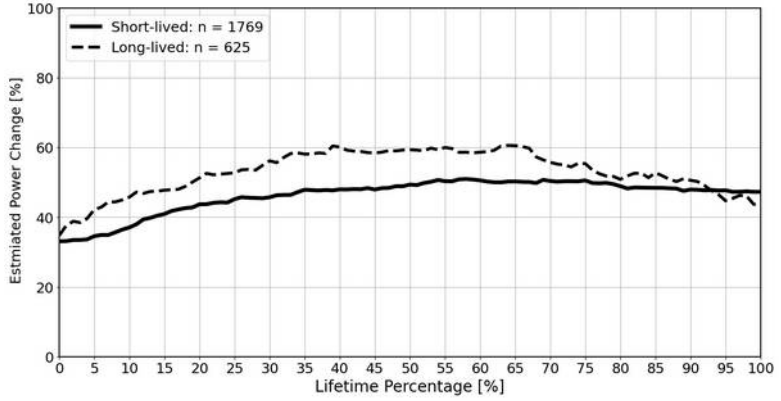
100-m Wind Speed



Estimated Power Output

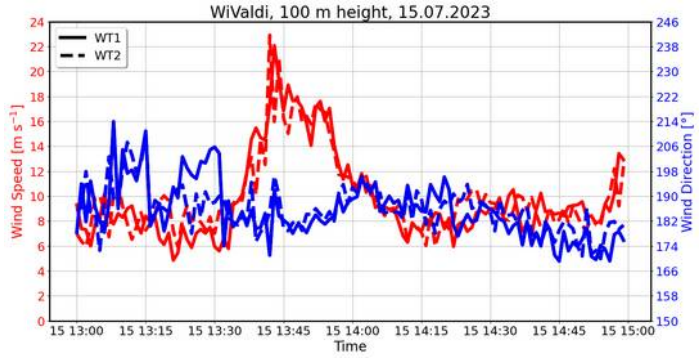


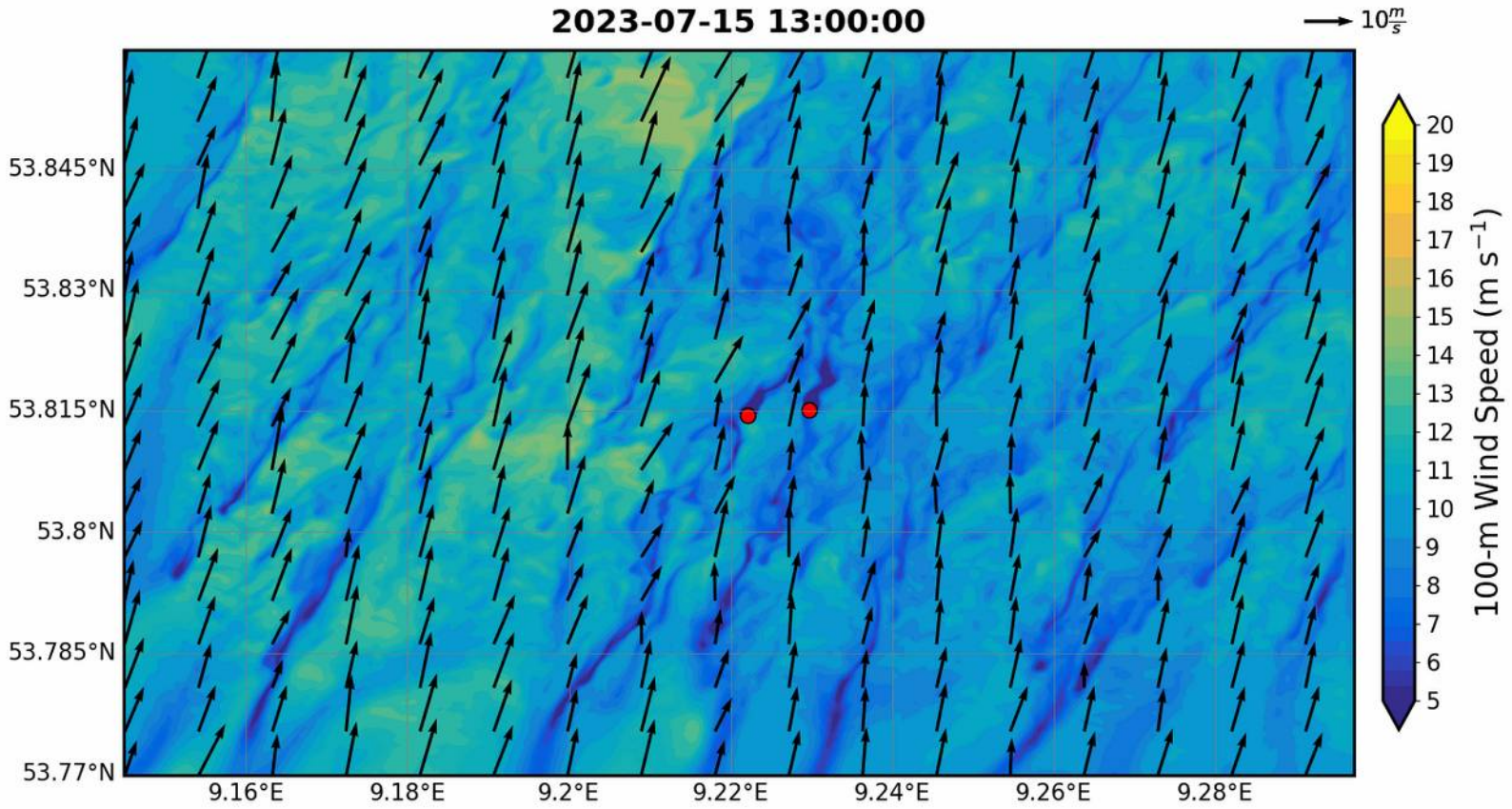
Estimated Power Output **increase** when compared background flow only



The power output due to **convective gust fronts** compared to the **mean flow alone** shows an increase of between 35-60% for longer-lived cells and 33-50% for shorter-lived cells. The largest increase occurs about halfway through the cell life cycle.

Wake Structure - GAD in WRF

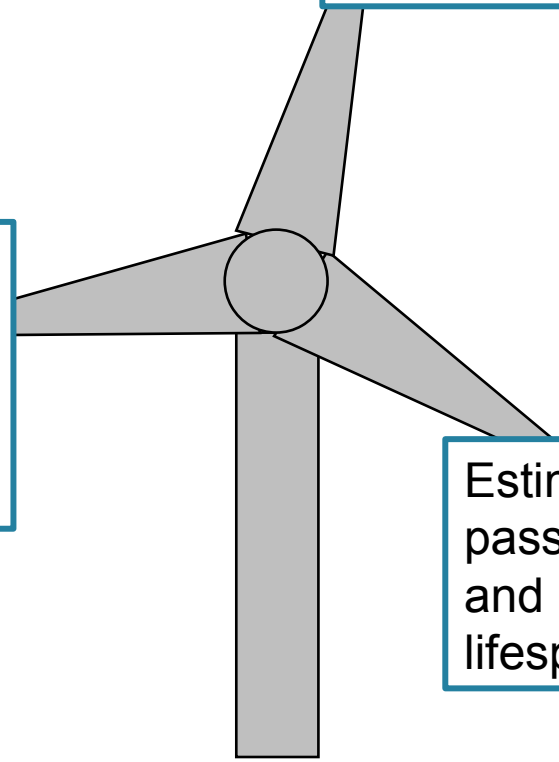




Conclusions

Downward-facing parabolic pattern in both WRF and observations for cell evolution: cell size, maximum rain rate, and mean radar reflectivity. WRF intensifies convective cells too quickly and overestimates rain rates

WRF captures the general distribution, morphology, and evolution of deep convection and the associated cold pools, though it tends to simulate smaller, more intensely raining cells.



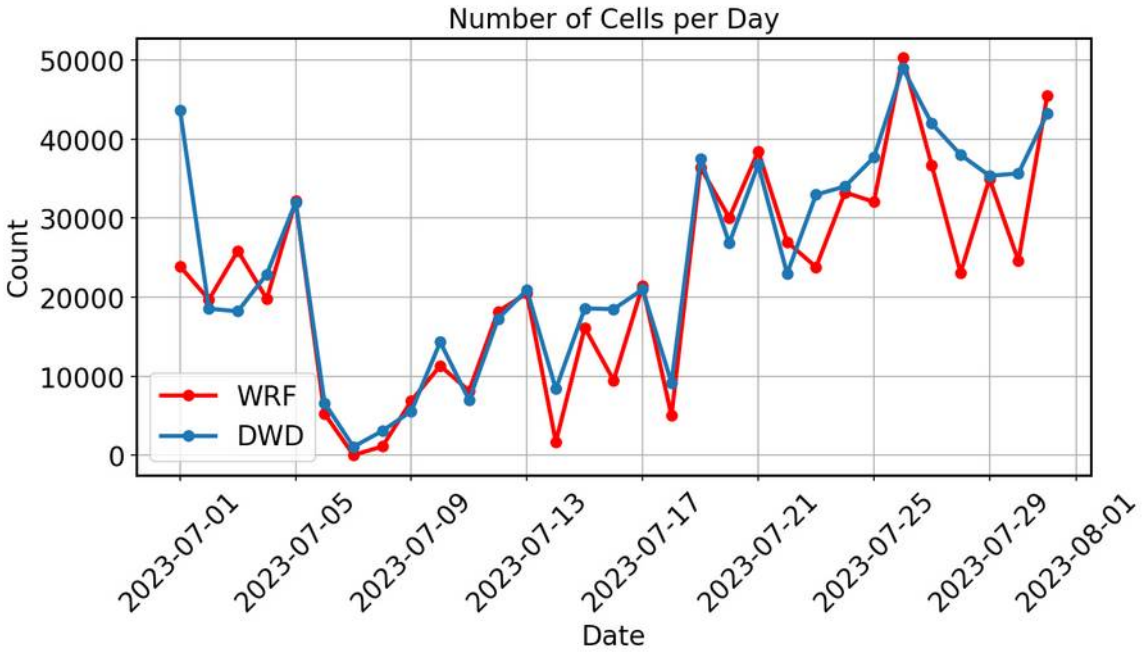
Estimated power output associated with cold-pool passages increasing by 35-60% for long-lived cells and 33-50% for short-lived cells, peaking mid-to-late lifespan.

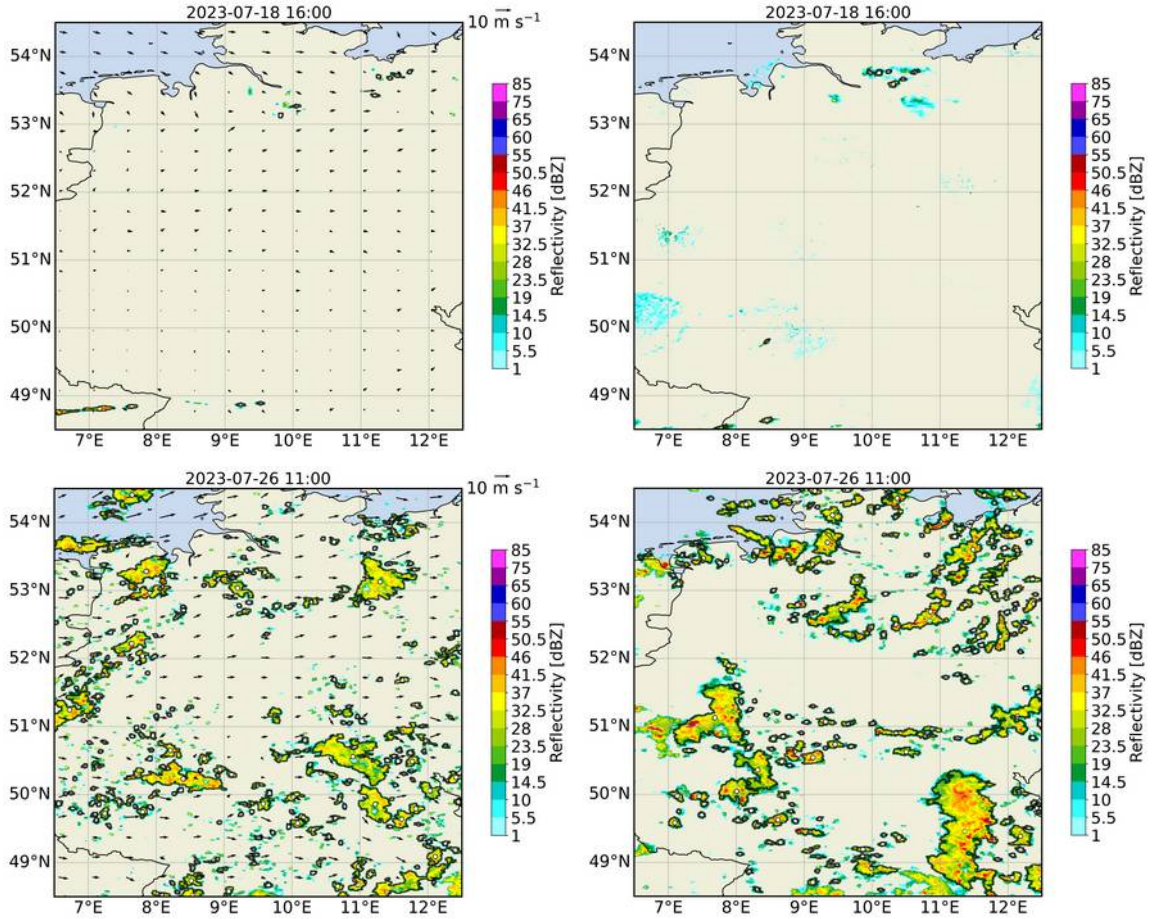
These findings emphasize the importance of understanding and forecasting cold-pool dynamics for optimizing wind energy production.

SLIDO

- How relevant are convective gusts to wind energy?
- Wind Park operators and turbine manufacturers would be interested in improving thunderstorm wind gust nowcasts.
- What is the most important aspect of a thunderstorm impacting a wind park?
- What is the strongest gust (difference from background flow) we detected at the WiValdi wind park during its operation so far?

WRF – DWD: Number of Convective Cells per Day



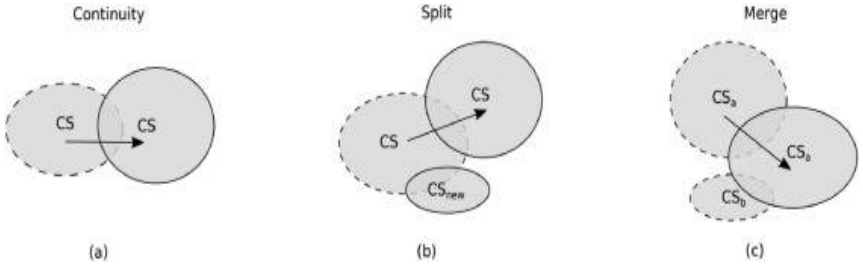


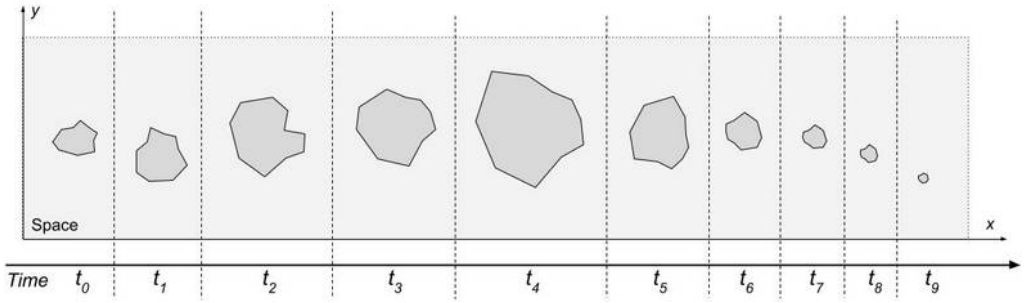
Sena *et. al*., (2024)

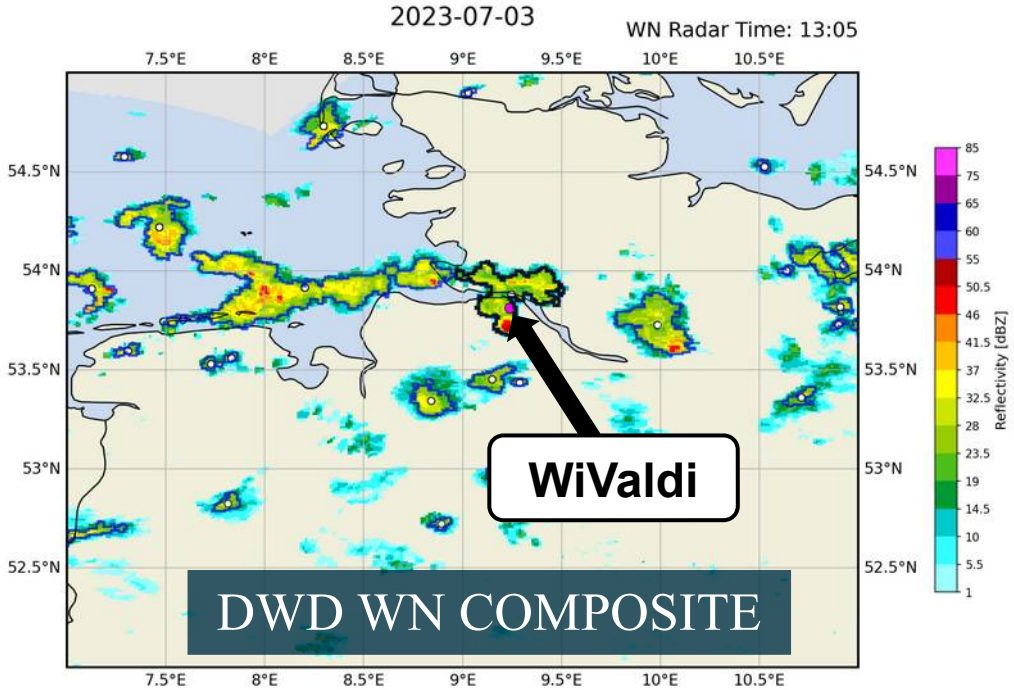
TATHU PYTHON PACKAGE FOR TRACKING AND ANALYZING THE LIFE CYCLE OF CONVECTIVE SYSTEMS

TATHU
Tracking and Analysis of Thunderstorms

- Cell Detection
  - **Minimum size (15 km²)**
  - **Minimum intensity (19 dBZ)**
  - Generates polygon coordinates
  - Snapshots of convection
- Describing
  - Statistics for each polygon
  - Count, max, mean, min, median, etc
- Tracking
  - **Polygon overlap criteria (10%)**
  - Connect snapshots in time
  - Determines whether merging/splitting occurs
- Cold Pool Detection
  - Increasing the cell polygon size by 20% and using the TATHU framework to extract gust front properties





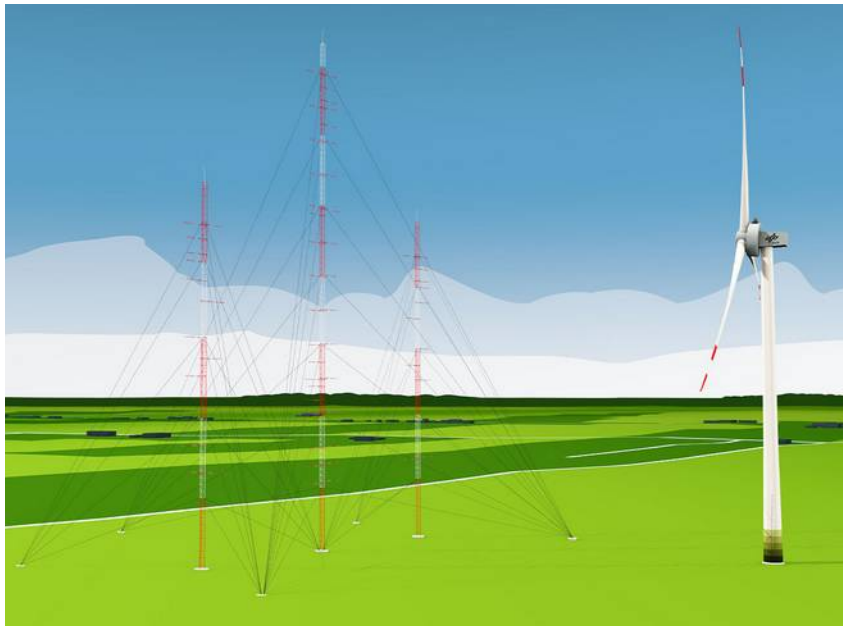


Met instrumentation

ENERCON E-115 EP3:
Hub height: 92 m
Rated power: 4.260 kW
Rotor diameter: 115,7m
Sensors from foundation to blade tip

Acoustics:
- Single microphones
- Microphone array

Met masts:
- IEC+ Met mast
  - Inflow profile, temperature, humidity, EC…
- Met mast array
  - 51 Sonics + 32 Cups



Remote Sensing:
- Ground lidar
- Nacelle lidar
- Spinner lidar
- MWR
- New: Ceilometer, MRR
- Temp: X-band radar