Sensitivity of Warm Rain Rates to Lower PBL Structure as Observed by Synthetic Aperture Radar over the Subtropical Ocean

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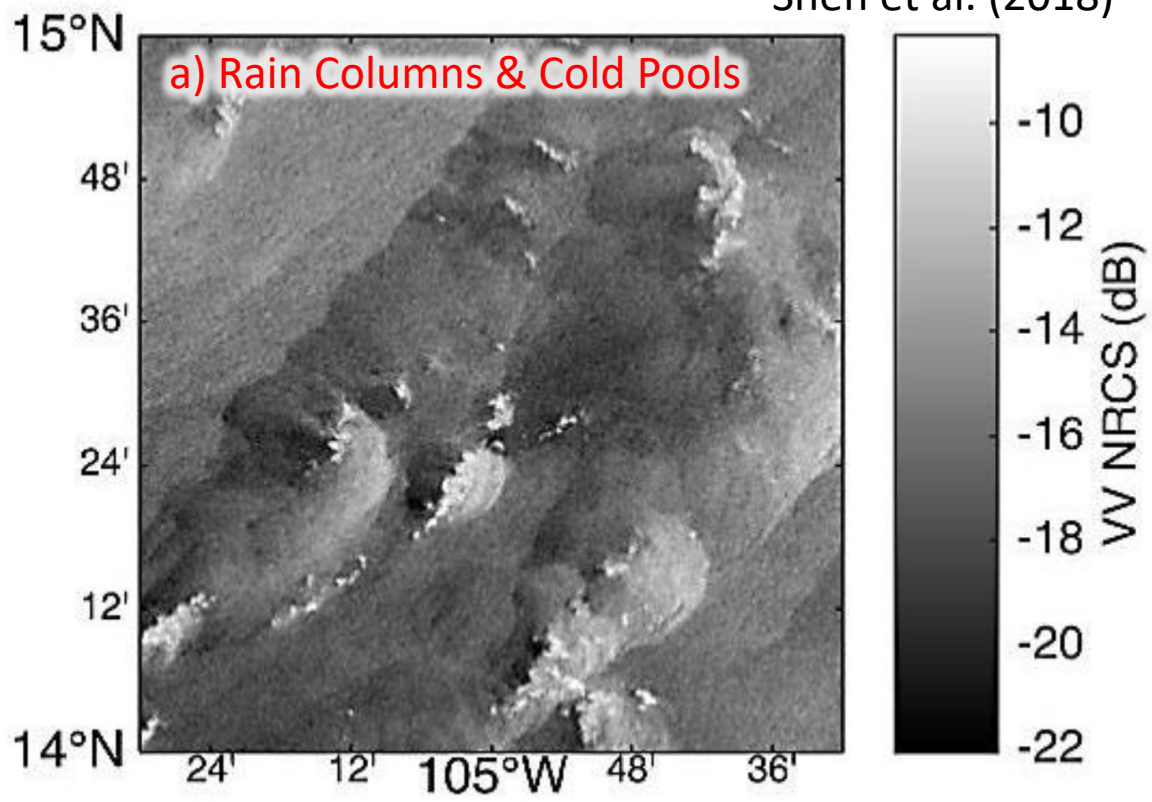
1. University of Washington, Dept of Atmospheric and Climate Science
2. University of Hawaii, Dept of Ocean and Resources Engineering
3. University of Washington Applied Physics Laboratory
4. University of New Hampshire
5. Danish Meteorological Institute

Image: Shen et al. 2018

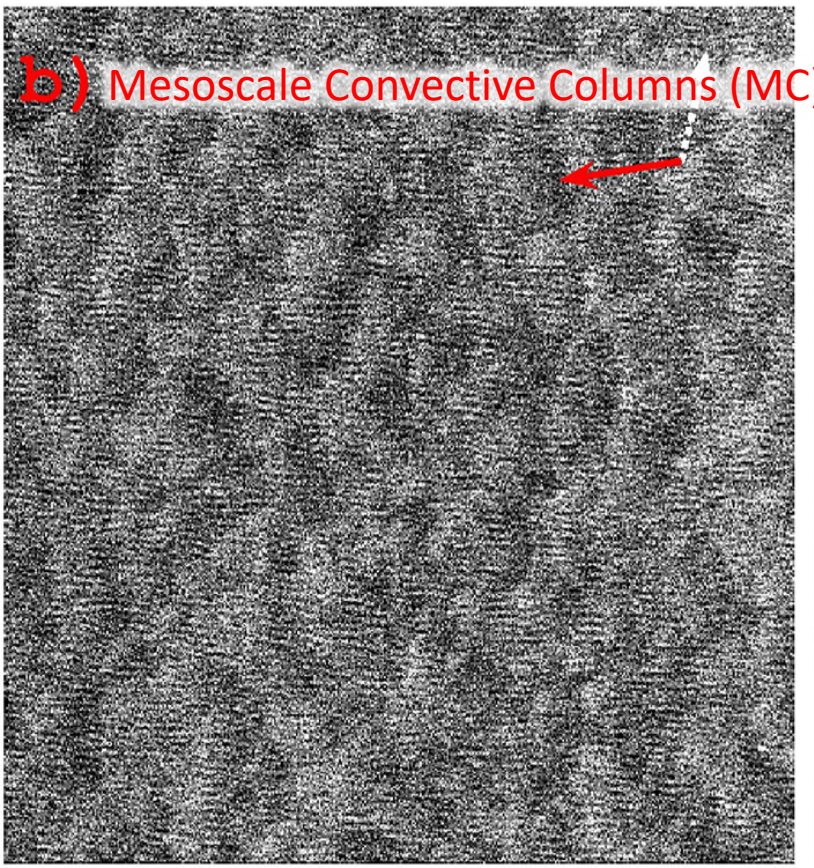
Synthetic Aperture Radar (SAR)

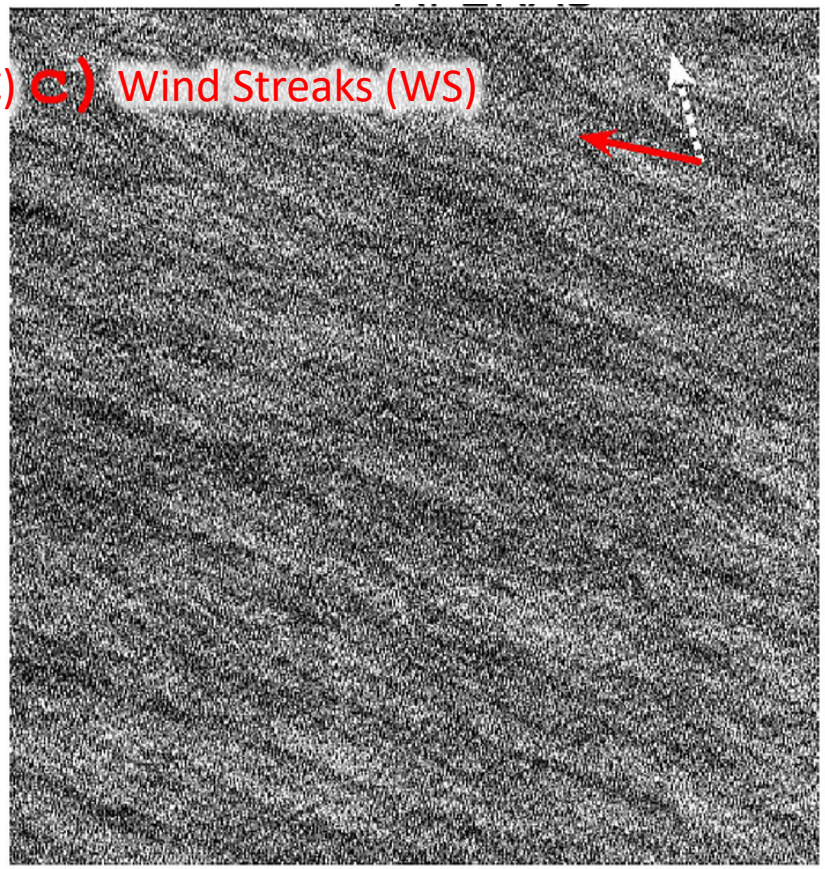
- High resolution C-band radar can identify small-scale structures in the wind field over the ocean.
- Viewing coherent patches of capillary waves at ~ 5 meter resolution.
- Structures observed include: rain columns, cold pools, and lower PBL convective/shear-driven organizations.
- Detection independent of cloud cover.

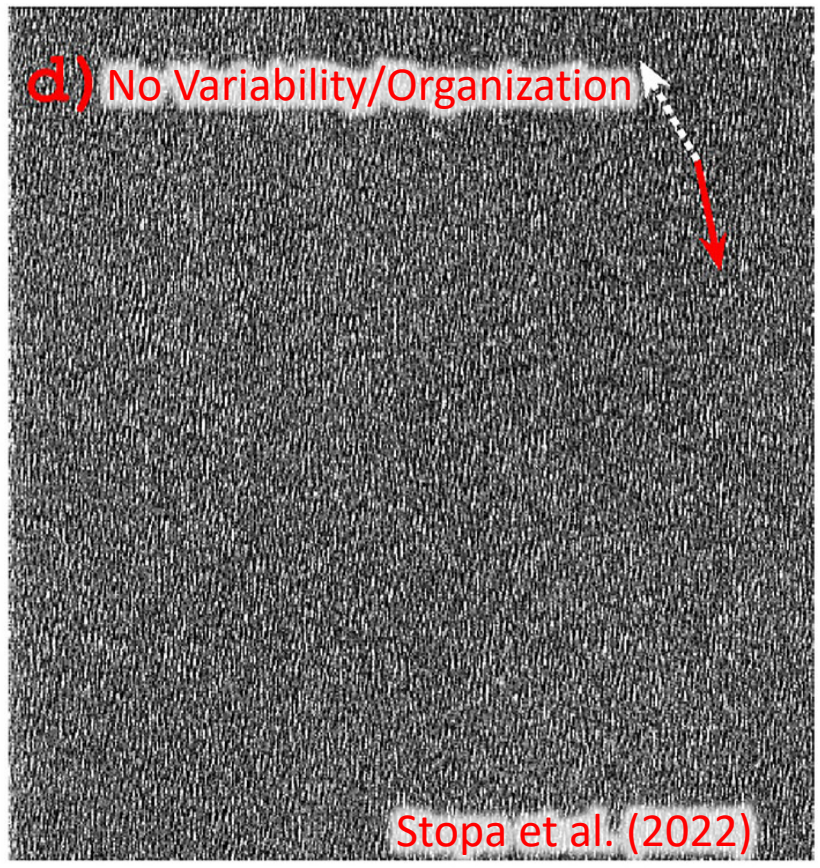
Shen et al. (2018)



|---------- ~20 km ----------|

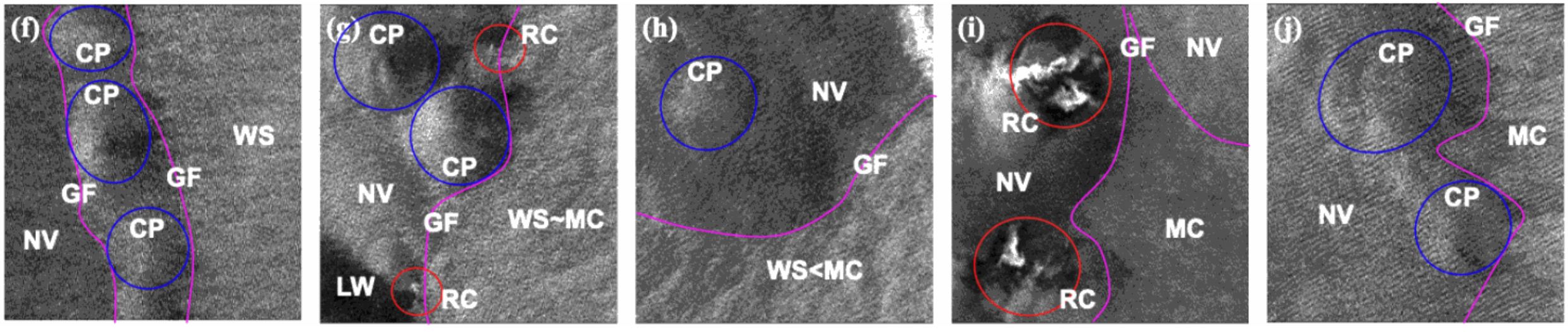






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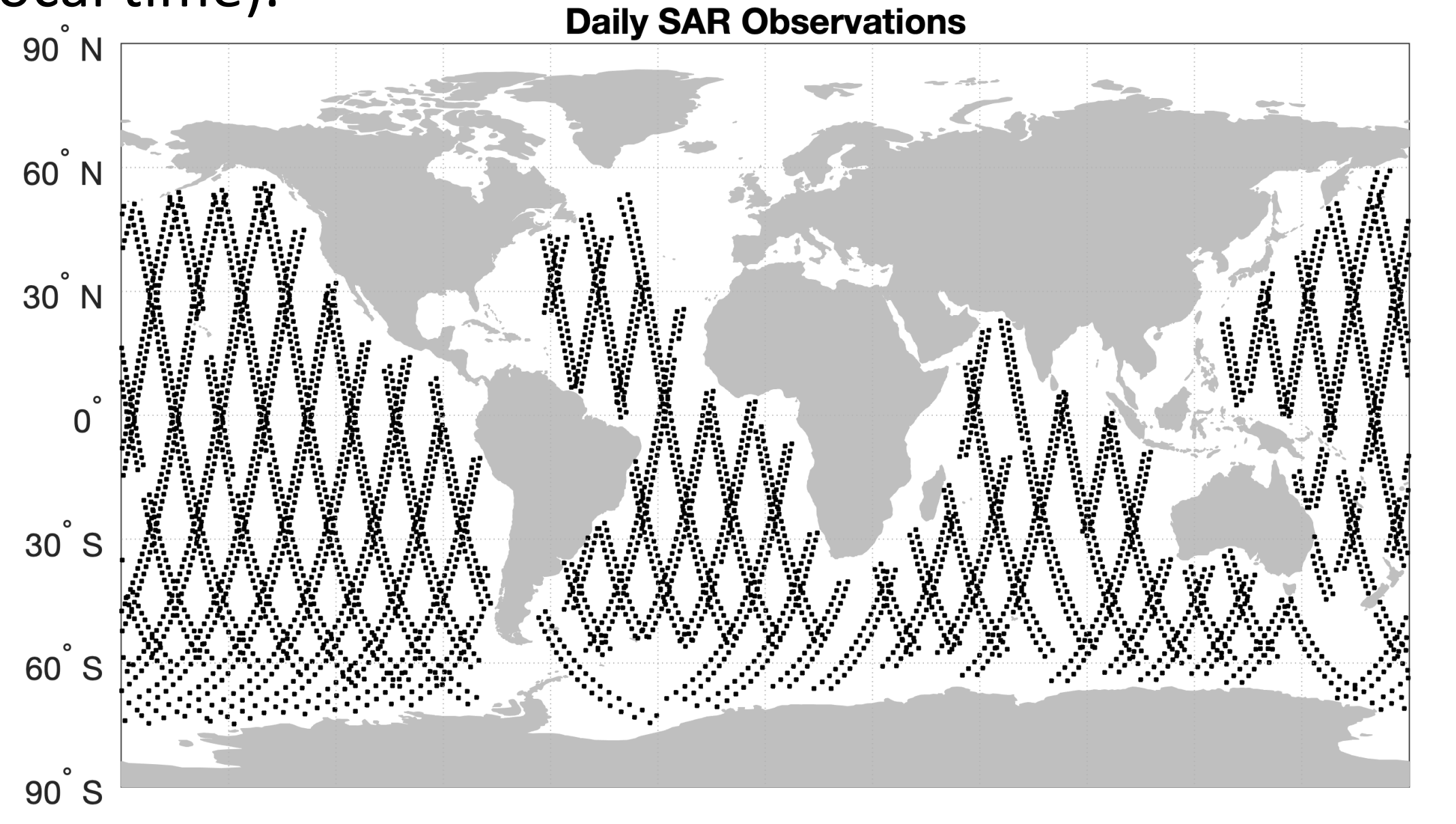
- A subset of observation boxes initially classified by humans.
- These classifications trained a machine learning algorithm, which was applied to all available images for the year 2018.
- Original data for this project come from Sentinel 1 satellite.
- Observations frequently contain multiple classifications.
  - The presence of cold pools, boundaries, and rain columns is flagged.
  - Boxes are classified as MC or WS depending on whether classification coverage/confidence exceed a 95% threshold.



From Wang et al. 2025

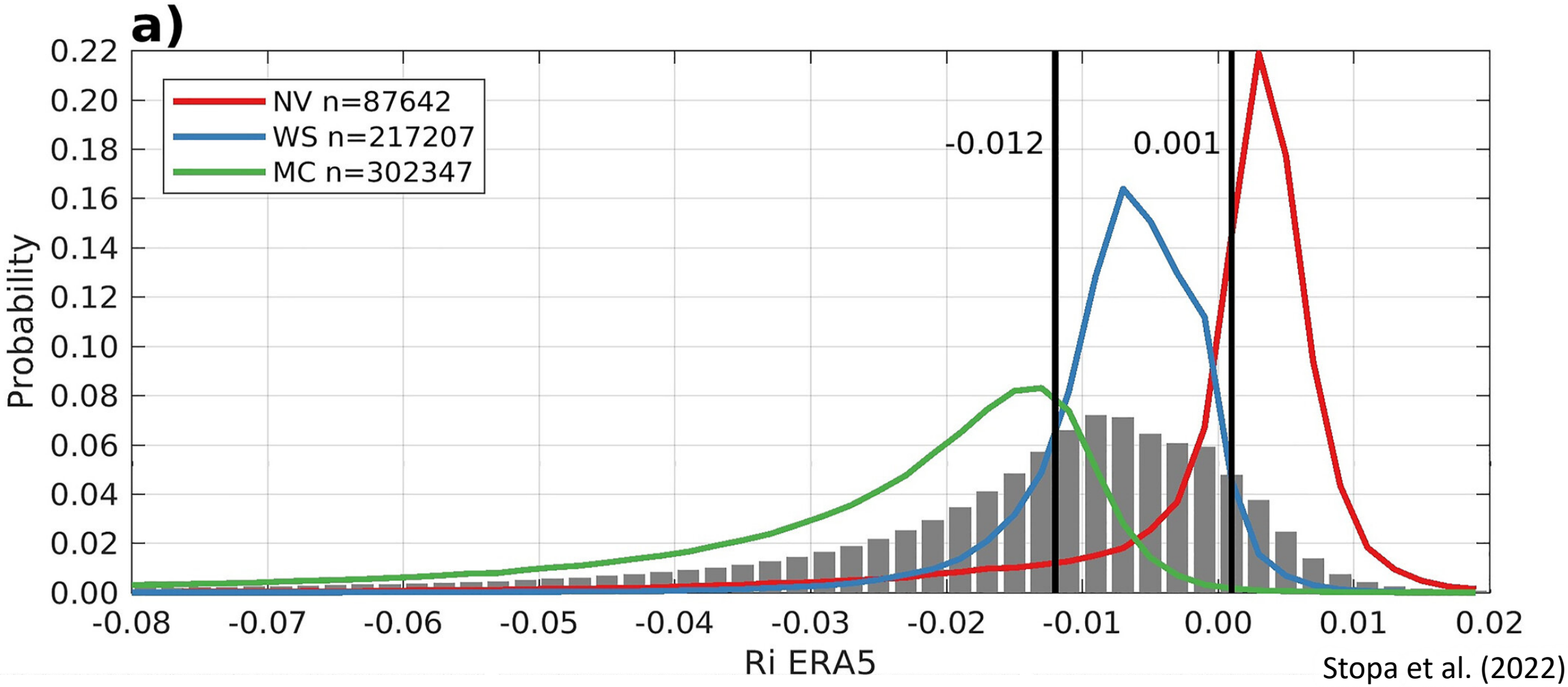
SAR Observations

- Observations taken in two rows along the satellite track.
- Spaced 100km apart along the track over the ocean.
- Sun-synchronous observations at sunrise/sunset (~6/18 local time).



Synthetic Aperture Radar Classifications

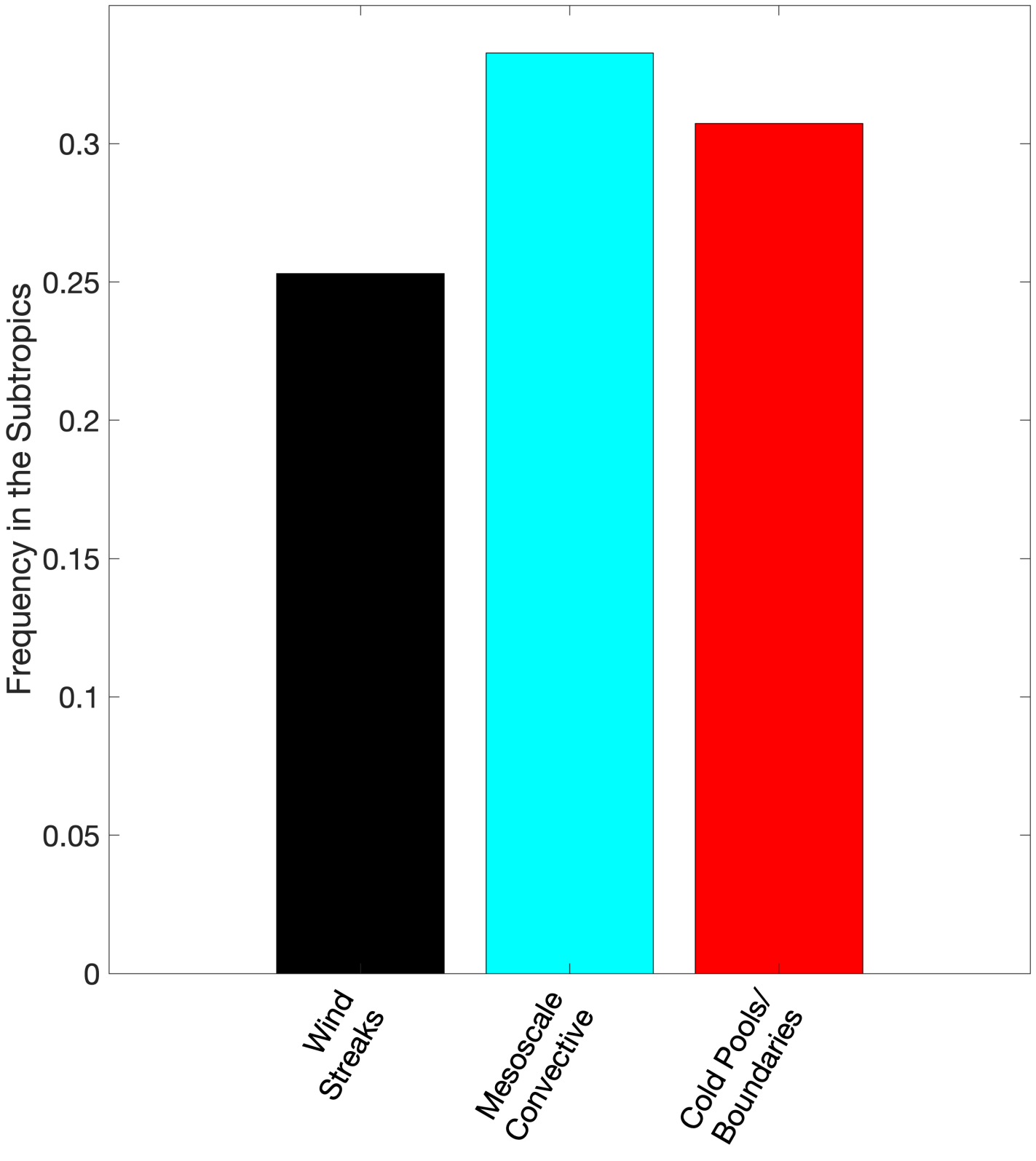
- Classified structures associated with different lower PBL convective/shear states:
  - Mesoscale Convective (MC): buoyancy driven lower PBL, unstable, little shear.
    - Convective ‘blobs’ evident, no linear features.
    - Weaker winds
  - Wind Streaks (WS): shear driven lower PBL, nearly stable.
    - Associated with stronger winds, PBL rolls, and obvious linear features.



Stopa et al. (2022)

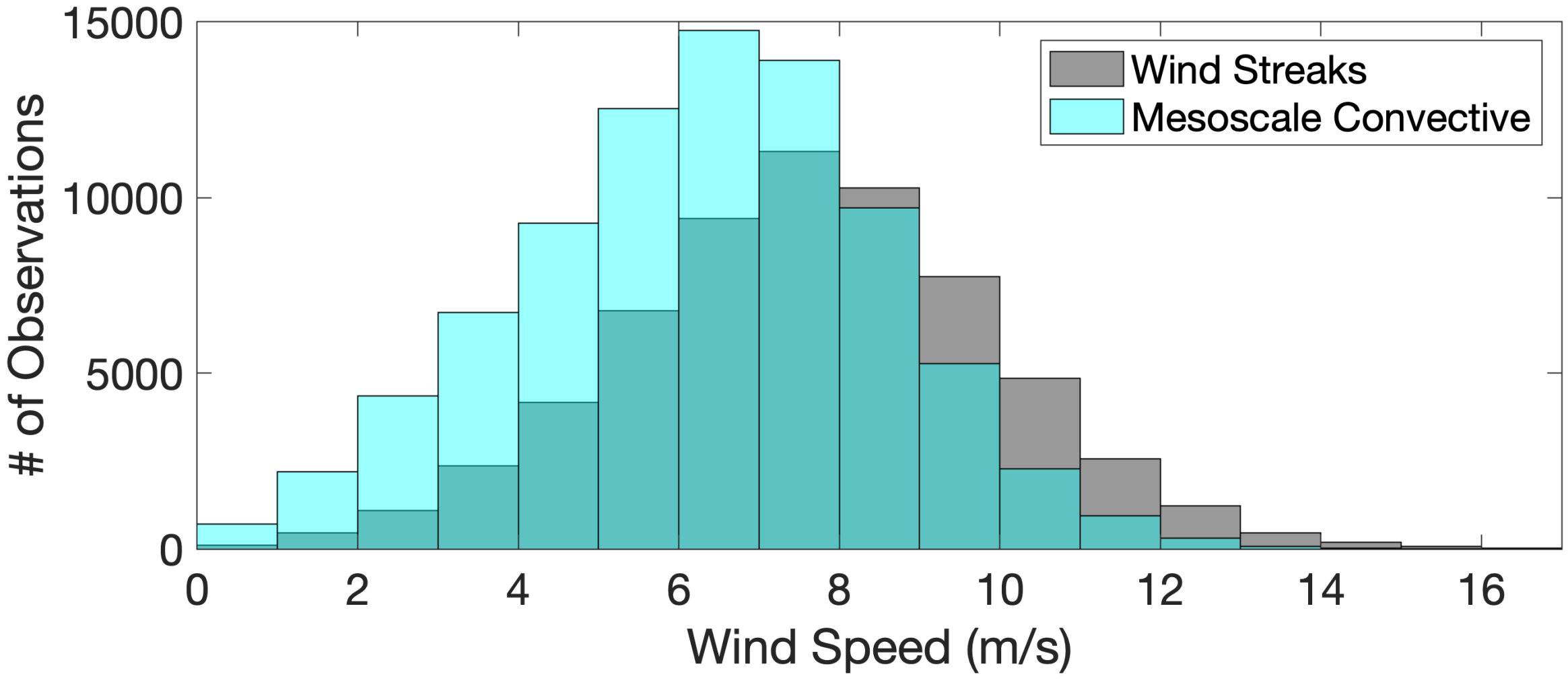
Frequency of Classifications

- For subtropical study regions.
- MC are slightly more common than WS, and are not co-observed in this study.
- MC or WS are observed nearly 60% of the time.
- Cold Pools/Boundaries are seen ~ 30% of the time.



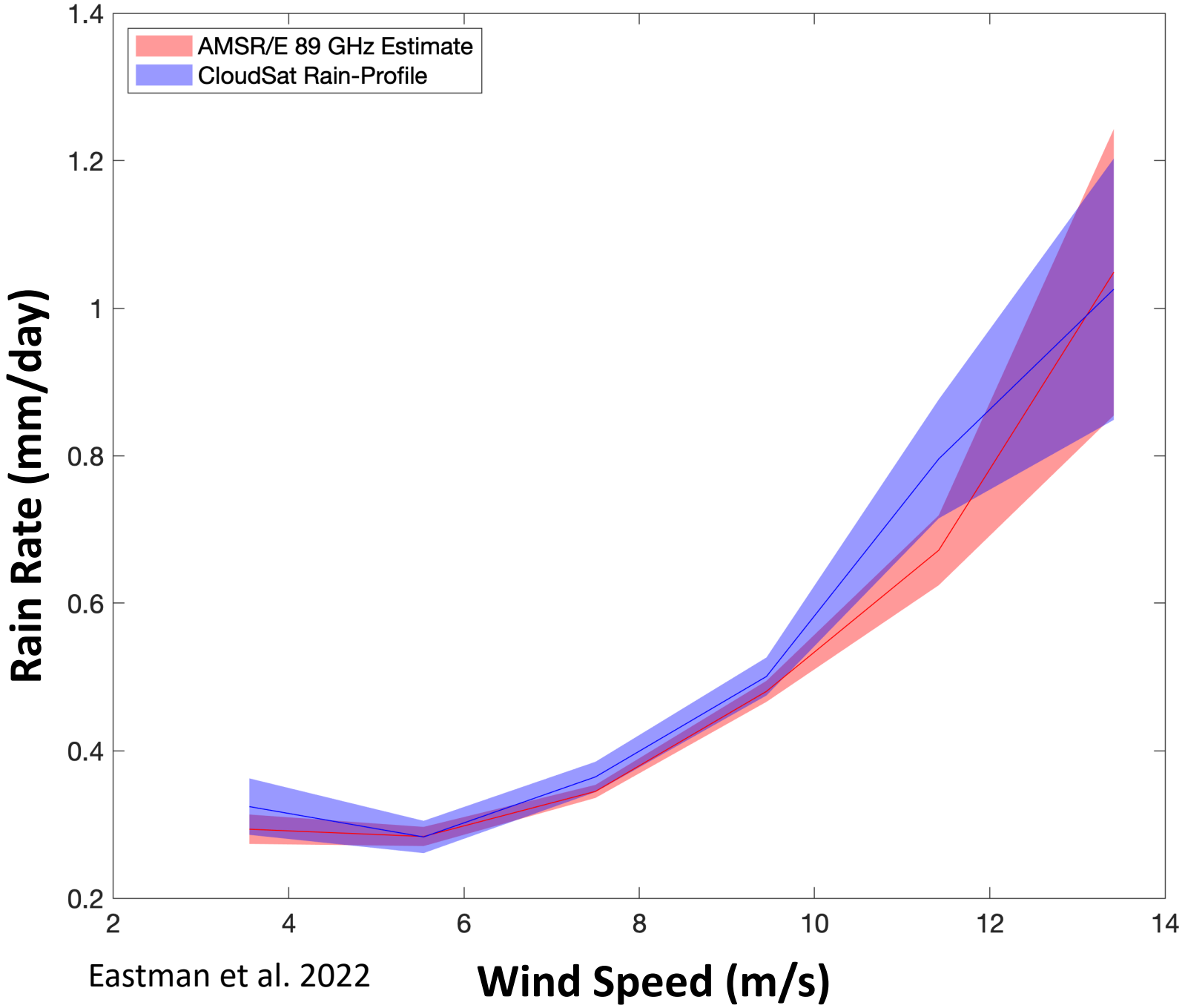
Comparing Wind Speeds

- Histogram comparison shows that wind streak boundary layers have stronger winds than mesoscale convective.
- Using ERA5 10m wind speeds coinciding with SAR observations in 1x1 grid boxes.
- Science question: **Do these structures affect clouds and precipitation independently from surface wind speed?**



Science Questions:

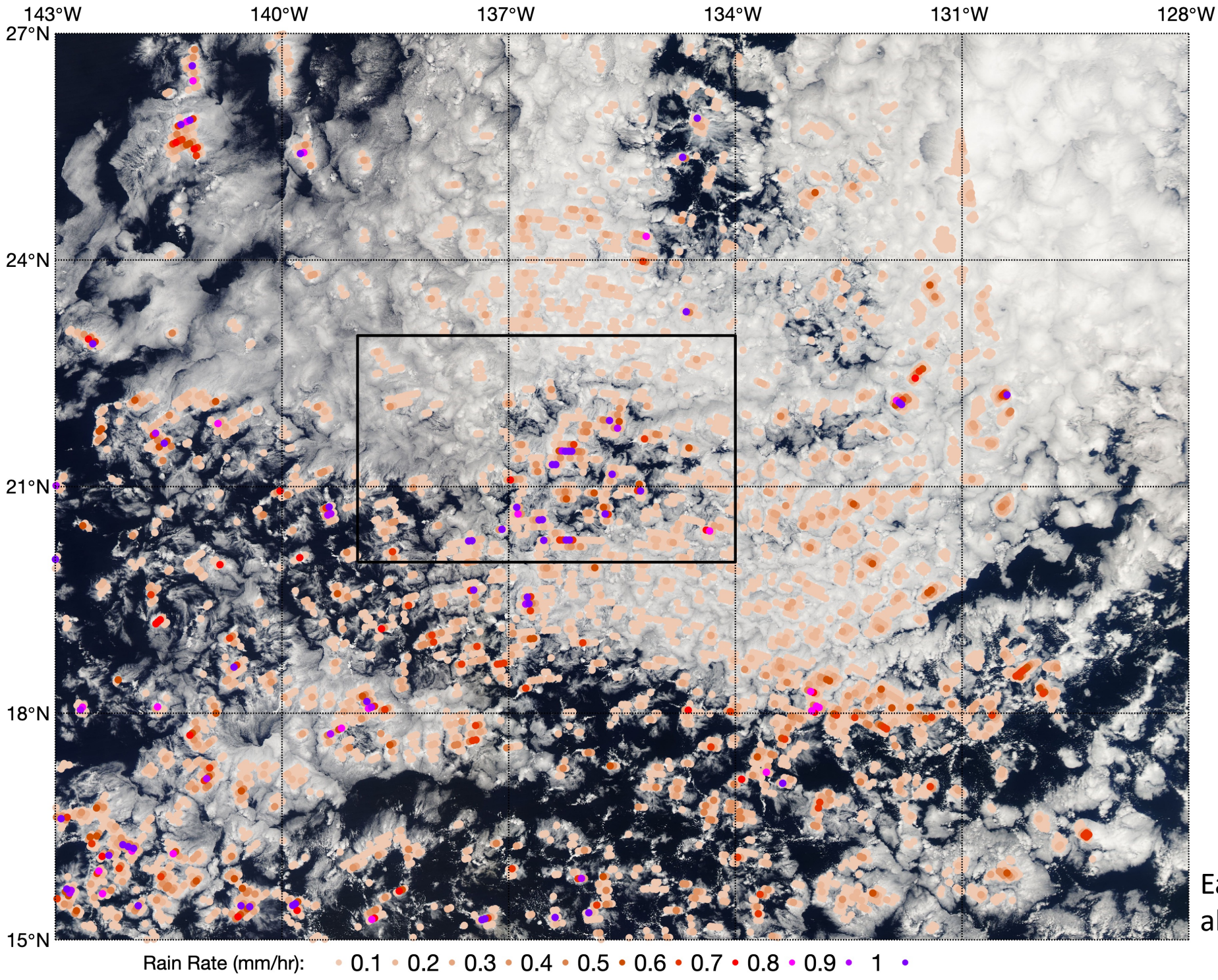
- **Strong wind is associated with higher surface-cloud fluxes** and greater rain rates. How much **does the lower PBL state, which varies with wind speed, affect this?**
- How well does the automated SAR image classifier do with rain detection?
- Can SAR classifications add value to precipitation and cloud process studies?



Eastman et al. 2022

Rain Observations for Comparison

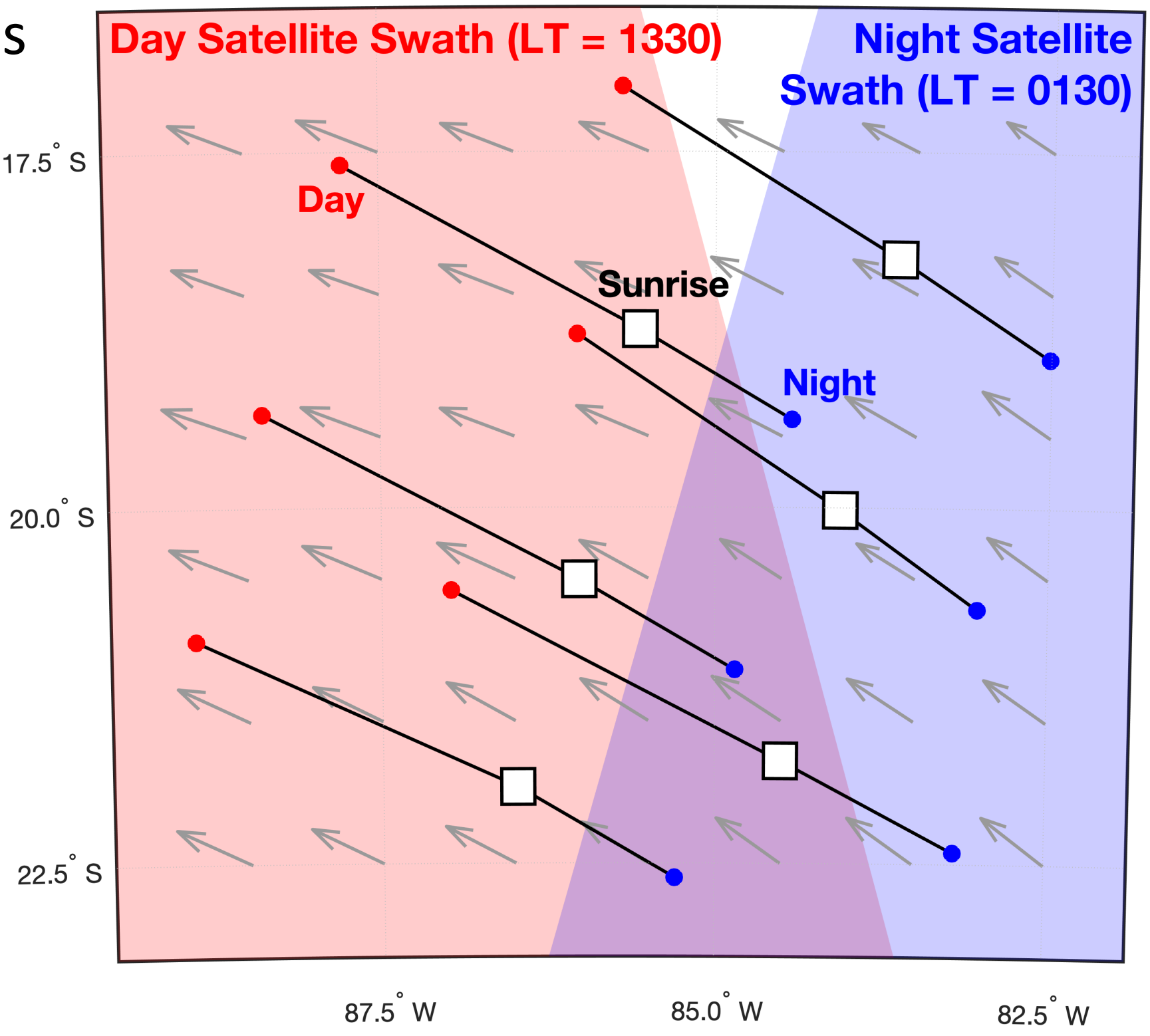
- Observed by AMSR/2 passive microwave sensor at 1:30/13:30 LT.
- 89GHz channel can estimate light, warm rain rates in shallow clouds.



Eastman et al. 2019

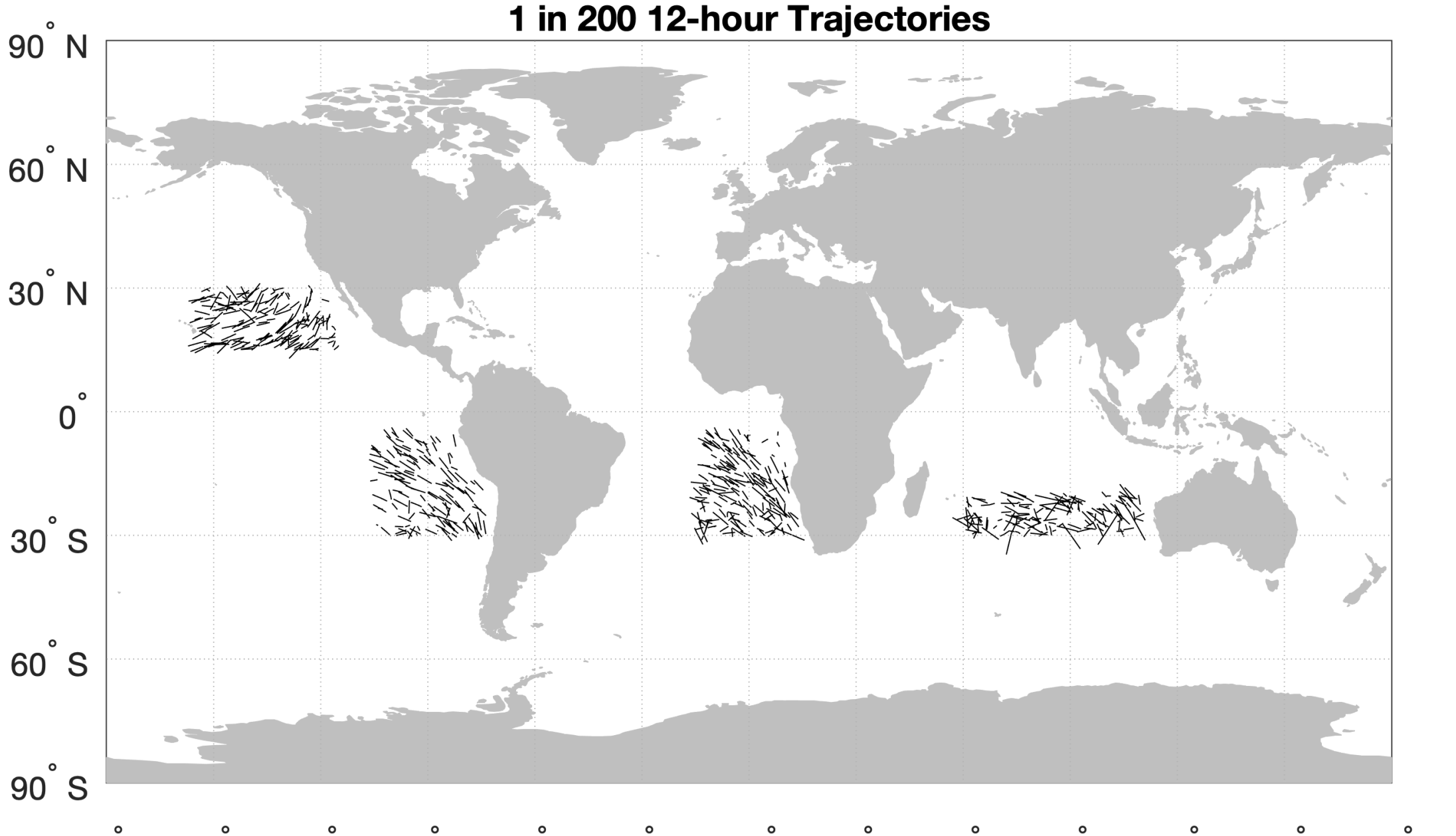
Tying SAR Observations to Rain Observations

- PBL Trajectories link SAR obs to rain obs, both before and after.
- SAR obs are ‘bracketed’ by rain information, ~5-7 hours removed.
- Trajectories built using ERA5 winds at 925 hPa.



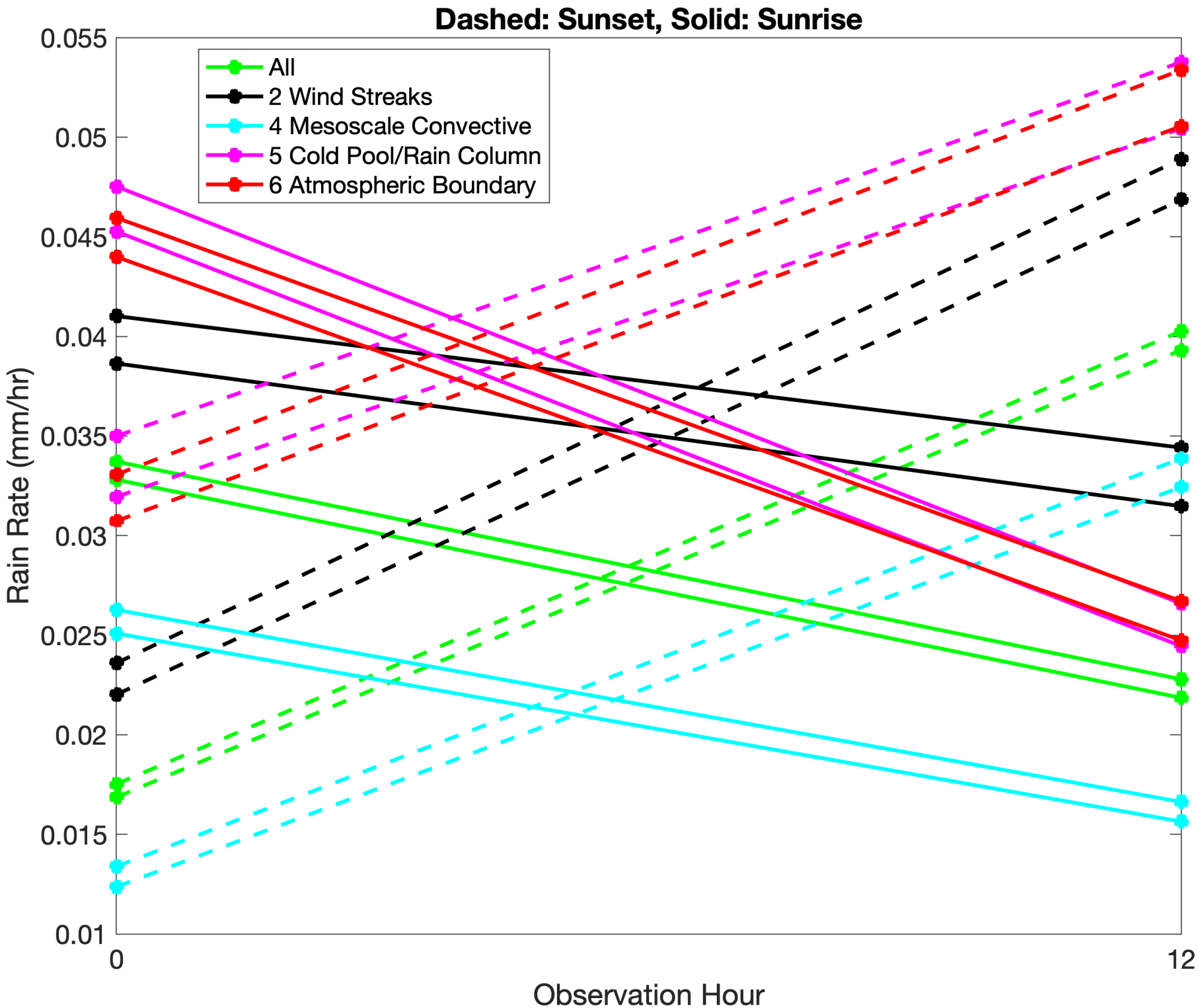
Subtropical Trajectories

- 120,000 trajectories link classified SAR images to AMSR/2 rain rates in the subtropical Sc regions for 2018.



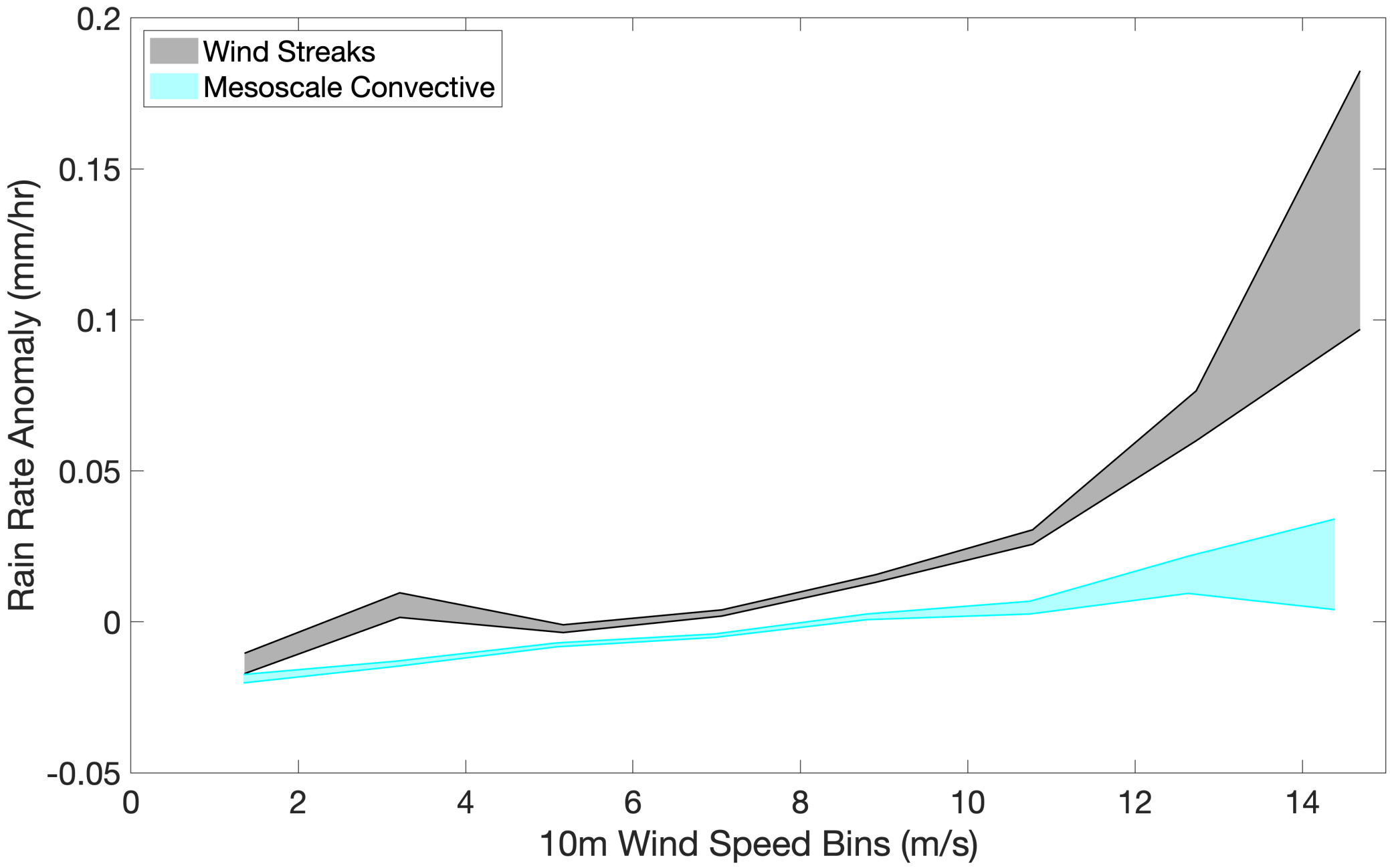
Results: Rain rates and SAR classifications

- Raw results show 1/2 diurnal cycle in rain rates bracketing SAR image.
- **Cold pools, rain columns, and atmospheric boundaries** (big cold pools) are associated with much **more rain**.
- **Wind Streaks** appear **rainier** than Mesoscale Convective PBLs.



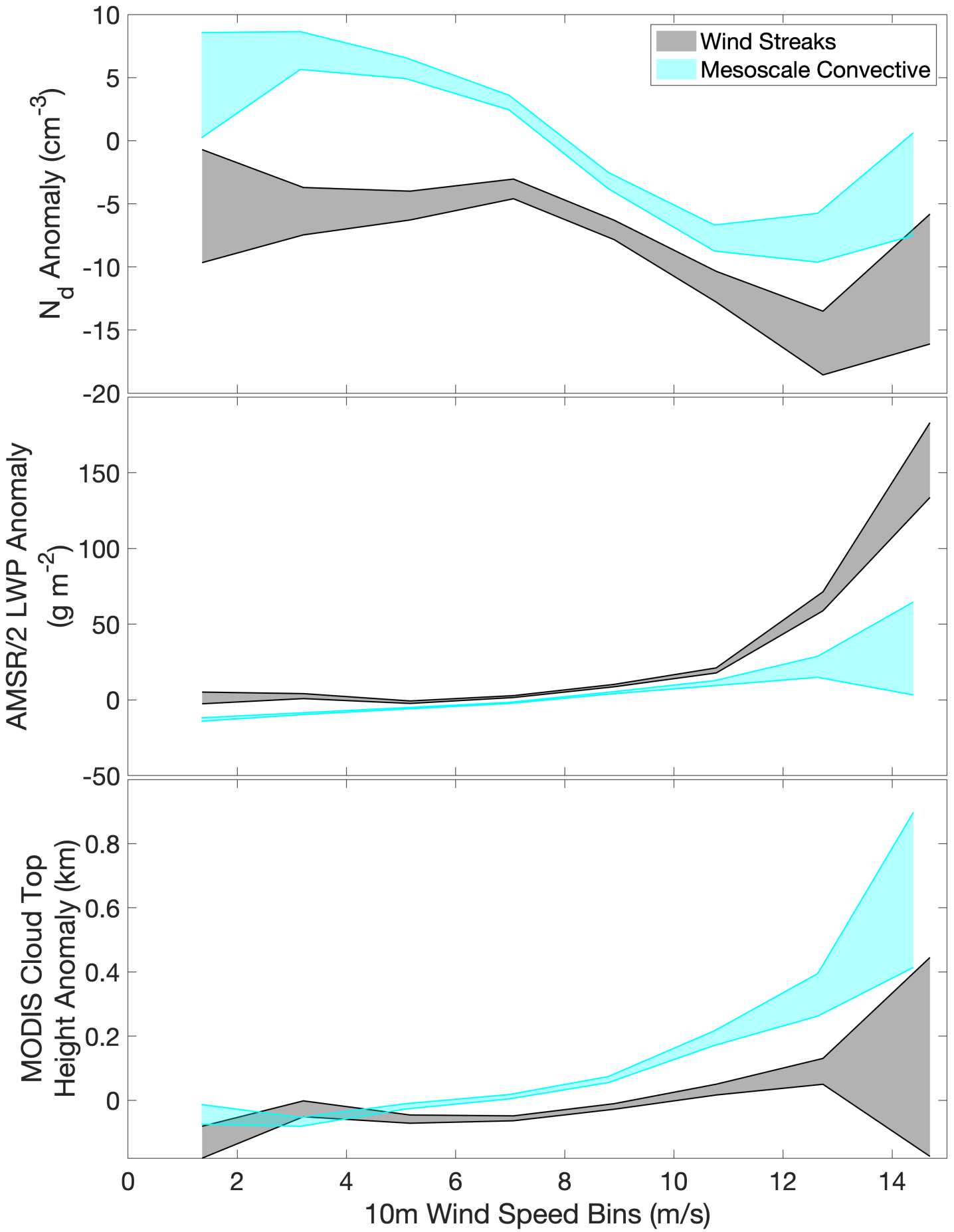
Controlling for Wind Speed

- Could WS PBLs rain more heavily because they are windier?
- Comparing rain rates in wind speed bins (x-axis), results show a strong signal after controlling for confounding winds.
- **Sea-Air fluxes may be stronger in the WS environment.**



Corroborating Data

- Cloud droplet concentrations (N_d) are lower for the more heavily raining WS PBLs.
- Cloud Liquid Water Path (LWP) is greater for WS PBLs.
- Both agree with a rainier WS environment.
- Curiously, WS cloud tops are significantly shallower than MC cloud tops.



Future questions:

- Why are the PBL depths so different for WS and MC?
  - Differing entrainment rates and moisture profiles?
  - Differences in cloud top turbulence?
- Why are are cold pool observations so much rainier?
  - Could be coincidental: cold pools are an indicator of the presence of rain, so we are choosing environments that are more likely to be raining.
  - Could processes such as cold pool collisions, or convection triggered at the gust front be propagating enhanced precipitation signal? Most likely both.
- Are these results applicable to other regions and climate regimes?

Conclusions

- SAR scenes analyzed over the ocean show distinct, classifiable PBL states, and indicate the presence of rain columns, cold pools, and atmospheric boundaries.
- Precipitation data, linked to SAR observations using Lagrangian trajectories shows that rain column/cold pool/boundary classifications are rainier than others.
- WS environments are rainier than MC environments, even after controlling for wind speed.
  - This hints at differences in sea-air fluxes depending on PBL state.
  - Corroborating satellite variables agree, adding credibility to precipitation results.

References, Further Reading

- Shen, H., Seitz, C., Perrie, W., He, Y., Powell, M., 2018. Developing a Quality Index Associated with Rain for Hurricane Winds from SAR. Remote Sensing 10, 1783. https://doi.org/10.3390/rs10111783
- Stopa, J.E., Wang, C., Vandemark, D., Foster, R., Mouche, A., Chapron, B., 2022. Automated Global Classification of Surface Layer Stratification Using High-Resolution Sea Surface Roughness Measurements by Satellite Synthetic Aperture Radar. Geophys Res Lett. https://doi.org/10.1029/2022GL098686
- Wang, C., Stopa, J.E., Vandemark, D., Foster, R., Ayet, A., Mouche, A., Chapron, B., Sadowski, P., 2025. A multi-tagged SAR ocean image dataset identifying atmospheric boundary layer structure in winter tradewind conditions. Geoscience Data Journal 12, e282. https://doi.org/10.1002/gdj3.282
- Eastman, R., McCoy, I.L., Wood, R., 2022. Wind, Rain, and the Closed to Open Cell Transition in Subtropical Marine Stratocumulus. Journal of Geophysical Research: Atmospheres 127. https://doi.org/10.1029/2022JD036795
- Eastman, R., Lebsock, M., Wood, R., 2019. Warm Rain Rates from AMSR-E 89-GHz Brightness Temperatures Trained Using CloudSat Rain-Rate Observations. Journal of Atmospheric and Oceanic Technology 36, 1033–1051. https://doi.org/10.1175/jtech-d-18-0185.1