What is Needed to Accelerate Understanding of Deep Convective Cloud Processes?

Adam Varble[1], Zhe Feng[1], Joseph Hardin[1], James Marquis[1], Nitin Bharadwaj[1], Scott Giangrande[2], and Kyle Pressel[1]

[1]Pacific Northwest National Laboratory
[2]Brookhaven National Laboratory

2021 ARM/ASR PI Meeting
June 23, 2021

**Early stages of the 25 January 2019 storm that reached nearly 21 km ASL.
Photo courtesy of Ramón Alberto Acuña (SMN).**

Outline

1. Convection-permitting model biases
2. Critical measurements and their limitations
3. Improved observational constraints on properties and processes
4. Improved model-observation integration for both model and observation advancement

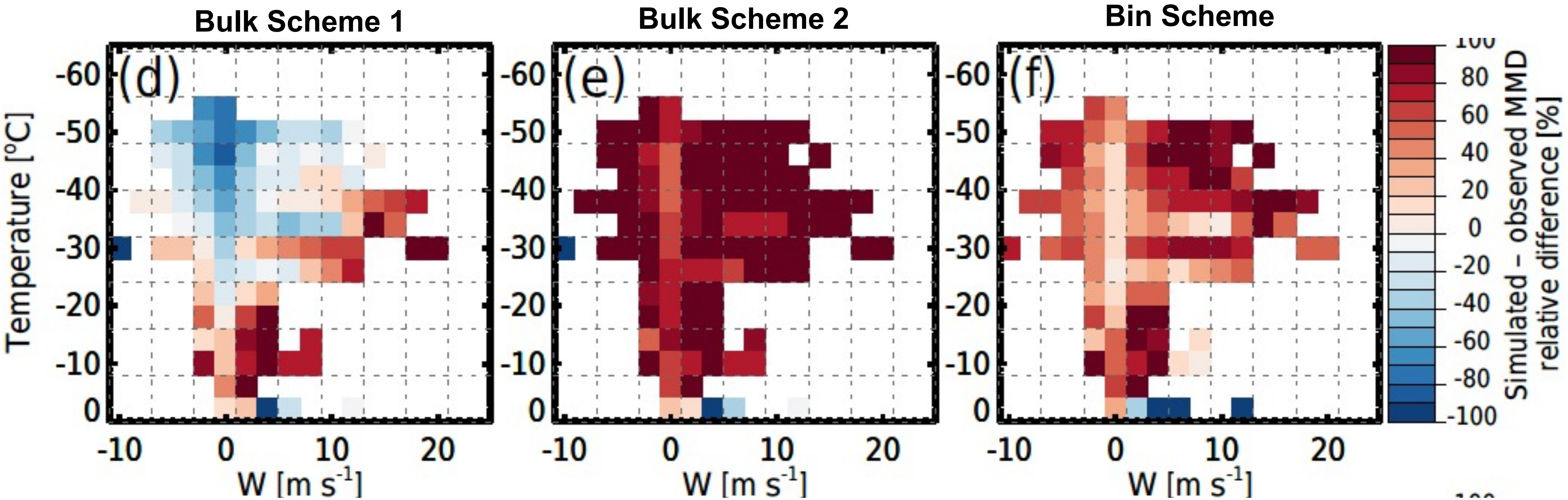
Persistent model microphysical biases

Reflectivity high bias due to excessively large hydrometeors, often associated with riming

Sensitivity to environmental conditions is too limited (e.g., land vs. ocean)

Biases stem from insufficient parameterization of microphysics, but also under-resolved convective dynamics

HIWC-Darwin Mean Hydrometeor Size Differences (Model - Observed in %)

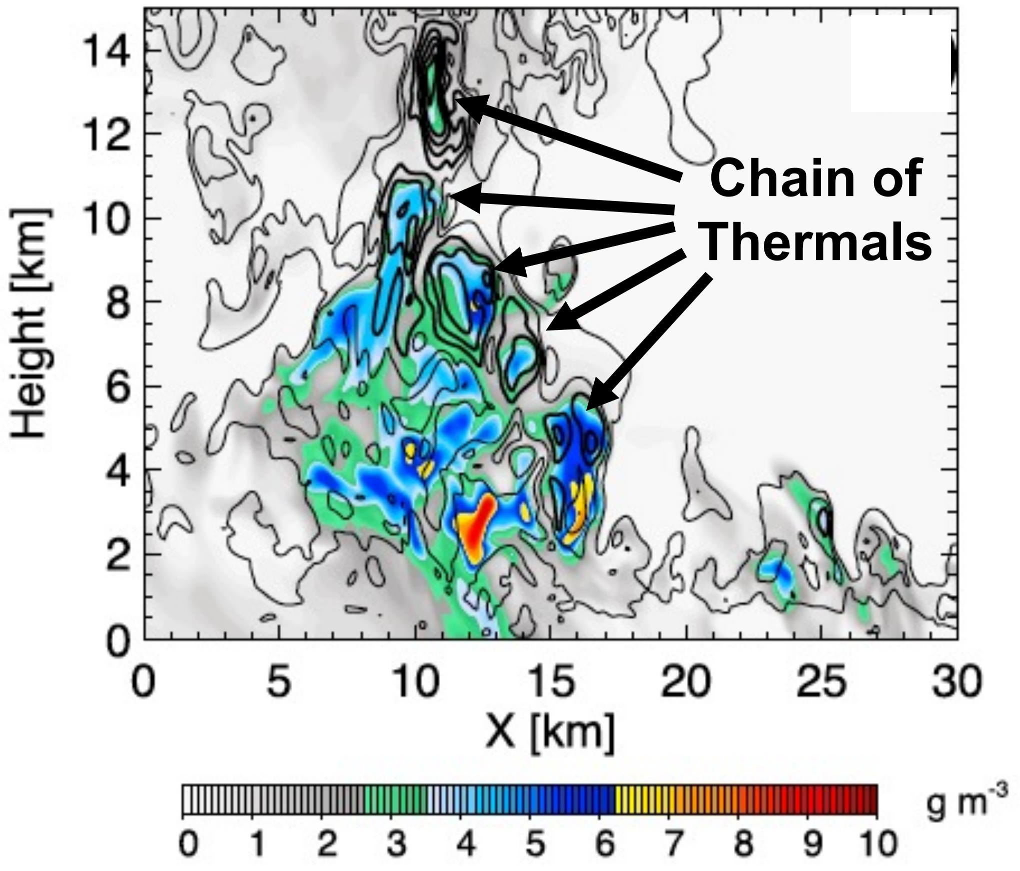


Stanford et al. (2017)

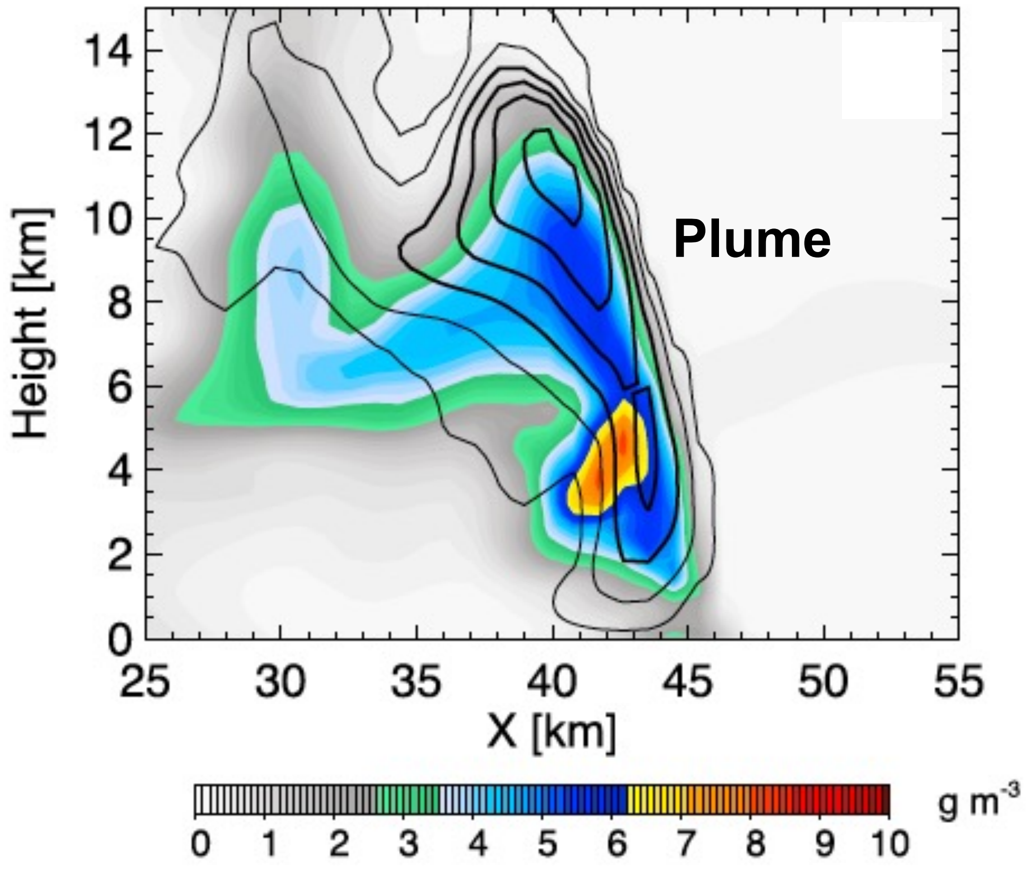
Model convective dynamics biases

- At ~1-km grid spacing, most updrafts are plumes that are too intense for a given width, but at < ~250-m grid spacing, most transform into thermal chains with enhanced entrainment, and decreased widths and vertical transport.
- Separating dynamical and microphysical causes for model biases given their interactions and feedbacks is complex, which results in arbitrary tuning.

TWP-ICE 100-m DHARMA-LES W (black) and Condensate (color)



TWP-ICE 900-m DHARMA-CRM W (black) and Condensate (color)



Varble et al. (2014)

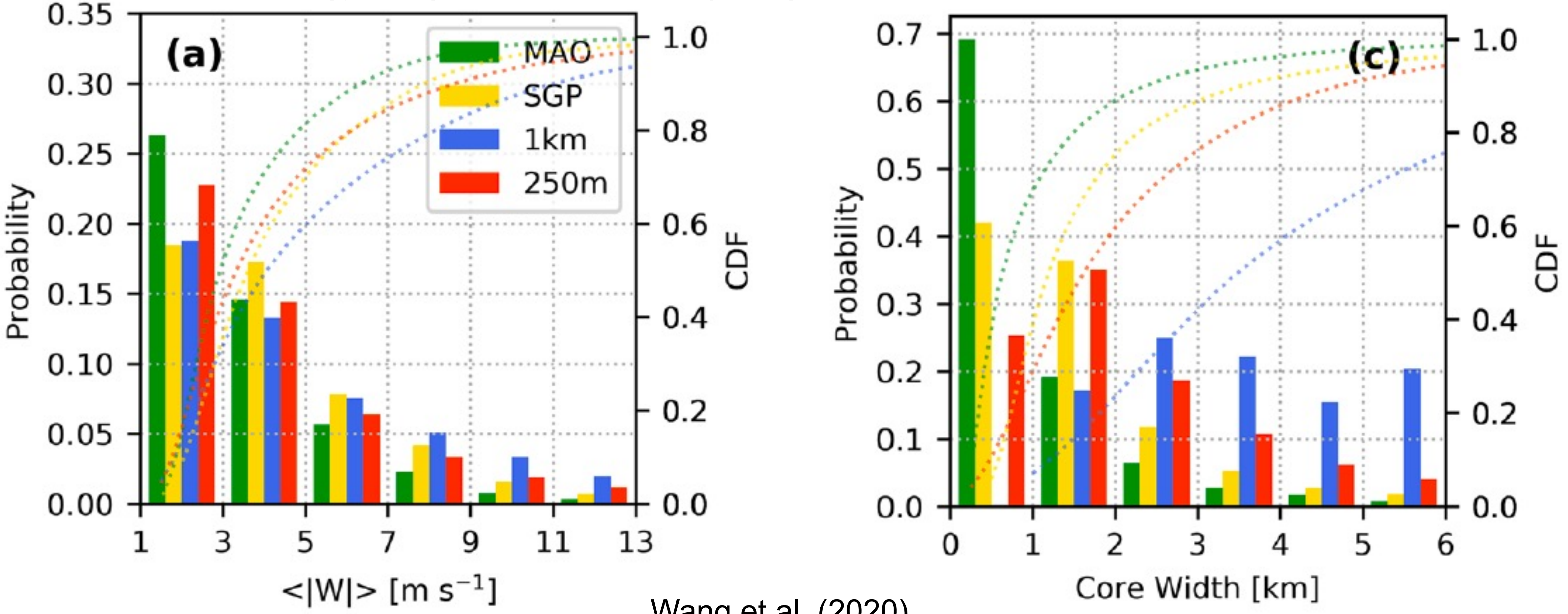
Pacific Northwest
NATIONAL LABORATORY

What resolution is needed?
Do we have the observations to validate LES?

LES start to resolve the updrafts that fuel convective clouds but remain poorly validated.

We still need to quantify the strength and structure of updrafts and are a long way away from observing their evolution in the context of well-observed environmental and cloud conditions.

Amazon (green) and Oklahoma (SGP) Vertical Profiler Updrafts vs. Models

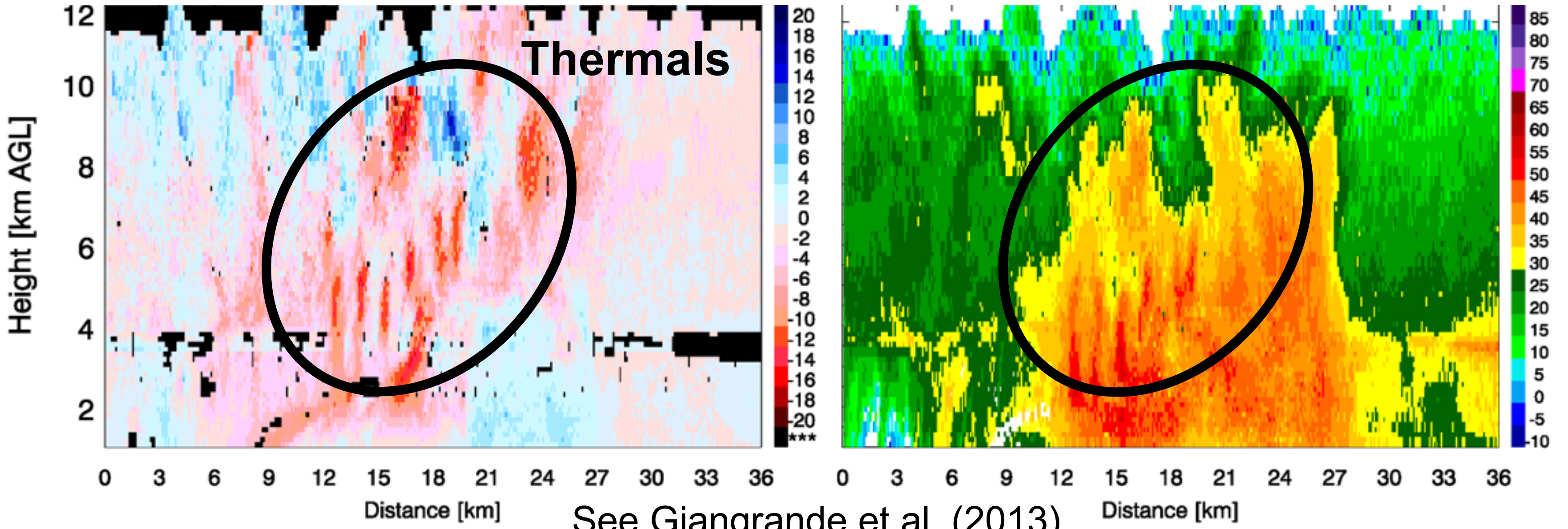


Wang et al. (2020)

Convective dynamics measurement limitations

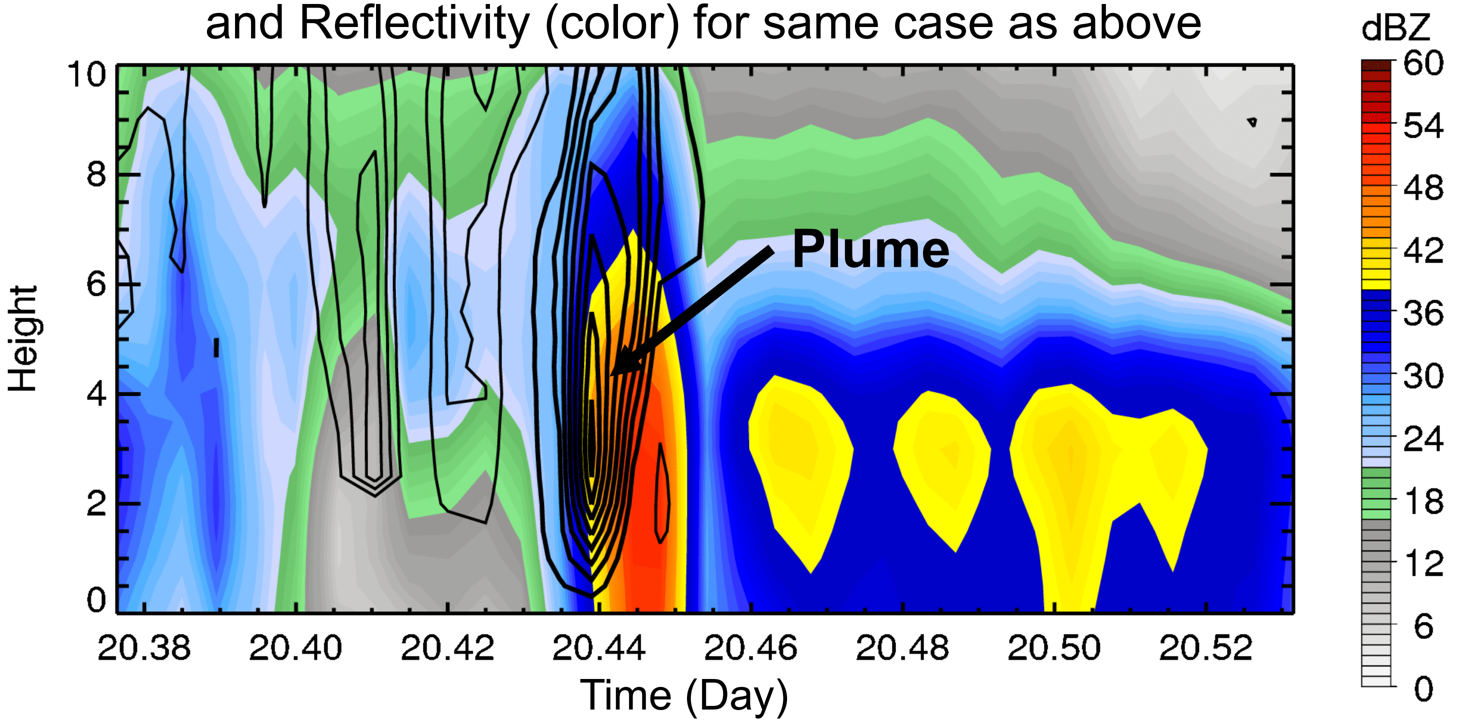
- LES and theory show convective updraft thermal to plume spectrum depends on environment (e.g., Morrison, Peters et al. 2020)
- How do updraft ***size, shape***, and strength influence entrainment, detrainment, and microphysics?
- Vertical profilers have high resolution but provide time-heights rather than tracked 3D evolution. Multi-Doppler provides tracked 3D but typically lacks sufficient space and time resolution (e.g., Oue et al. 2019).
    - Both have **very limited sampling**.

MC3E Time-Height of **Vertical Profiler** Retrieved W (left) and Reflectivity (right)



See Giangrande et al. (2013)

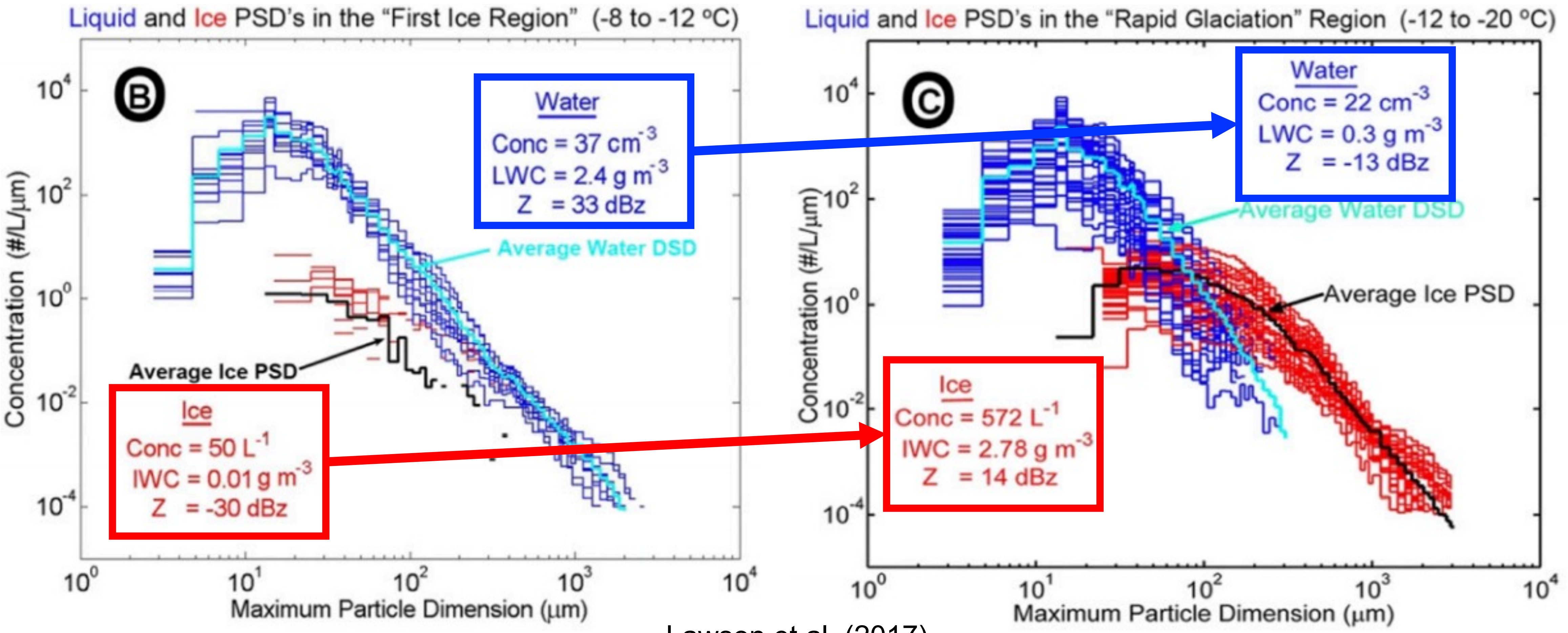
MC3E Time-Height of **Dual-Doppler** Retrieved W (black) and Reflectivity (color) for same case as above



Microphysical measurement limitations

Mixed phase processes (e.g., secondary ice production) are likely an important source for model convective microphysical biases

Need in situ hydrometeor type, number, and mass in updrafts of varying systems, life cycle stages, and environments in greater sample sizes within scanning radar context → ***field campaigns have not been comprehensive enough to provide sufficient constraints***



Lawson et al. (2017)

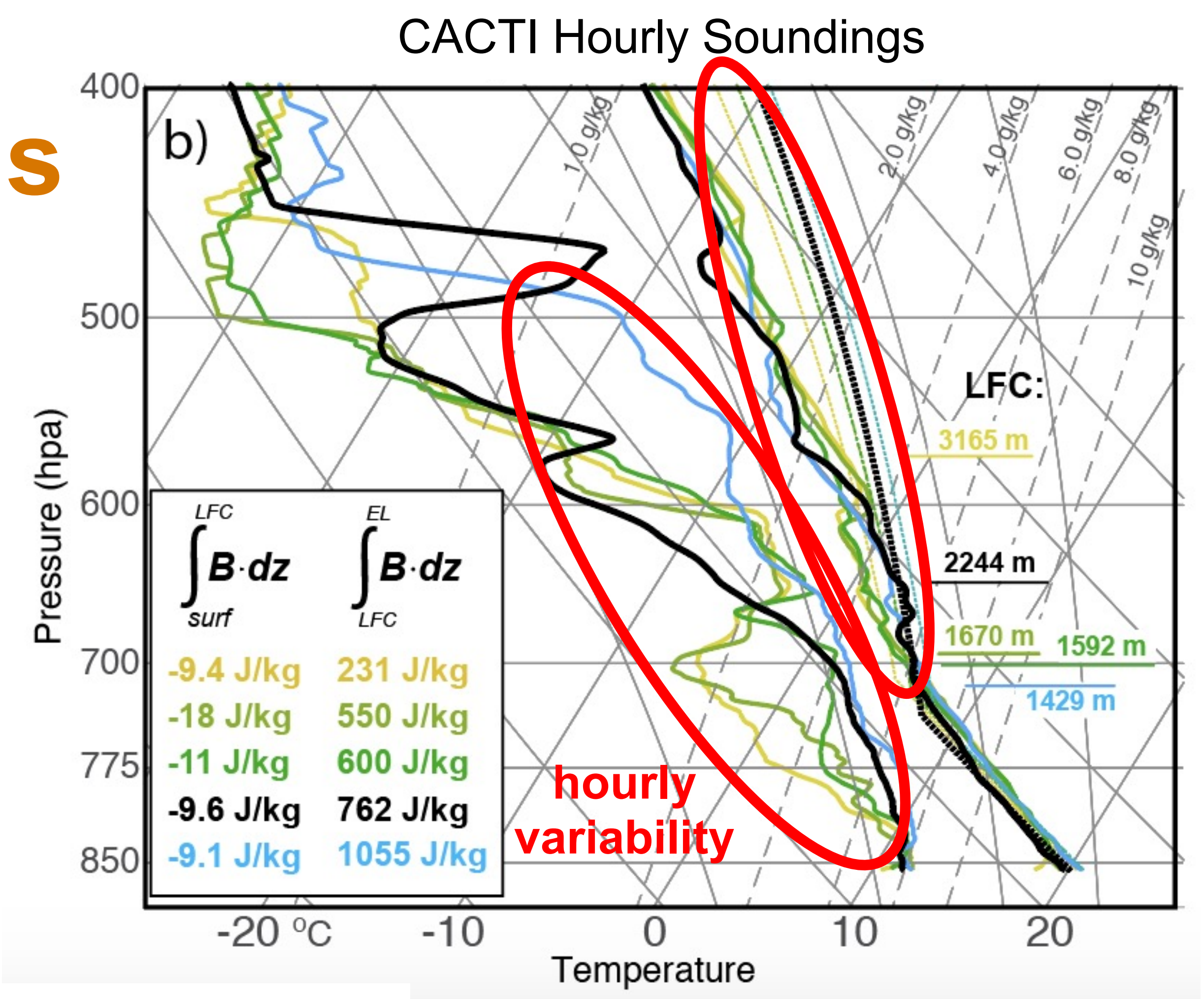
Environmental measurement limitations

Meteorological variability

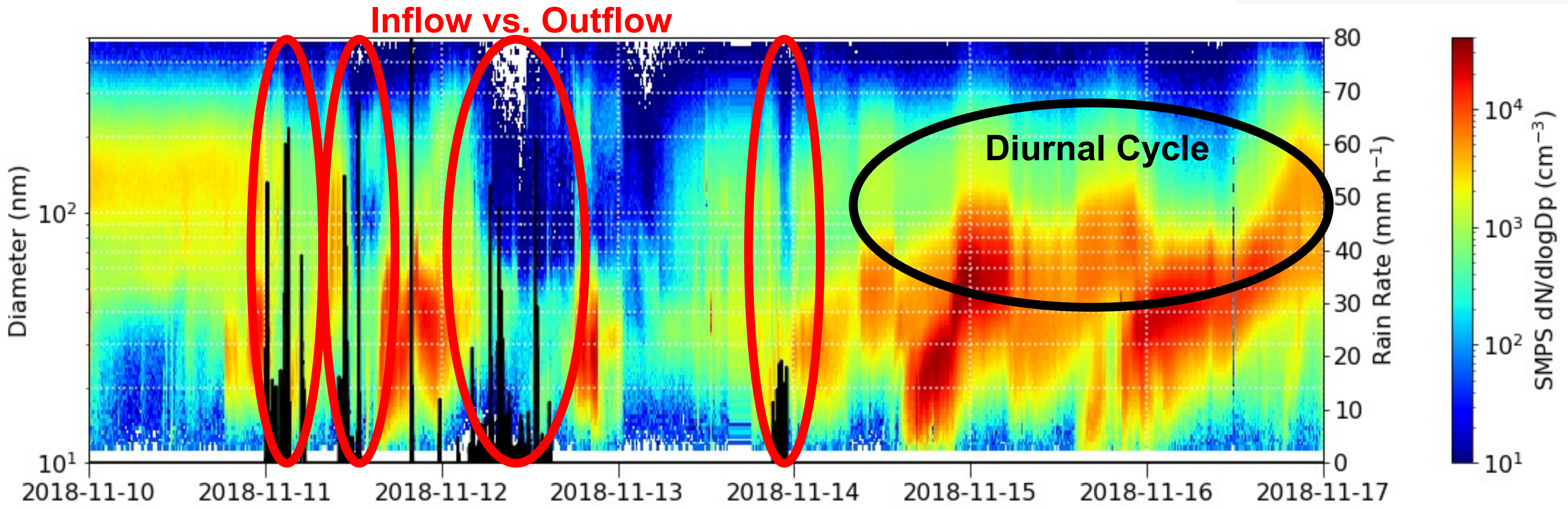
- 30 km and 1-h scales are important (Nelson et al. 2021)
- Need to separate updraft inflow and cold pool outflow
- Difficult to get comprehensive observations off the surface

Aerosol variability

- Limited surface data and even less aloft
- AOD and lidar have limitations in representing CCN
- Correlations with meteorology caused by clouds (inflow vs. outflow) and diurnal cycle



Marquis et al. (2021)



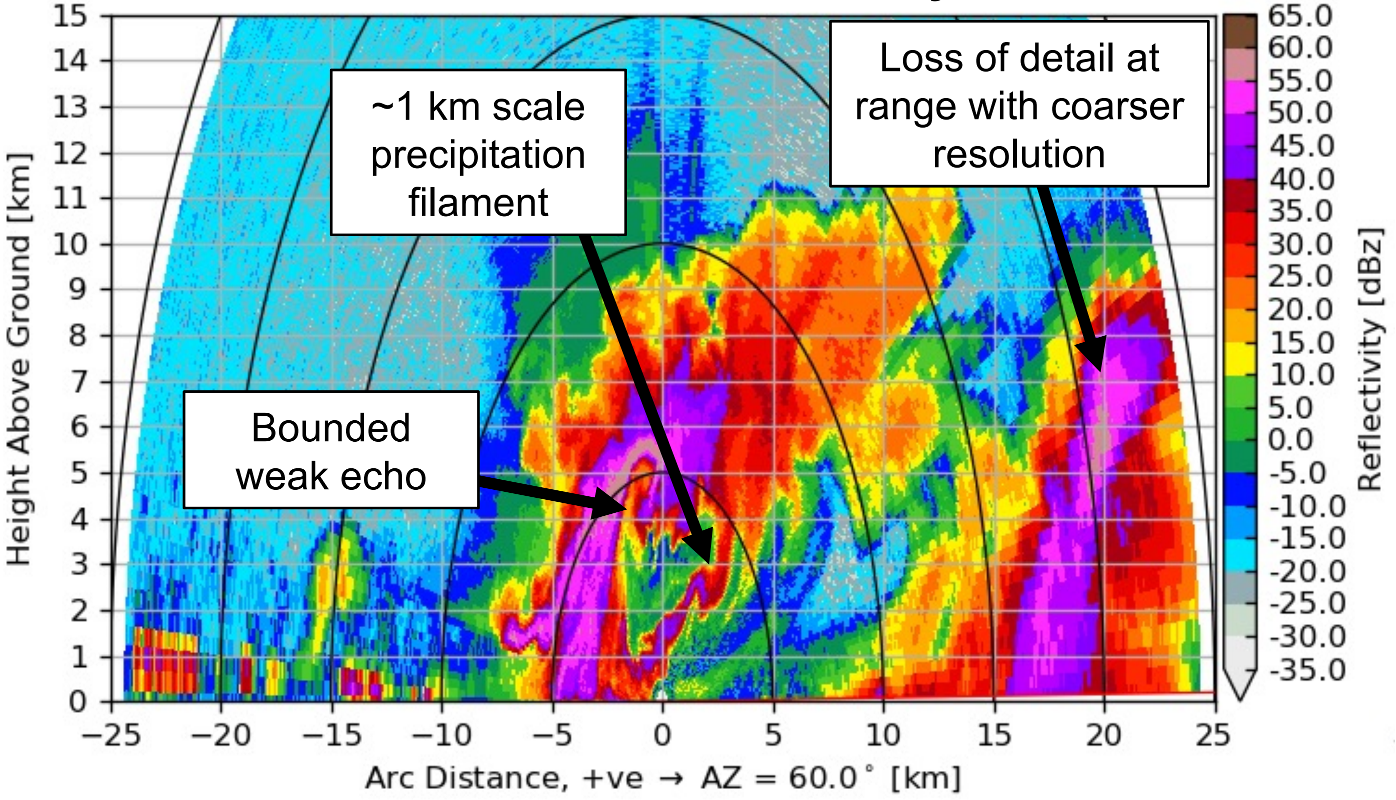
Varble et al. (2021)

Structural shapes and sizes as observational constraints rather than geophysical retrievals

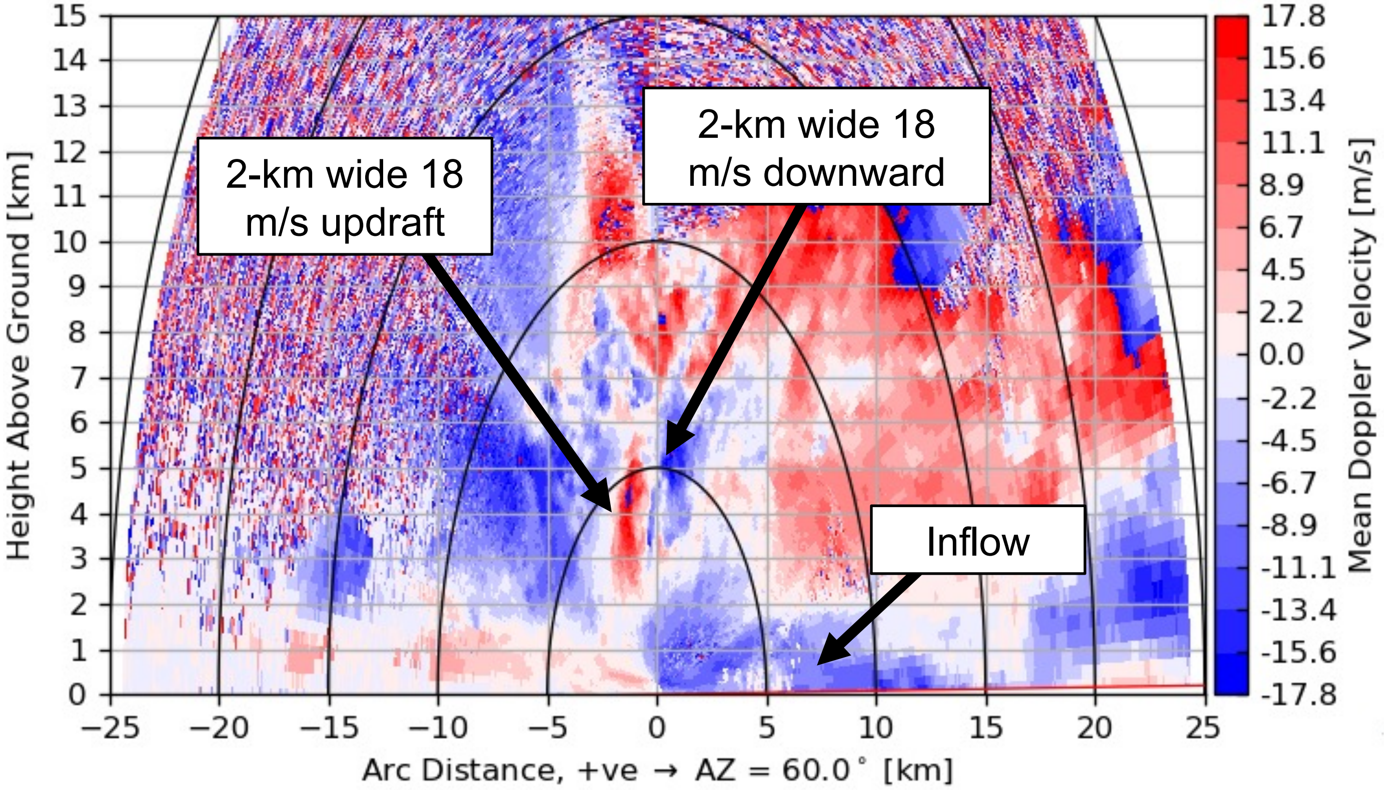
High-resolution measurements regularly show km-scale structures associated with inflow, outflow, updrafts, downdrafts, and precipitation processes.

These can be accumulated in greater numbers than vertical velocity or microphysical retrievals. How can they be used to inform difficult to observe variables and evaluate models?

CACTI X-band Reflectivity

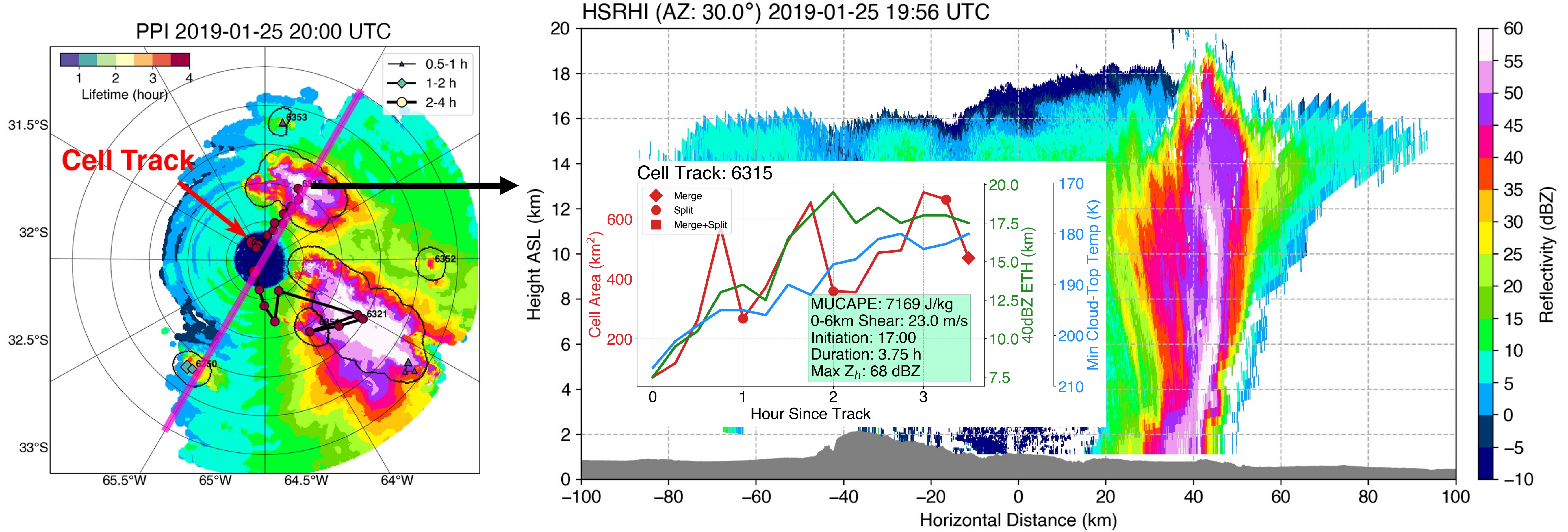


CACTI X-band Doppler Velocity



Courtesy Joseph Hardin and Nitin Bharadwaj (PNNL)

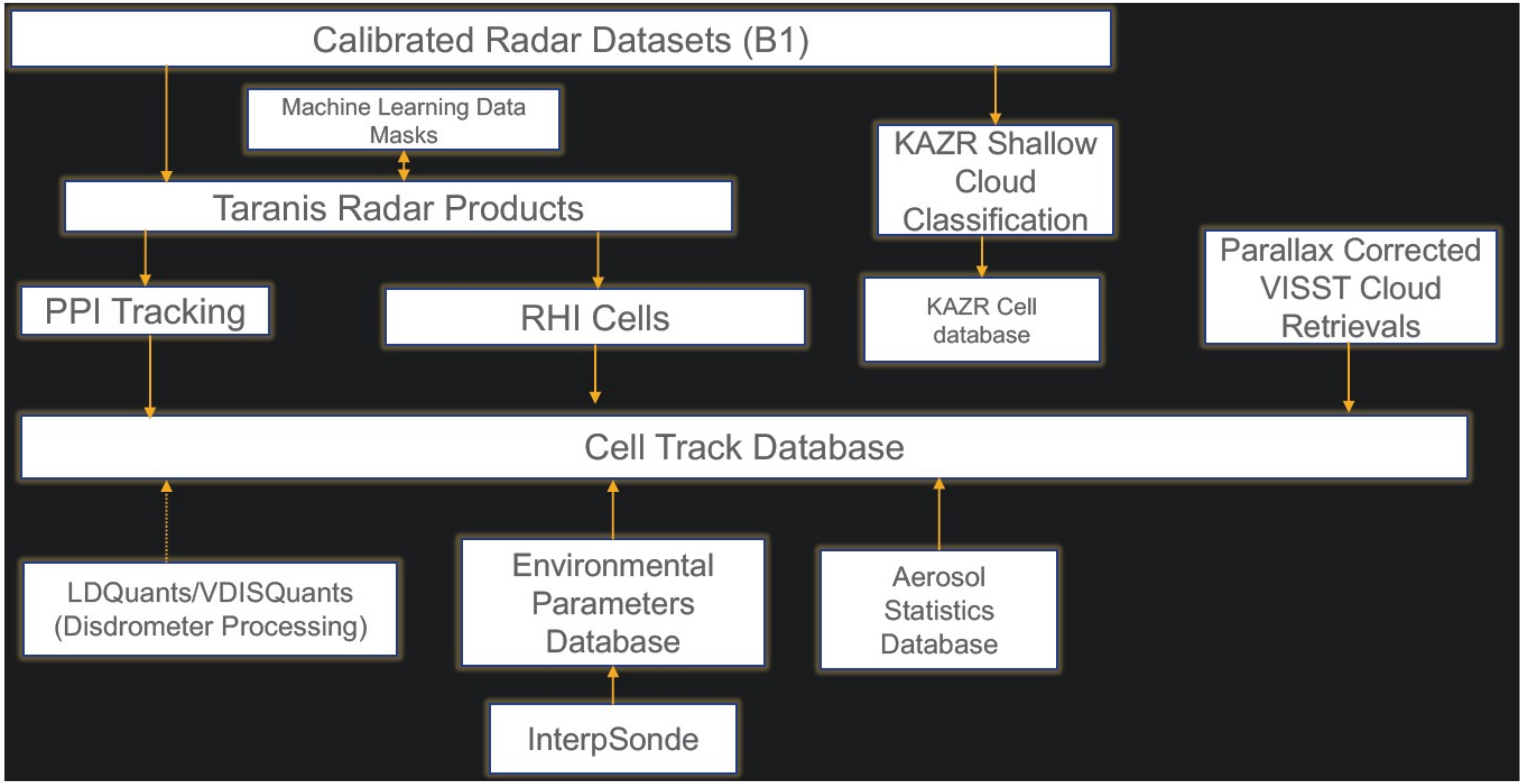
Temporal changes of large, integrated datasets as process constraints



- Processes can be approximated by **changes of measurable structures in space and time (D/Dt)** and **comprehensive integration of complementary, quality controlled datasets**
  - Signals of dynamics and microphysics impacts on one another are lagged in time
  - Satellite/radar feature tracking database with detailed snapshots and in situ measurements targeting resolved environmental and microphysical features covering many events (e.g., CACTI cell track database; Feng et al., in prep.)

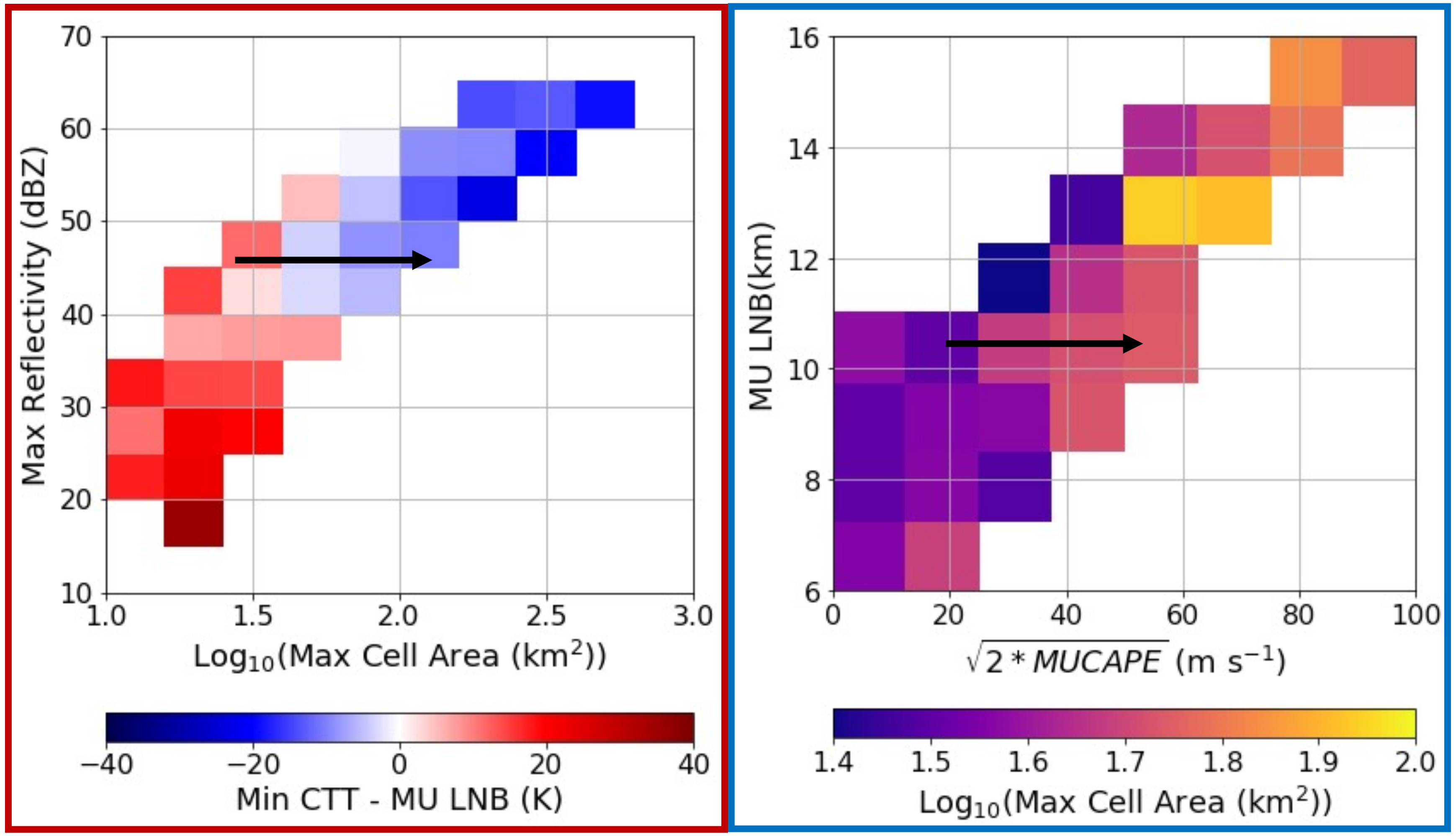
An Example: CACTI Cell Track Database

- Integration of many complementary datasets covering the entire CACTI campaign with nearly 7000 tracked cells and complexes.
- Retrievals are only as good as the quality of the data they are based upon. QC is critical.
- Frameworks should be applicable to simulated observations for integration with models (e.g., we are applying this to a campaign-long WRF simulation).



Example of what can be done with a cell track database: Convective cell life cycle controls

- Left: Lifetime-minimum cloud top temperature (CTT) falls short of undilute parcel potential (MU LNB) for narrow cells but exceeds it for wide cells → related to entrainment?
- Right: Lifetime-maximum cell area increases with updraft speed potential (MUCAPE) but is not sensitive to potential depth (MU LNB) → related to updraft/downdraft buoyancy and size?
- A simulated cell track database is being compared and used to better understand these relationships.



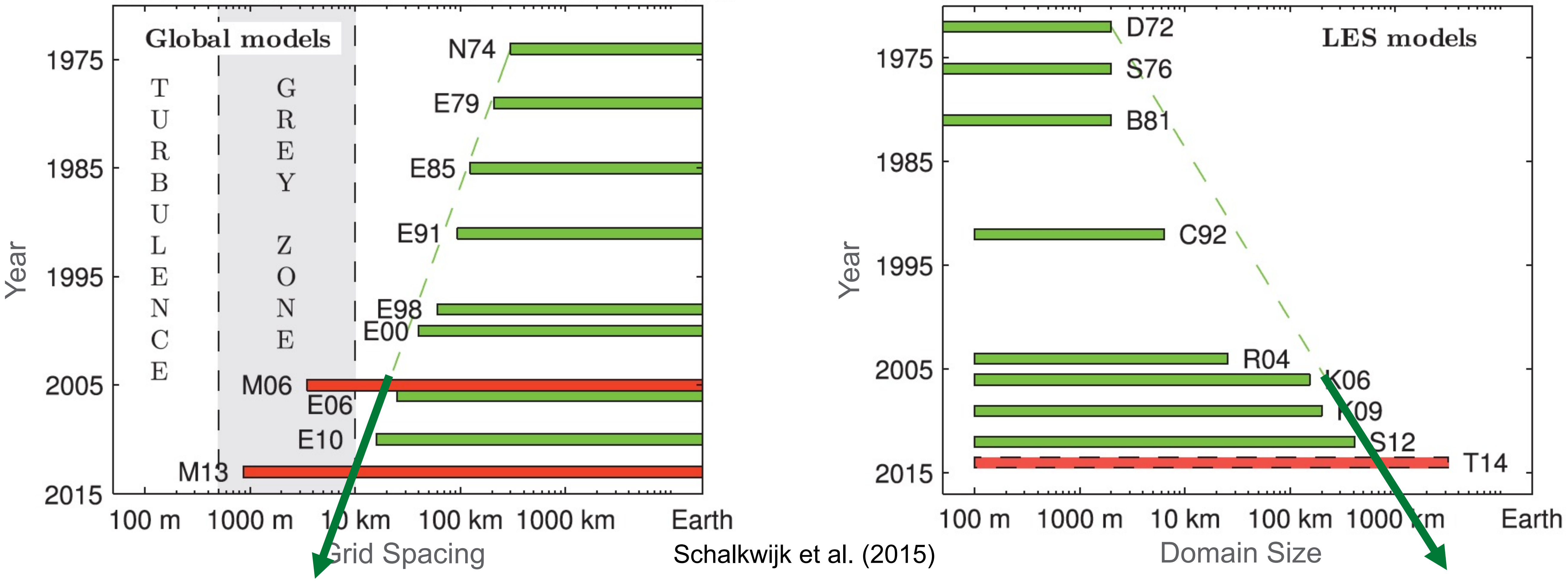
How should quickly improving models be best used with observations to advance understanding?

Km-scale global and regionally refined climate models have arrived

LES is becoming standard for deep convection process studies

Some model fields now outperform retrievals, and we continue to be observations limited

→ ***more model integration and less evaluation***

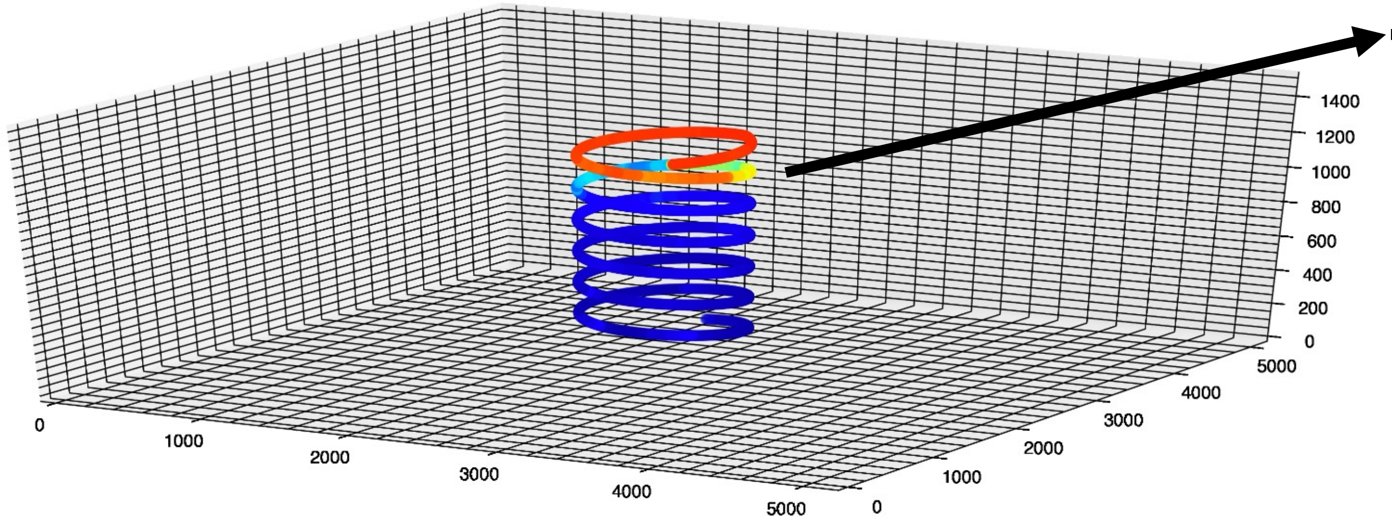


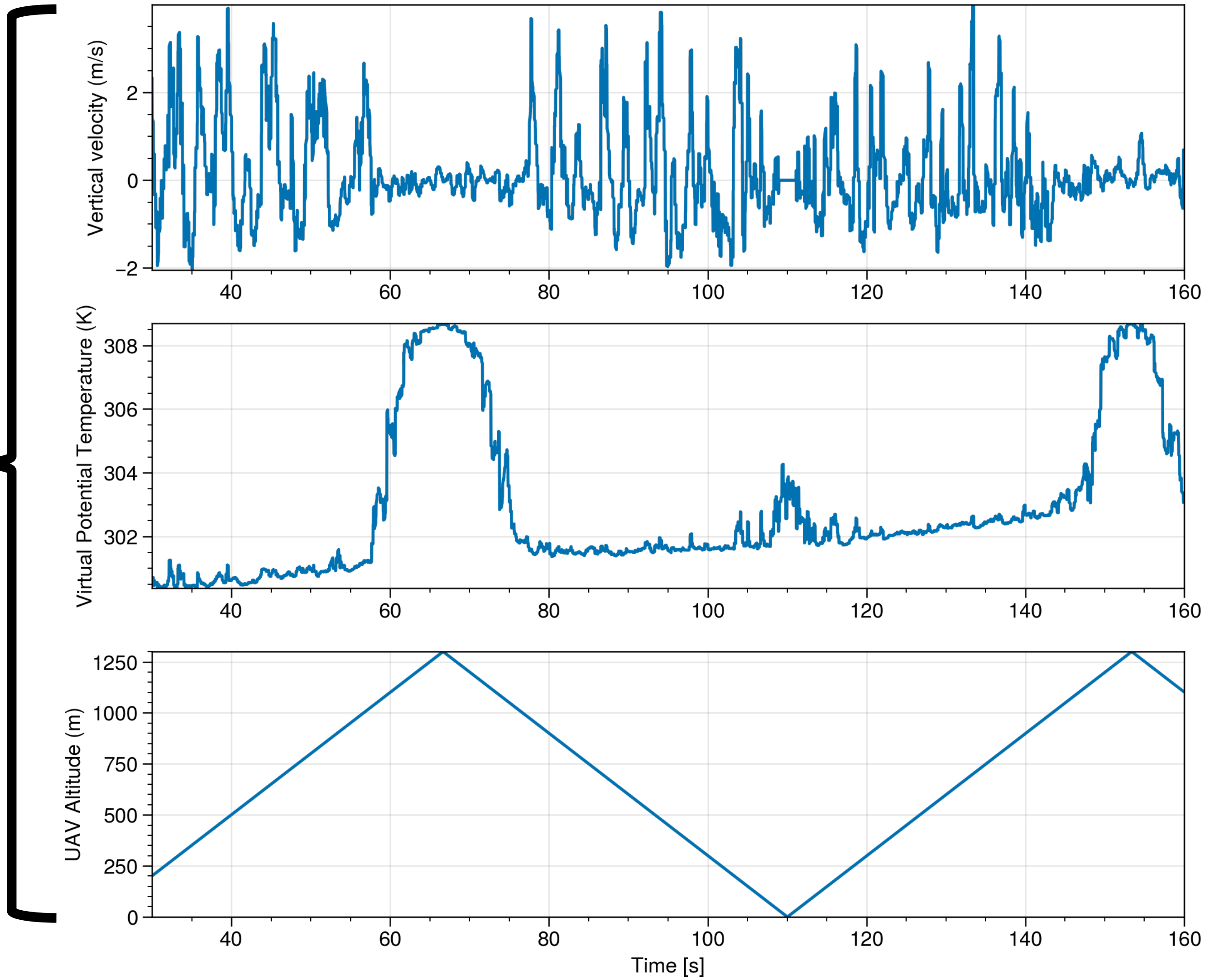
Schalkwijk et al. (2015)

Better model-observation integration?

- LES built-in observation simulators and OSSEs can contextualize observational sampling bias and connect measurements (e.g., through ML) to critical unobservable processes, providing new constraints and guidance for future measurement strategies
- LES case libraries (e.g., LASSO) plus emulators for filling in environmental sensitivities
- Translating domains to follow clouds as they adjust with the environment over hours to days

Simulated Aircraft Spiral Through PBL and Inversion at 1-Hz





PINACLES LES Model, kyle.pressel@pnnl.gov

Summary

- Convection-permitting models continue to have **persistent convective dynamical and microphysical biases.**
- **Observational sampling will continue to have major limitations** in representativeness, resolving relevant scales, and retrieving critical variables, which will hold us back from robustly quantifying important convective cloud sensitivities to environment.
- Can we better utilize **high-resolution observations of cloud and precipitation structures** and expand **Lagrangian (D/Dt)** approaches to inform difficult to retrieve variables and improve understanding?
  - Using comprehensive integration of complementary, quality-controlled observations (satellite, surface network, and field campaign) across large sample sizes for better constraints (e.g., CACTI cell track database).
- Can we move to an **observation-model integration framework** that better supports process understanding and joint model and observation improvement**?**
  - Observational retrievals are not always more accurate than models, and models are rapidly advancing.
  - Libraries of LES runs with built in instrument simulators and emulators to link (e.g., through ML) observations to poorly observed variables and unobservable processes.
  - Pull out all the information content in observations and learn which observational strategies are needed to constrain specific processes.

References

Giangrande, S. E., and Coauthors (2013), A Summary of Convective-Core Vertical Velocity Properties Using ARM UHF Wind Profilers in Oklahoma. *J. Appl. Meteorol. Climatol.,* 52, 10, 2278-2295, doi:10.1175/JAMC-D-12-0185.1.

Lawson, P., and Coauthors (2017), Aircraft Observations of Cumulus Microphysics Ranging from the Tropics to Midlatitudes: Implications for a "New" Secondary Ice Process. *J. Atmos. Sci.,* 74, 9, 2899-2920, doi:10.1175/JAS-D-17-0033.1.

Marquis J. N., and Coauthors (2021), Low-level Mesoscale and Cloud-scale Interactions Promoting Deep Convective Initiation. *Mon. Wea. Rev*., doi:10.1175/MWR-D-20-0391.1, In Press.

Morrison H., and Coauthros (2020), Thermal Chains and Entrainment in Cumulus Updrafts, Part 1: Theoretical Description. *J. Atmos. Sci.,* 77, 3637–3660, doi:10.1175/JAS-D-19-0243.1.

Nelson T. C., and Coauthors (2020), Radiosonde Observations of Environments Supporting Deep Moist Convection Initiation during RELAMPAGO-CACTI. *Mon. Wea. Rev*., 149, 289–309. doi:10.1175/MWR-D-20-0148.1.

North, K. W., and Coauthors (2017), Vertical air motion retrievals in deep convective clouds using the ARM scanning radar network in Oklahoma during MC3E. *Atmos. Meas. Tech*., 10, 2785–2806, doi:10.5194/amt-10-2785-2017.

Oue, M., and Coauthors (2019), Investigation of observational error sources in multi-Doppler-radar three-dimensional variational vertical air motion retrievals. *Atmos. Meas. Tech*., 12, 1999–2018, doi:10.5194/amt-12-1999-2019.

Peters J. M., and Coauthors (2020), Thermal Chains and Entrainment in Cumulus Updrafts, Part 2: Analysis of Idealized Simulations. *J. Atmos. Sci.,* 77, 3661–3681, doi:10.1175/JAS-D-19-0244.1.

Schalkwijk, J., Jonker, H. J. J., Siebesma, A. P., and Van Meijgaard, E. (2015), Weather Forecasting Using GPU-Based Large-Eddy Simulations. *Bull. Amer. Meteorol. Soc.,* 96, 5, 715-723, doi:10.1175/BAMS-D-14-00114.1.

Stanford, M. W., and Coauthors (2017), A ubiquitous ice size bias in simulations of tropical deep convection. *Atmos. Chem. Phys*., 17, 9599-9621, doi:10.5194/acp-17-9599-2017.

Varble, A., and Coauthors (2014), Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations: 1. Deep convective updraft properties. *J. Geophys. Res.,* 119, 13,891-13,918, doi:10.1002/2013JD021371.

Varble, A. C., and Coauthors (2021), Utilizing a Storm-Generating Hotspot to Study Convective Cloud Transitions: The CACTI Experiment. *Bull. Amer. Meteorol. Soc.,* doi:10.1175/BAMS-D-20-0030.1, In Press.

Wang, D., and Coauthors (2020), Updraft and downdraft core size and intensity as revealed by radar wind profilers: MCS observations and idealized model comparisons. *J. Geophys. Res*., 125, e2019JD031774. doi:10.1029/2019JD031774.