On 10 years of science from the ARM Eastern North Atlantic (ENA) observatory

Rob Wood, Virendra Ghate, Pavlos Kollias, Mark Miller

And numerous contributions from the ARM/ASR community

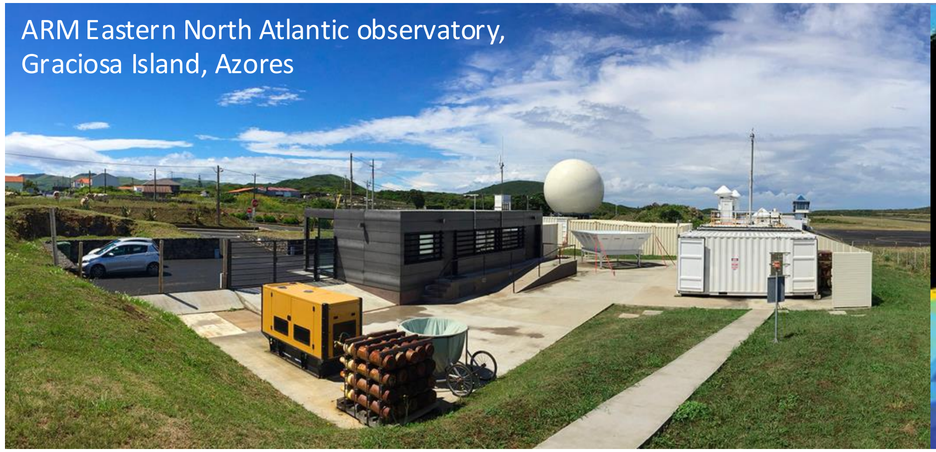
ARM CLIMATE RESEARCH FACILITY

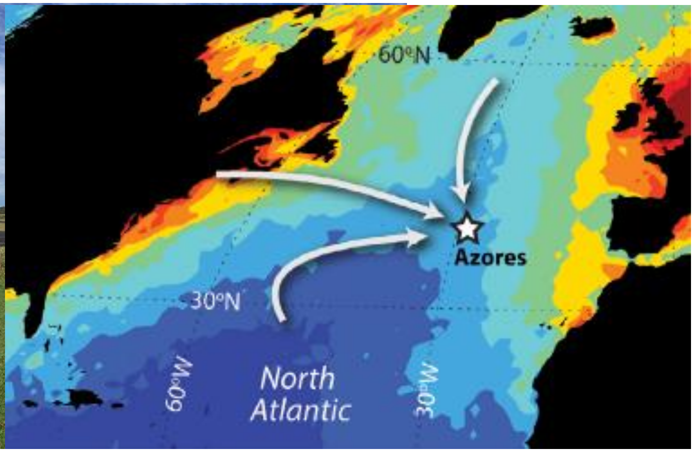
ASR Atmospheric System Research

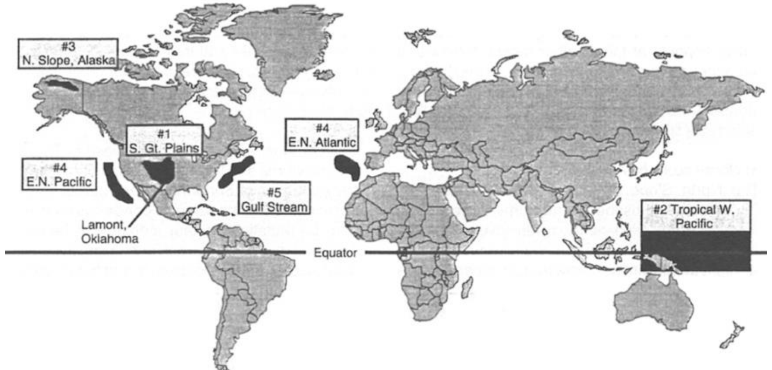
U.S. DEPARTMENT OF ENERGY | Office of Science

Eastern North Atlantic Atmospheric Observatory (ENA)

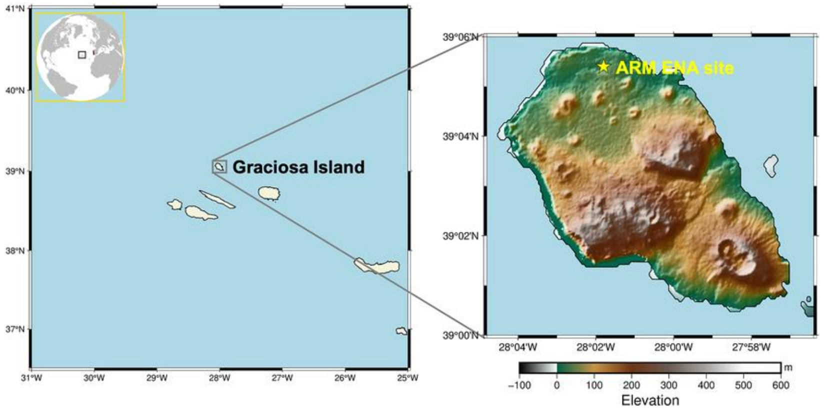
- A fixed site on the Azores was part of original ARM infrastructure plan (~1991) but was not realized in the first wave of sites
- CAP-MBL Deployment (2009-2010) saw AMF deployed for 19 months
- ENA Observatory operations from 2013-present
- ACE-ENA aircraft campaigns in Summer 2017 and Winter 2018
- 17 Intensive Operational Periods (IOPs) that lasted anywhere between few weeks to more than 2 years







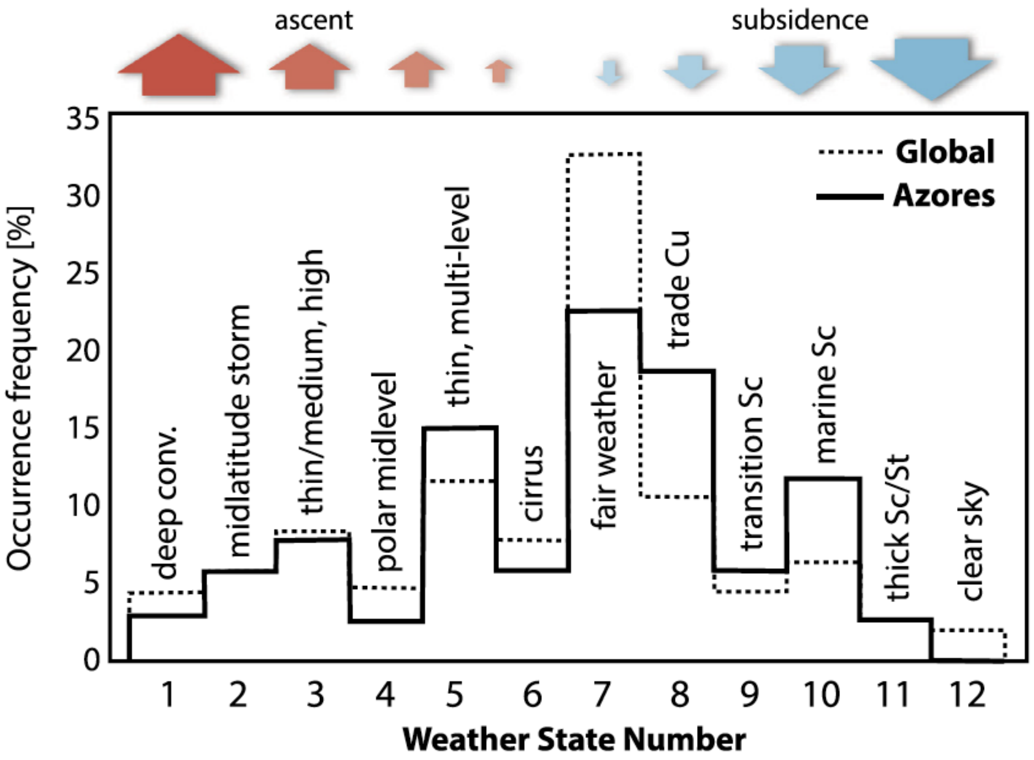
Stokes and Schwartz, 1994: *Bull. Amer. Meteor. Soc.*, **75**, 1201–1221.



PLANNING THE NEXT DECADE OF COORDINATED RESEARCH TO BETTER UNDERSTAND AND SIMULATE MARINE LOW CLOUDS

BY ROBERT WOOD, MICHAEL P. JENSEN, JIAN WANG, CHRISTOPHER S. BRETHERTON, SUSANNAH M. BURROWS, ANTHONY D. DEL GENIO, ANN M. FRIDLIND, STEVEN J. GHAN, VIRENDRA P. GHATE, PAVLOS KOLLIAS, STEVEN K. KRUEGER, ROBERT L. MCGRAW, MARK A. MILLER, DAVID PAINEMAL, LYNN M. RUSSELL, SANDRA E. YUTER, AND PAQUITA ZUIDEMA

Tselioudis et al. (2013)



Major themes for research focus areas:

- **Precipitation**
- **Aerosol indirect effects and the CCN budget**
- **Entrainment (and mixing)**
- **Mesoscale organization**

Wood, R., Jensen, M. P., Wang, J., Bretherton, C. S., Burrows, S. M., Del Genio, A. D., Fridlind, A. M., Ghan, S. J., Ghate, V. P., Kollias, P., Krueger, S. K., McGraw, R. L., Miller, M. A., Painemal, D., Russell, L. M., Yuter, S. E., & Zuidema, P. (2016). Planning the Next Decade of Coordinated Research to Better Understand and Simulate Marine Low Clouds. Bulletin of the American Meteorological Society, 97(9), 1699–1702.

Tselioudis, G., Rossow, W., Zhang, Y., & Konsta, D. (2013). Global Weather States and Their Properties from Passive and Active Satellite Cloud Retrievals. Journal of Climate, 26(19), 7734–7746.

Comprehensive characterization of shallow precipitation

combining information from different instruments during the 2nd phase of the ACE-ENA field campaign

2nd Generation Radars

Ka-band ARM Zenith Radar

- ❑ Profiling
- ❑ Most sensitive (range effect)
- ❑ 1 profile every 2 sec

Ka-band Scanning ARM Cloud Radar

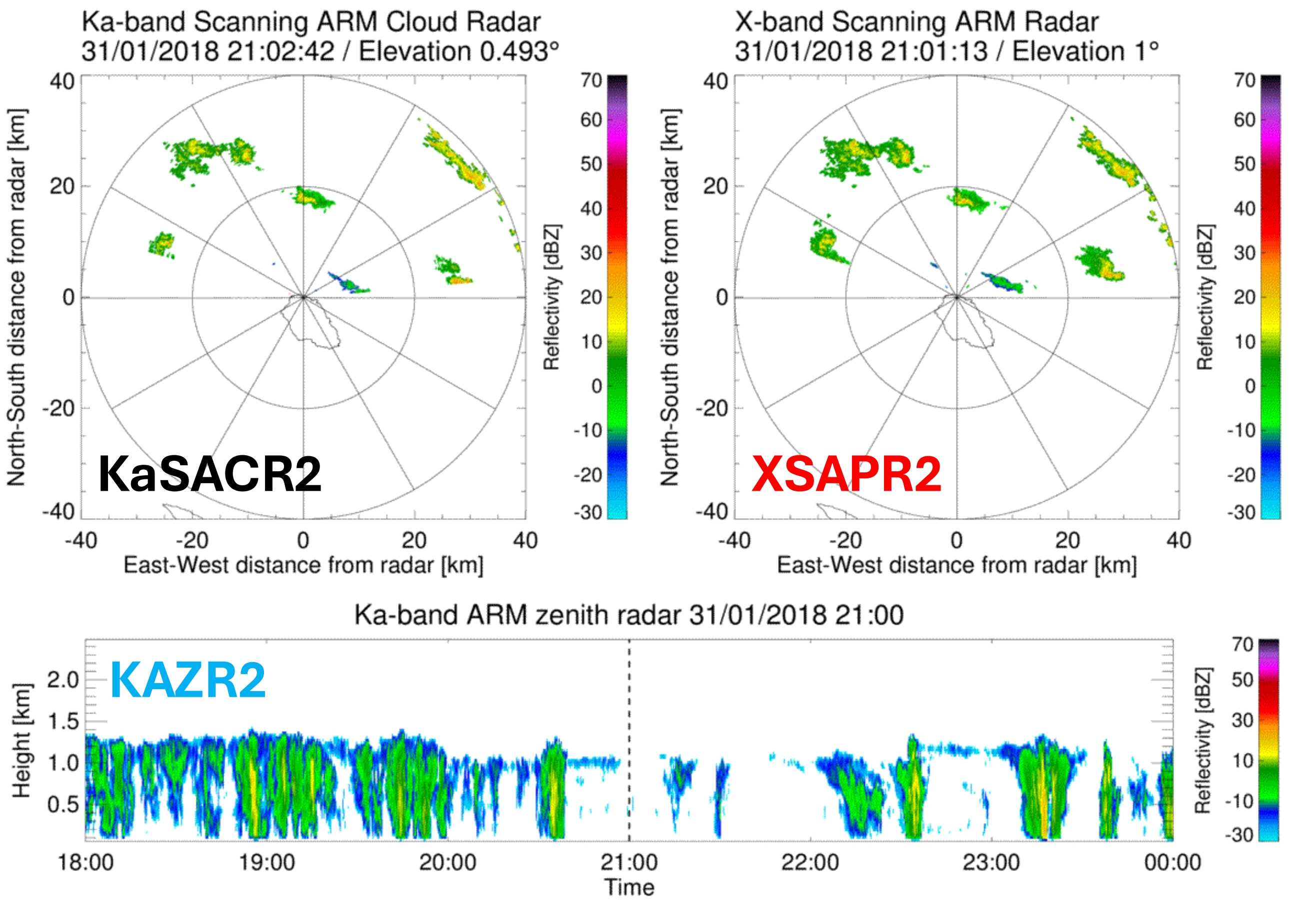
- ❑ 1 scan every 15min
- ❑ Covers only low levels (0.5º)
- ❑ Attenuates (~0.25 dB/km)
- ❑ Contaminated by clutter

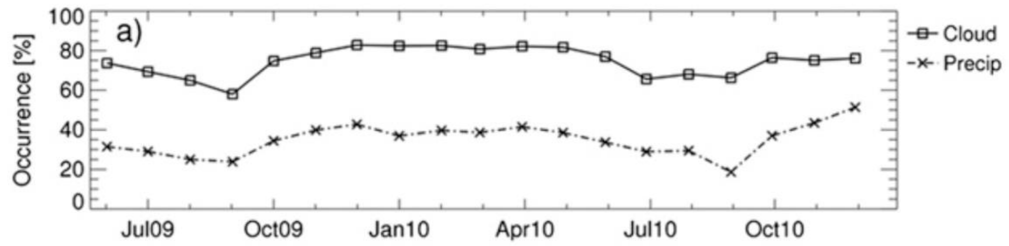
X-band Scanning ARM Precipitation Radar

- ❑ 1 volume scan every 5min
- ❑ Multiple elevations
- ❑ No attenuation (~0.01dB/km)
- ❑ Contaminated by clutter

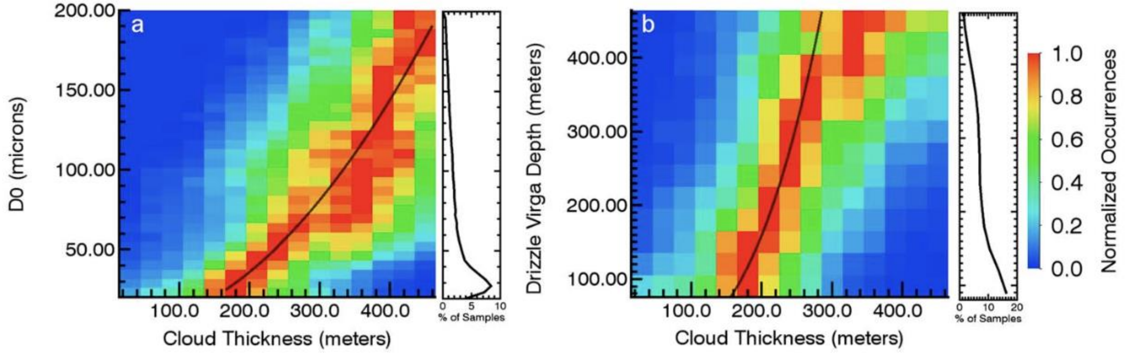
- Light rain is important for controlling low clouds and for removing aerosol particles
- Multi-wavelength scanning and vertically-pointing radars at ENA provide the most comprehensive ground measurements of light precipitation anywhere to date

Light precipitation measured by scanning and vertically-pointing radars at ENA





▲50% of ENA clouds precipitate (Rémillard et al., 2012)



▲80% of marine Sc precipitate, but over half is virga (Yang et al., 2018)

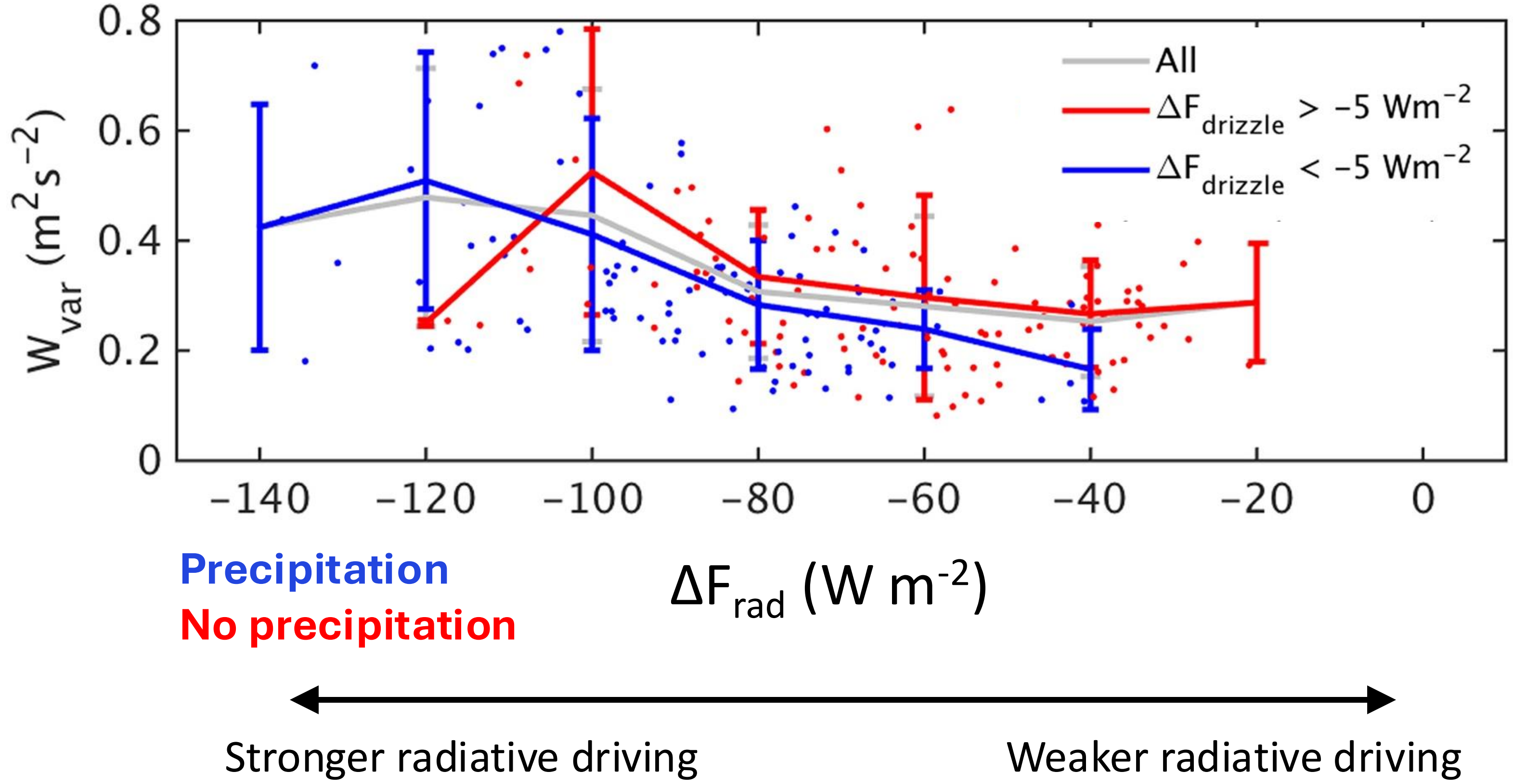
See Lamer, K., Puigdomènech Treserras, B., Zhu, Z., Isom, B., Bharadwaj, N., & Kollias, P. (2019). Characterization of shallow oceanic precipitation using profiling and scanning radar observations at the Eastern North Atlantic ARM observatory. *Atmospheric Measurement Techniques*, **12**(9), 4931–4947.

Rémillard, J., Kollias, P., Luke, E., & Wood, R. (2012). Marine Boundary Layer Cloud Observations in the Azores. Journal of Climate, 25(21), 7381–7398.

Yang, F., Luke, E. P., Kollias, P., Kostinski, A. B., & Vogelmann, A. M. (2018). Scaling of Drizzle Virga Depth With Cloud Thickness for Marine Stratocumulus Clouds. Geophysical Research Letters, 45(8), 3746–3753.

First observational evidence that light rain reduces turbulent motions in overcast low clouds

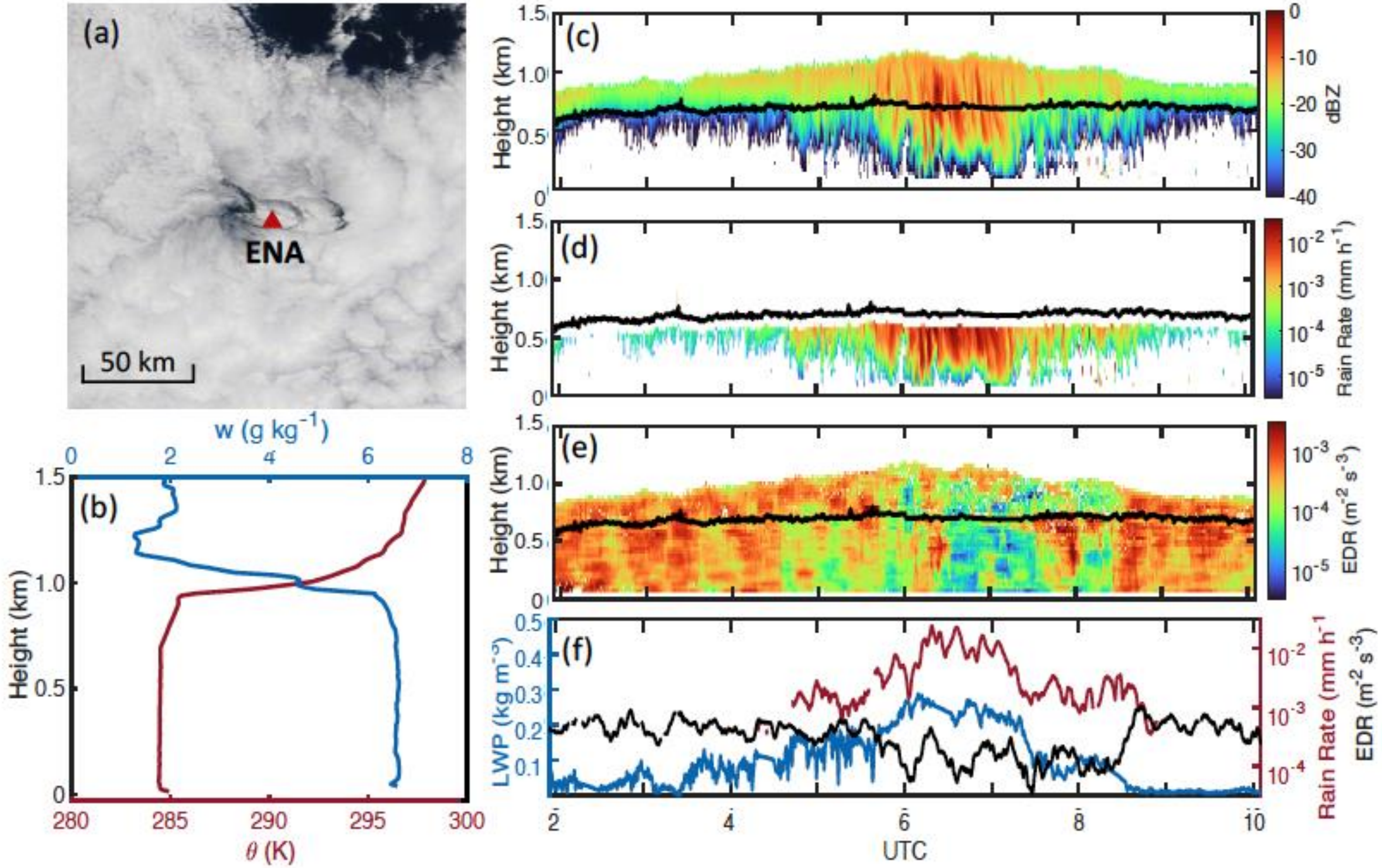
- Low cloud turbulence is driven by infrared emission at cloud top, which cools air making it sink
- Controlling for this process reveals that precipitation suppresses turbulence, which can lead to cloud breakup
- Results can be used to test climate models



Ghate, V. P., & Cadeddu, M. P. (2019). Drizzle and Turbulence Below Closed Cellular Marine Stratocumulus Clouds. *J. Geophys. Res.*, 124(11), 5724–5737.

Ghate, V. P., Cadeddu, M. P., Zheng, X., & O'Connor, E. (2021). Turbulence in the Marine Boundary Layer and Air Motions below Stratocumulus Clouds at the ARM Eastern North Atlantic Site. *Journal of Applied Meteorology and Climatology*, **60**(10), 1495–1510. https://doi.org/10.1175/JAMC-D-21-0087.1

Investigate the effect of turbulence on the MBL precipitation process



KAZR Reflectivity

Precipitation Rate retrieved from Ceilometer, KAZR *[O'Connor., 2005]*

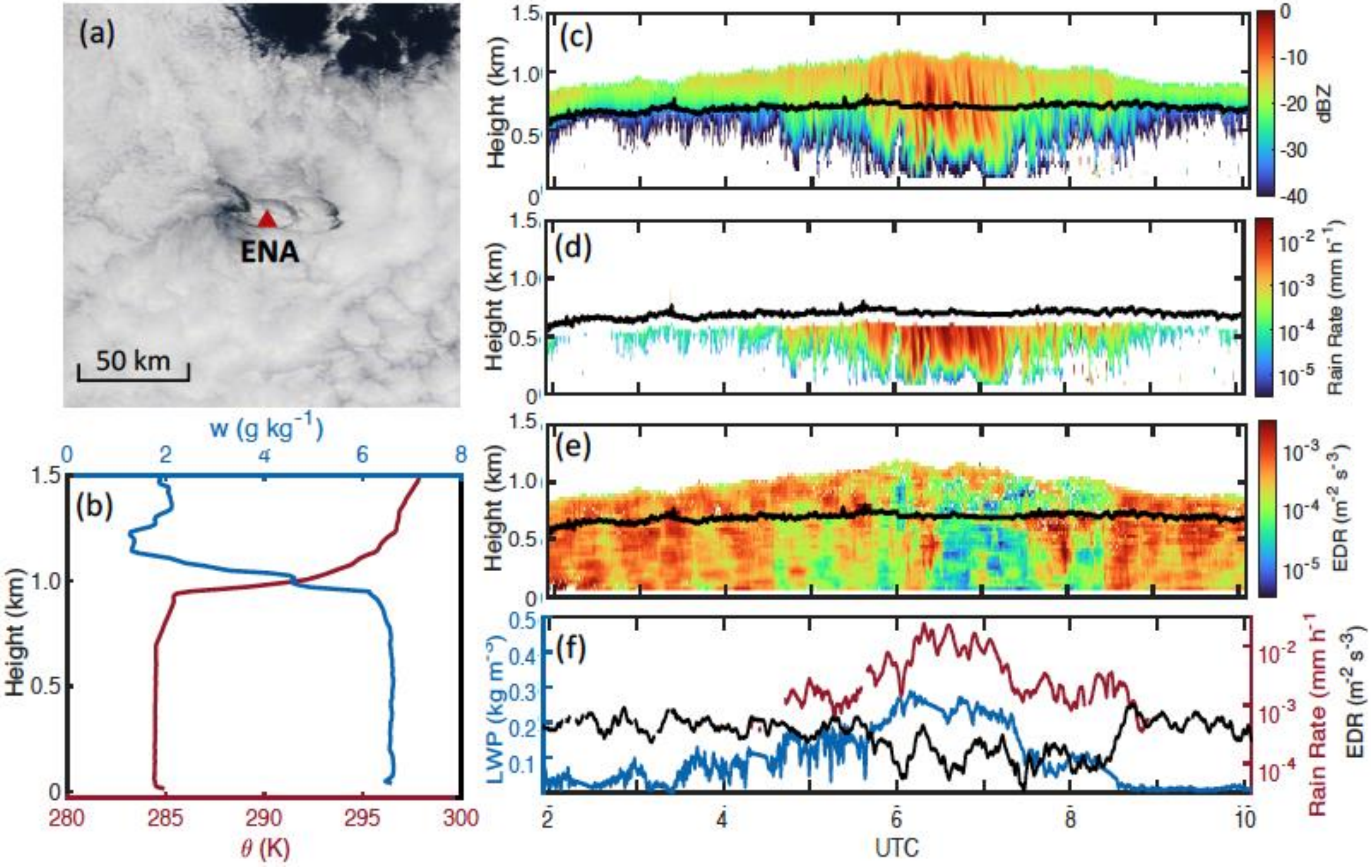
Eddy Dissipation Rate (EDR) Retrieved from DL,KAZR *[Borque., 2016]*

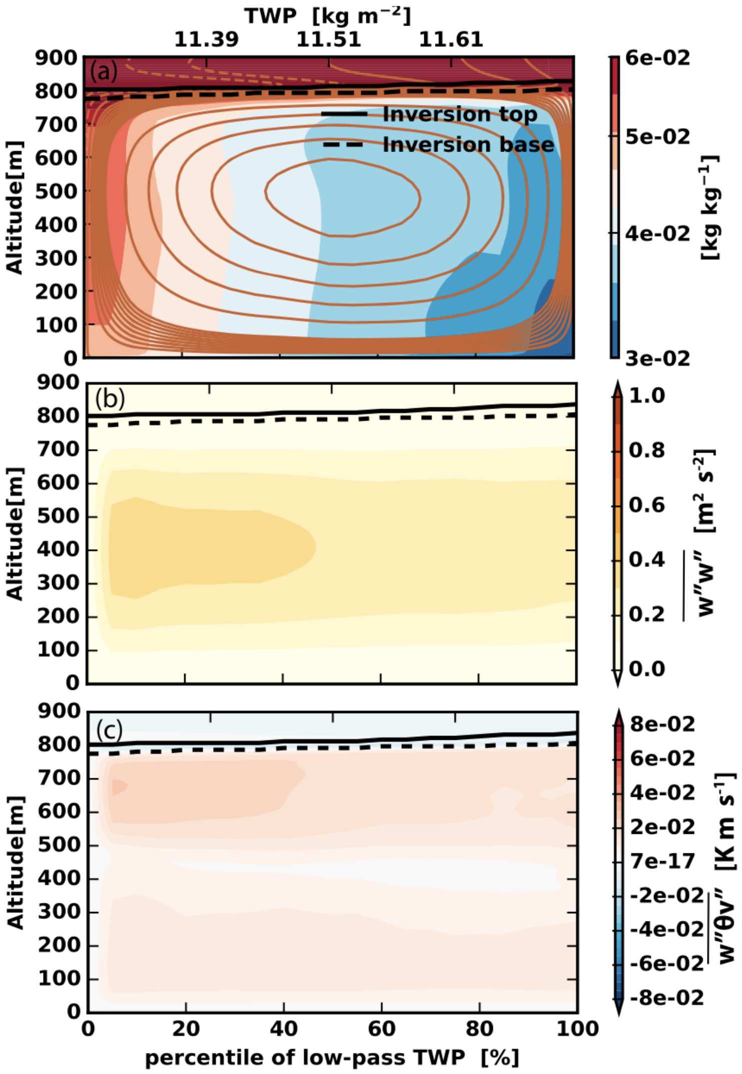
MWR-observed LWP
Precipitation Rate at CB
Median EDR in cloud layer

O'Connor, E. J., Hogan, R. J., & Illingworth, A. J. (2005). Retrieving stratocumulus drizzle parameters using Doppler radar and lidar. J. Appl. Meteorol., **44**, 14–27.

Borque, P., Luke, E., & Kollias, P. (2016). On the unified estimation of turbulence eddy dissipation rate using Doppler cloud radars and lidars. J. Geophys. Res., **121**(10), 2015JD024543.

Investigate the effect of turbulence on the MBL precipitation process





Zhou and Bretherton (2019)

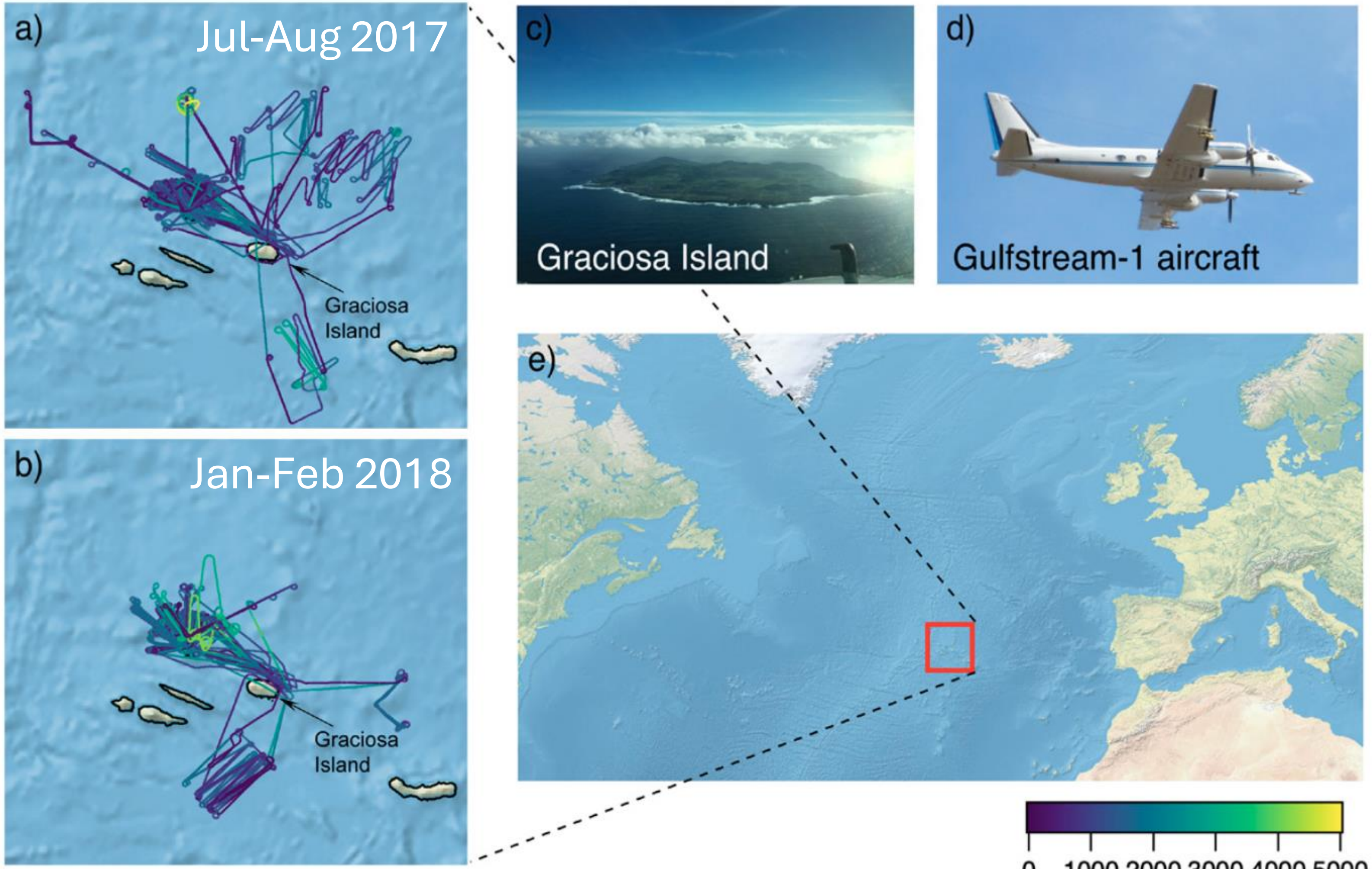
O'Connor, E. J., Hogan, R. J., & Illingworth, A. J. (2005). Retrieving stratocumulus drizzle parameters using Doppler radar and lidar. *J. Appl. Meteorol.*, **44**, 14–27.

Borque, P., Luke, E., & Kollias, P. (2016). On the unified estimation of turbulence eddy dissipation rate using Doppler cloud radars and lidars. *J. Geophys. Res.*, **121**(10), 2015JD024543.

Zhou, X., & Bretherton, C. S. (2019). Simulation of Mesoscale Cellular Convection in Marine Stratocumulus: 2. Nondrizzling Conditions. *J. Adv. Model. Earth Syst.*, **11**(1), 3–18.

Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA)

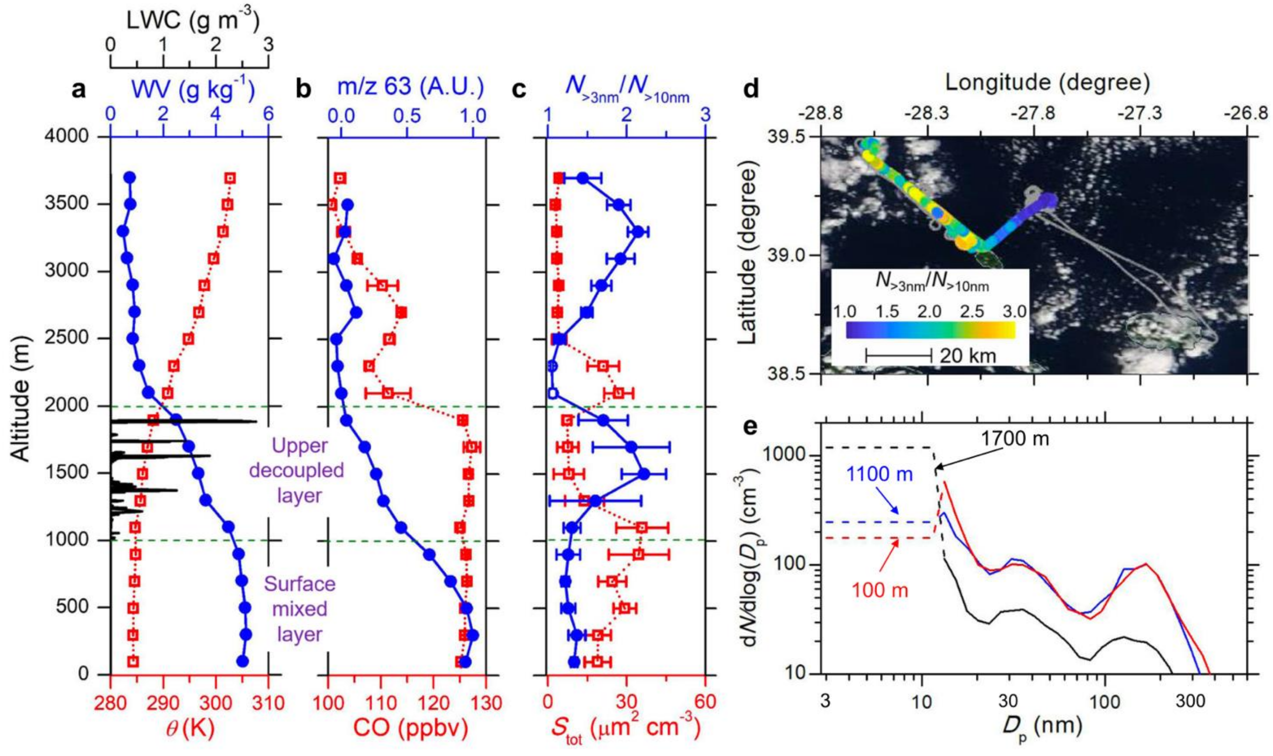
- G-1 aircraft measurements focused on:
  - Mechanisms controlling the aerosol population in the marine boundary layer
  - Effects of aerosol on clouds and precipitation
  - Cloud microphysical and macrophysical structures and entrainment mixing
  - Evaluating and improving the current retrievals of MBL cloud and drizzle properties from ground-based remote sensing

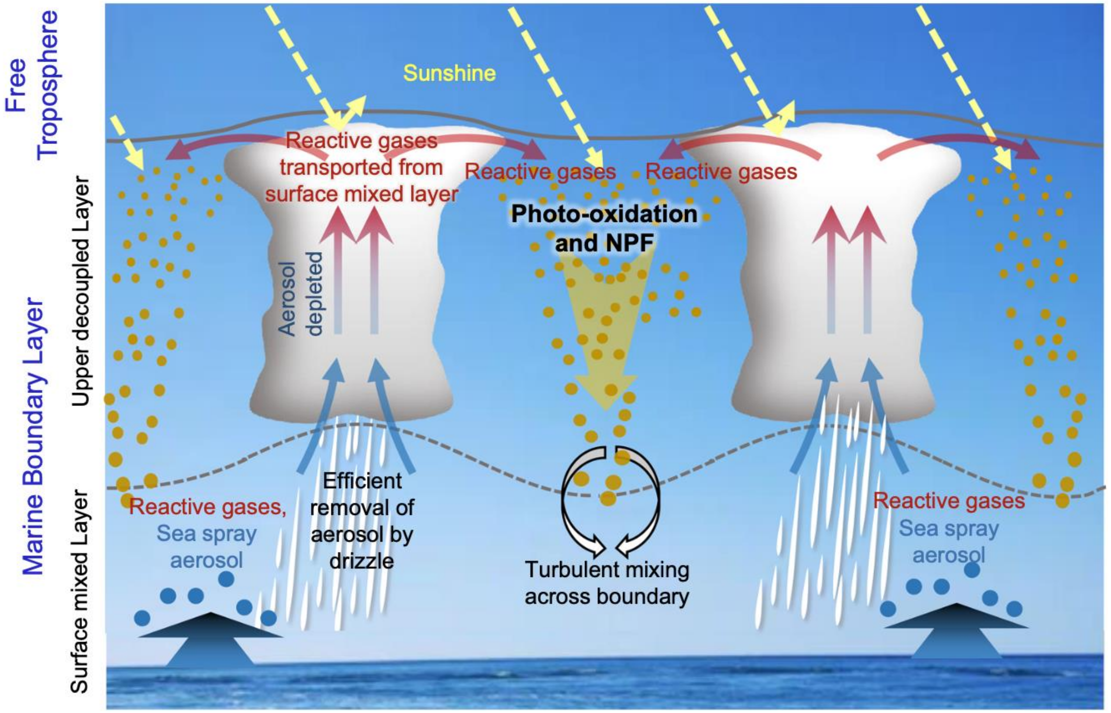


BAMS Article

Wang, J. and coauthors (2022). Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA). *Bull. Amer. Meteorol. Soc.*, **103**(2), E619–E641.

New Particle Formation (NPF) in the MBL

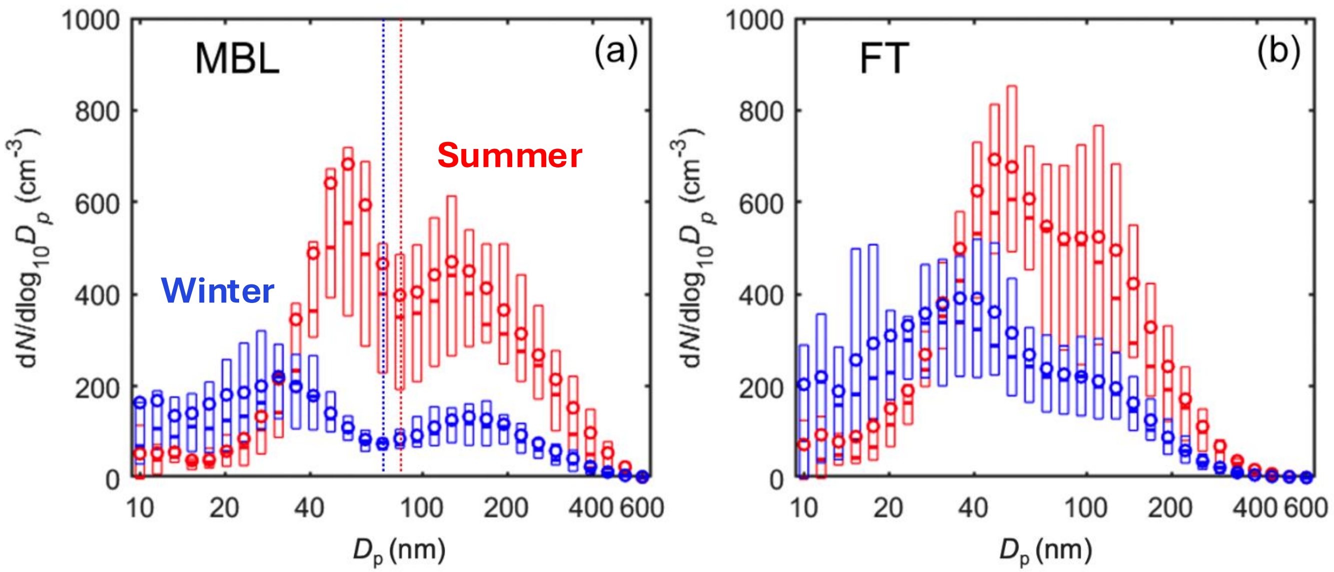




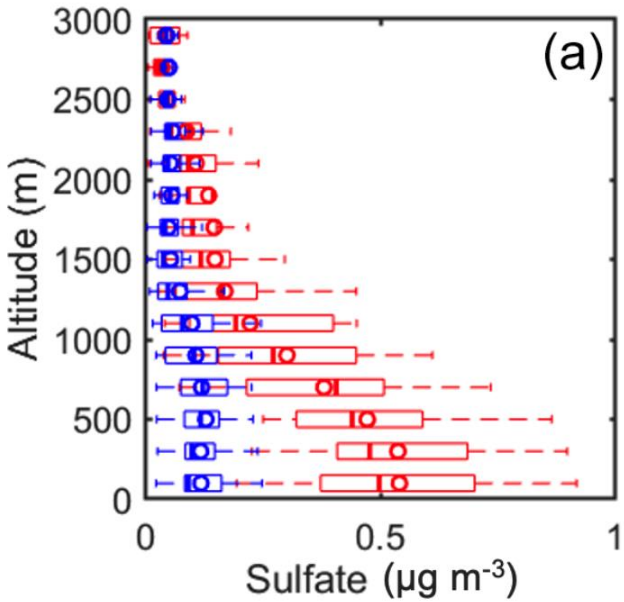
- Longstanding debate regarding the occurrence of NPF in the MBL
- NPF found to occur relatively frequently, especially in postfrontal conditions
- Mostly, NPF occurs in the ultraclean layers near the top of the MBL, perhaps evading surface obs.

Zheng, G., Wang, Y., Wood, R., Jensen, M. P., Kuang, C., McCoy, I. L., Matthews, A., Mei, F., Tomlinson, J. M., Shilling, J. E., Zawadowicz, M. A., Crosbie, E., Moore, R., Ziemba, L., Andreae, M. O., & Wang, J. (2021). New particle formation in the remote marine boundary layer. *Nature Communications*, 12(1), Article 1.

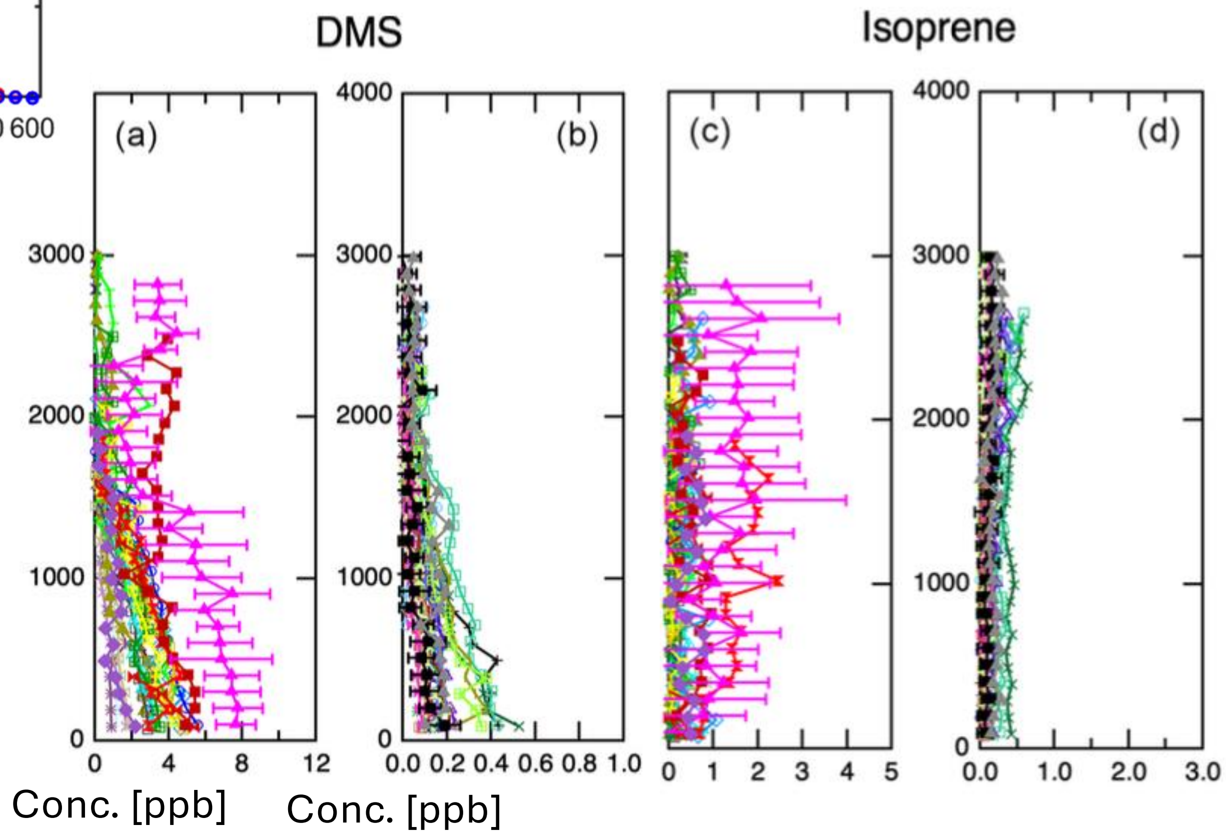
Free troposphere as source of CCN in the PBL



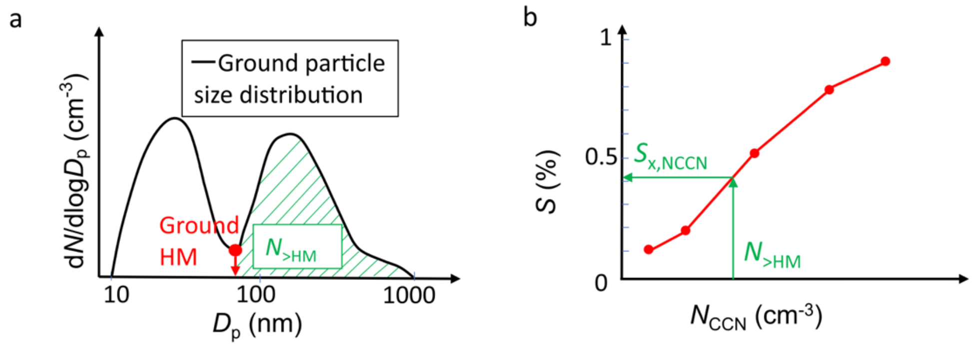
► Wang, Y., and coauthors (2021): Vertical profiles of trace gas and aerosol properties over the eastern North Atlantic: Variations with season and synoptic condition. *Atmos. Chem. Phys.*, **21**, 11079–11098.

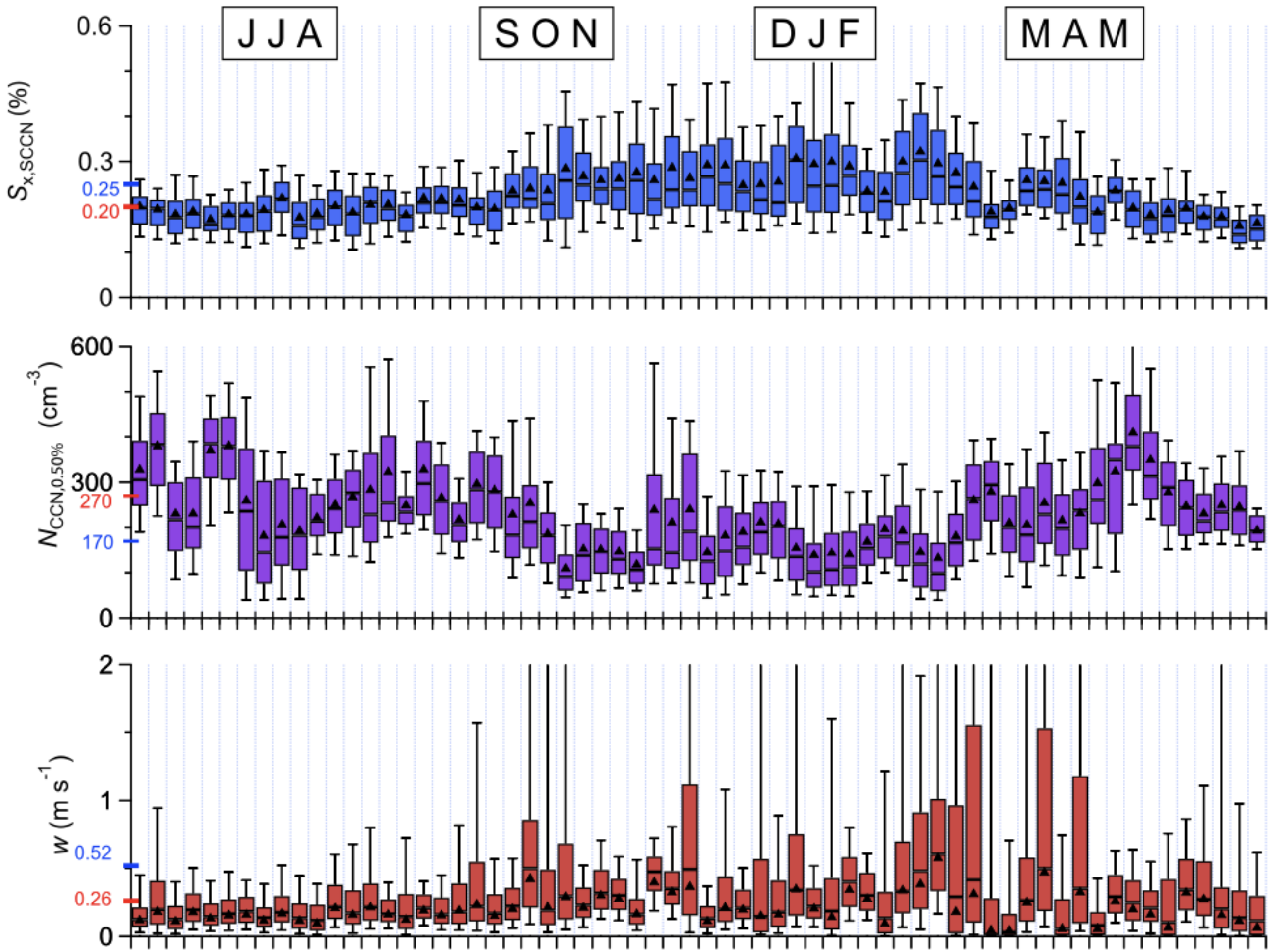


▼ Zawadowicz, M. A., and coauthors (2021): Aircraft measurements of aerosol and trace gas chemistry in the Eastern North Atlantic. *Atmos. Chem. Phys*. **21**, 7983–8002



Deducing peak supersaturations in marine low clouds using the Hoppel minimum

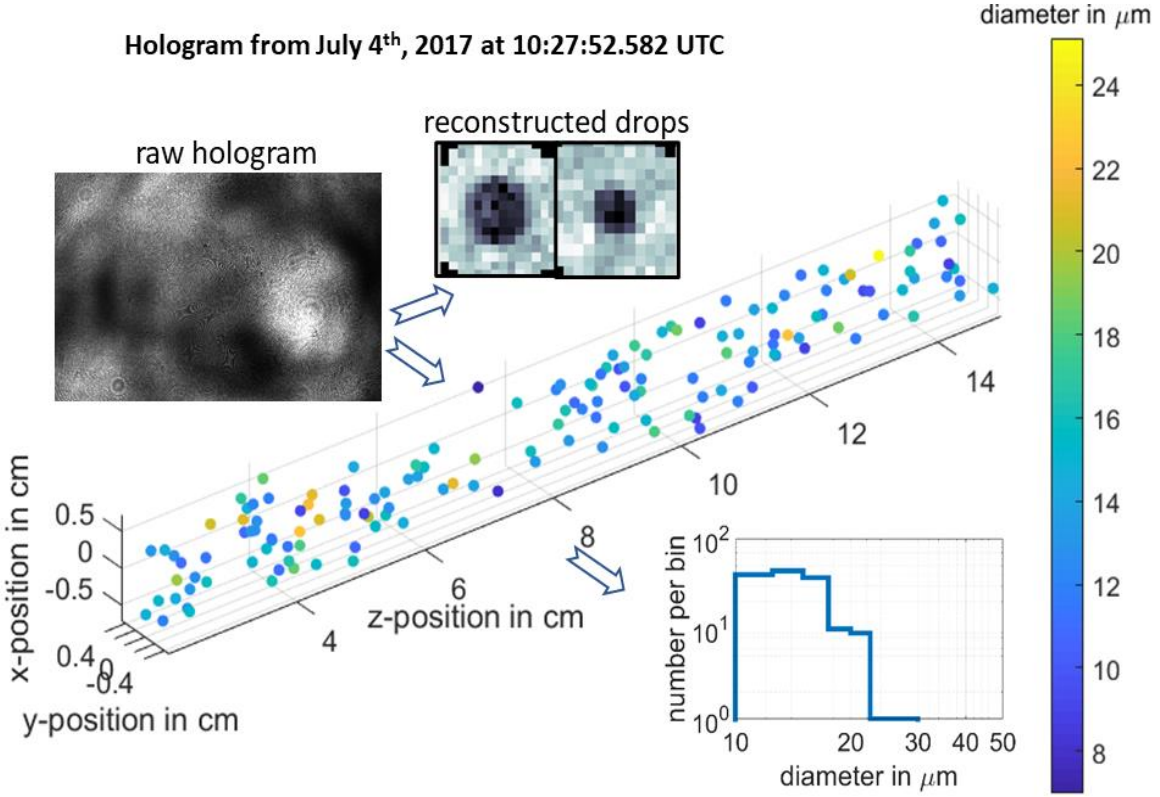


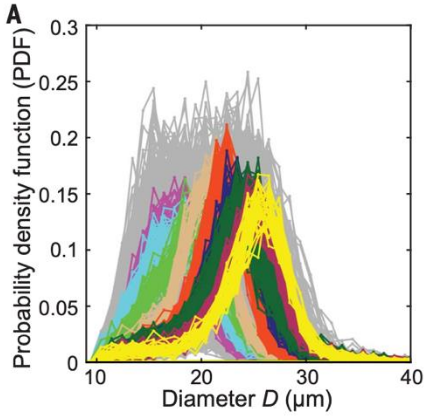


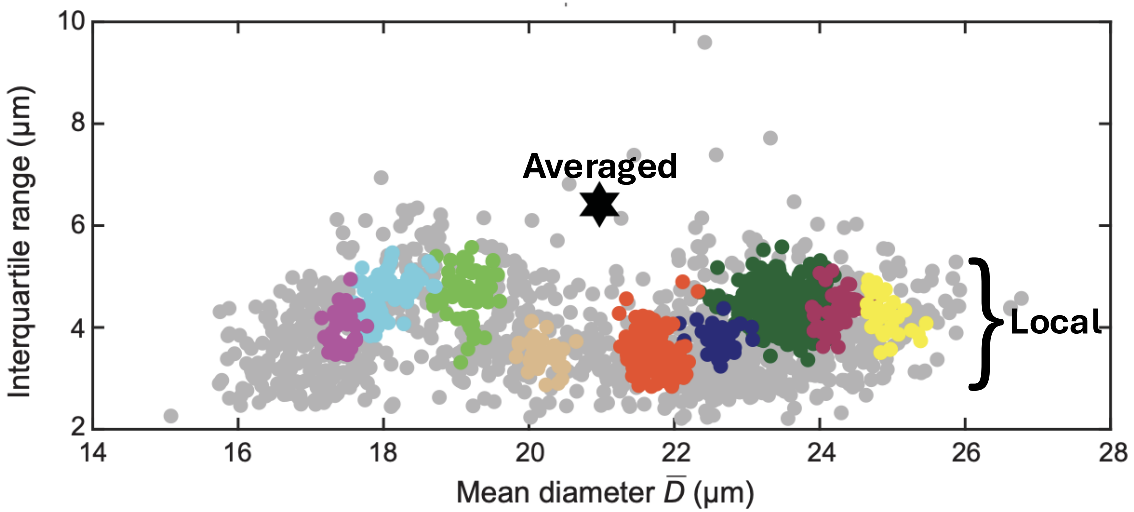
- Peak supersaturations higher during winter
  - stronger updrafts in winter
  - Lower CCN concentrations in winter
- Higher supersaturations in winter “buffer” the seasonal variability of cloud droplet concentration compared with CCN/accumulation mode concentration

Gong, X., Wang, Y., Xie, H., Zhang, J., Lu, Z., Wood, R., Stratmann, F., Wex, H., Liu, X., & Wang, J. (2023). Maximum Supersaturation in the Marine Boundary Layer Clouds Over the North Atlantic. AGU Advances, 4(6), e2022AV000855. https://doi.org/10.1029/2022AV000855

Mixing and entrainment







- Individual (local) droplet size distributions are much narrower than the averaged (global) distribution

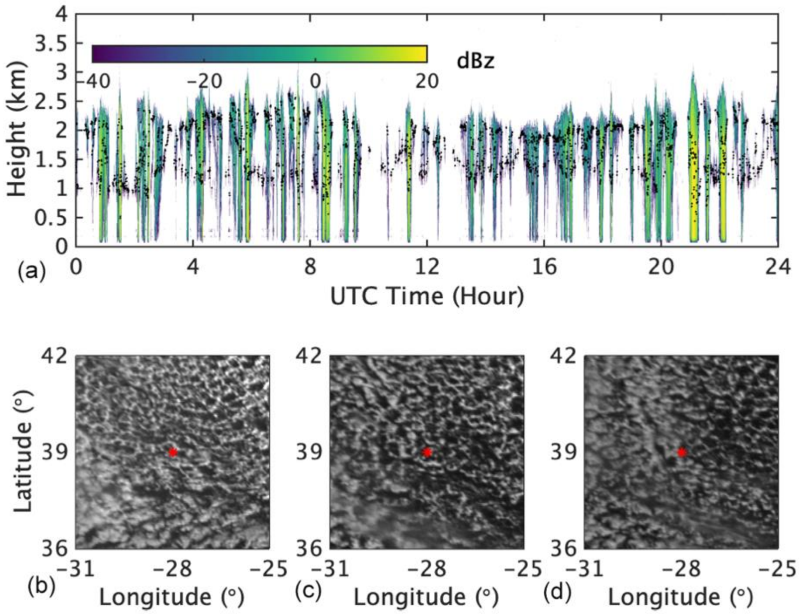
Allwayin, N., Larsen, M. L., Glienke, S., & Shaw, R. A. (2024). Locally narrow droplet size distributions are ubiquitous in stratocumulus clouds. *Science*, **384**(6695), 528–532.

MBL Mesoscale Organization

- MBL clouds often self-organize into mesoscale cellular convection (CC)

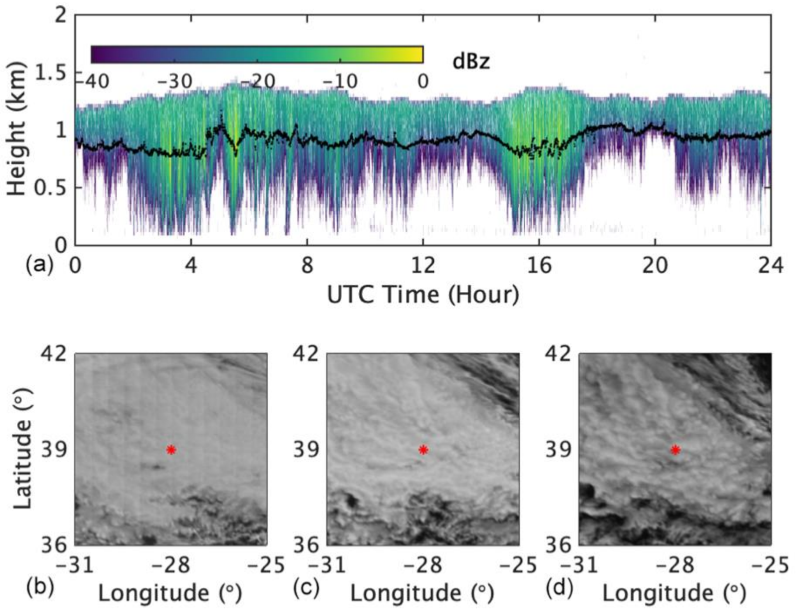
open-cellular

shallow cumulus clouds that surround a central downdraft.



closed-cellular

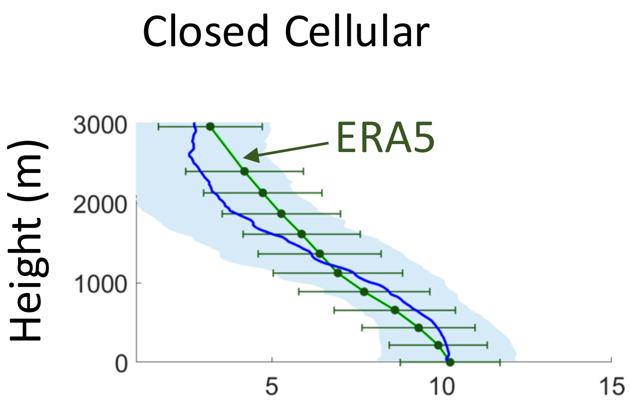
single-layer stratocumulus overcast.

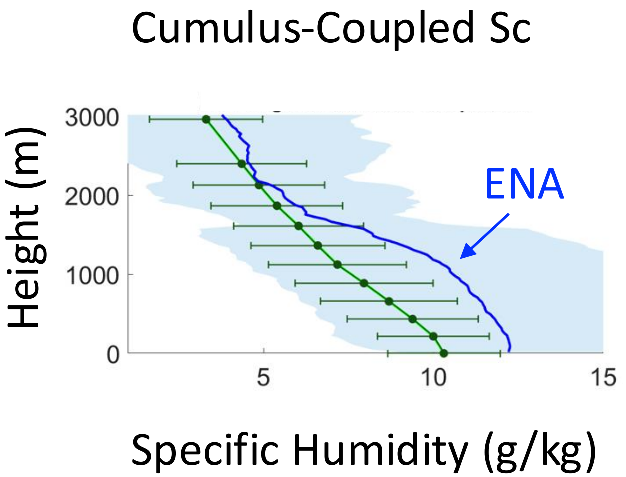


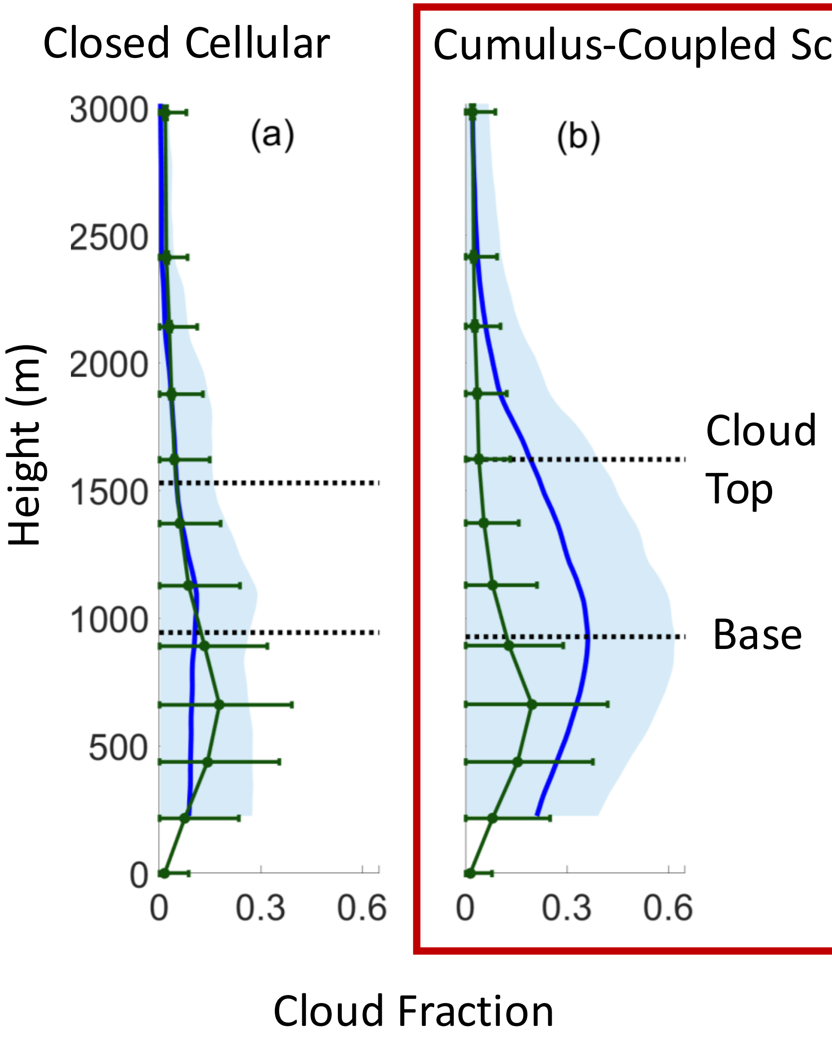
Jensen et al. 2021

Jensen, M. P., Ghate, V. P., Wang, D., Apoznanski, D. K., Bartholomew, M. J., Giangrande, S. E., Johnson, K. L., & Thieman, M. M. (2021). Contrasting characteristics of open- and closed-cellular stratocumulus cloud in the eastern North Atlantic. Atmos. Chem. and Phys., **21**(19), 14557–14571.

ENA Summertime Transition Cloudiness in ERA5



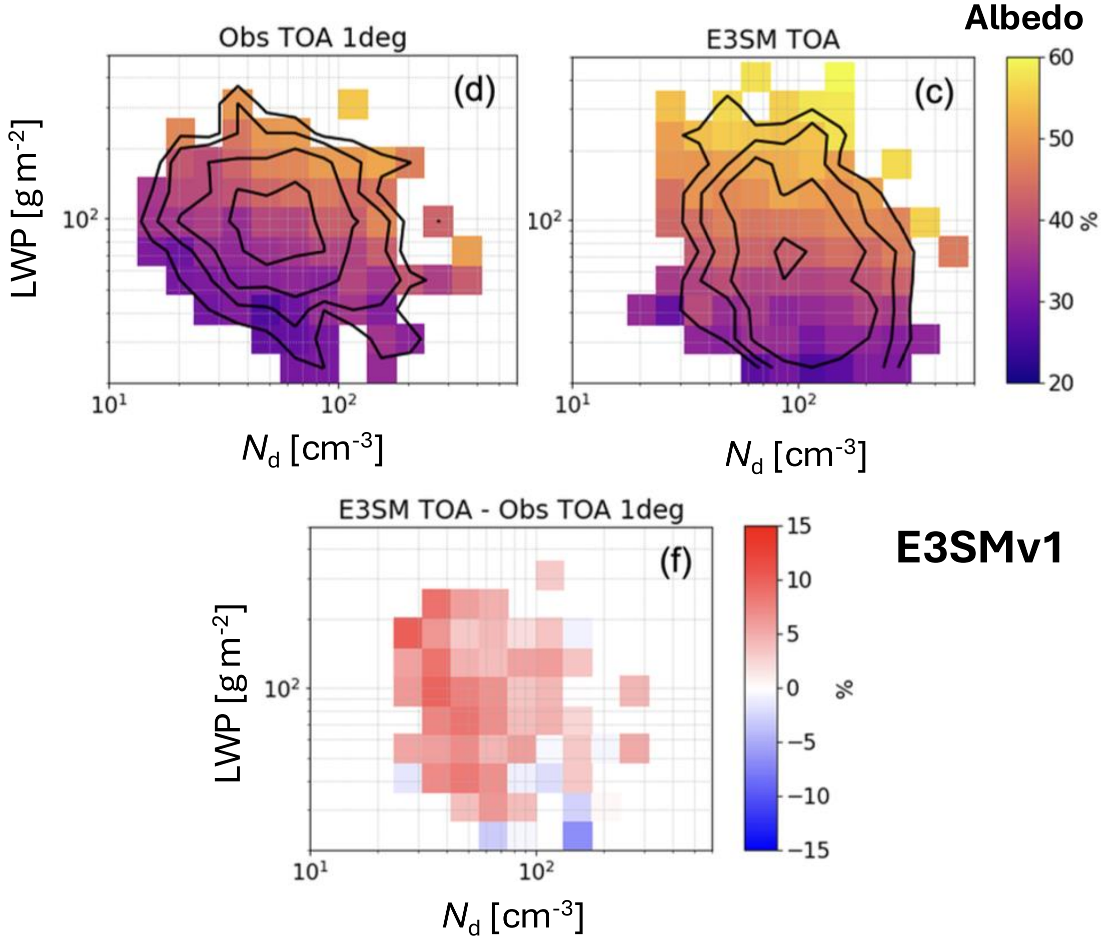


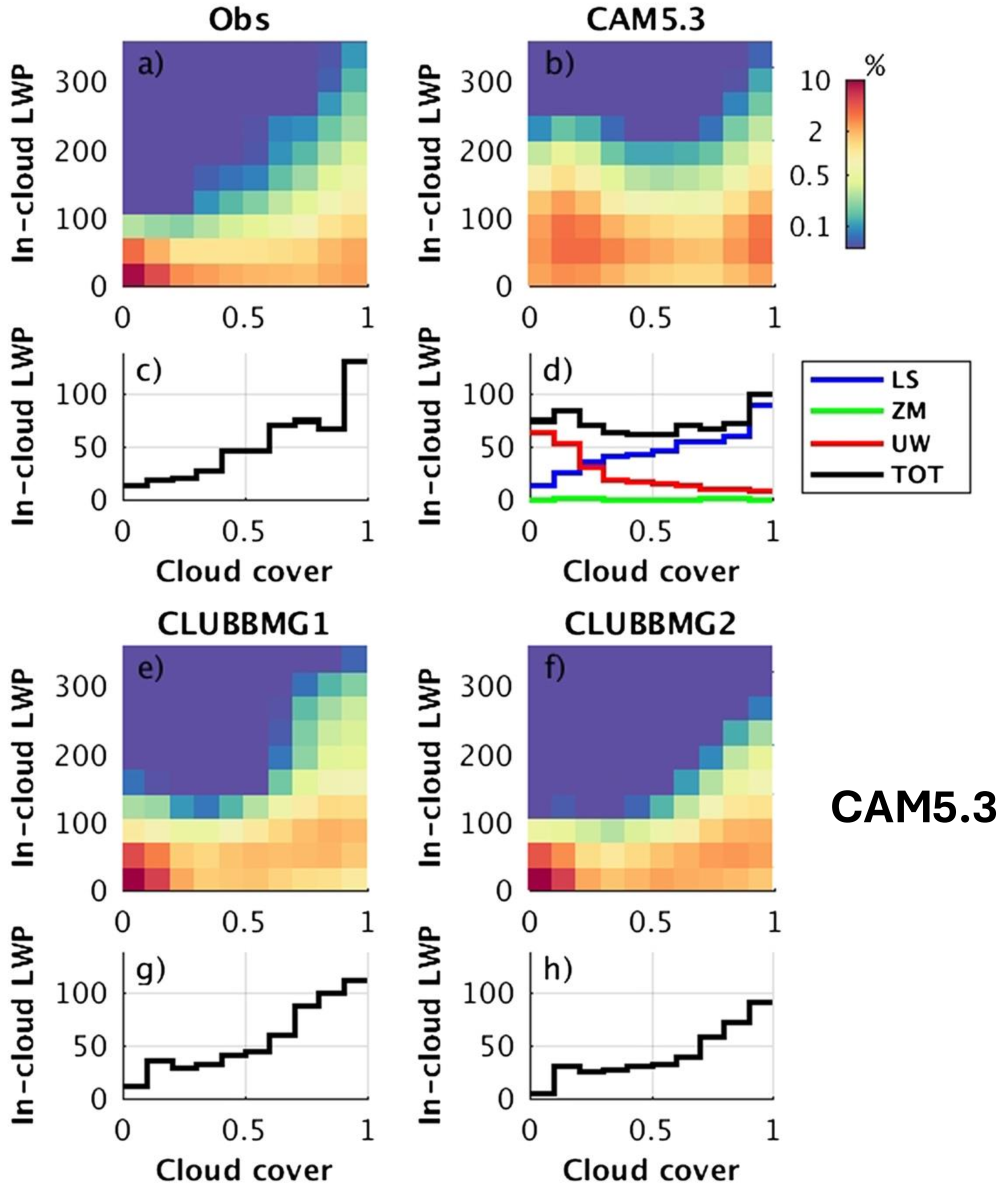


- **Closed Cellular**
  Convection handled well
- **Open Cellular**:
  Cumulus-Coupled Stratocumulus problematic
  - ✓ Mean Specific Humidity too low
  - ✓ RH too low (not shown)
  - ✓ Cloud fraction too low in upper half of MBL

Zheng, Q., & Miller, M. A. (2022). Summertime Marine Boundary Layer Cloud, Thermodynamic, and Drizzle Morphology over the Eastern North Atlantic: A Four-Year Study. *Journal of Climate*, **35**(14), 4805–4825.

Evaluation and improvement of large-scale models

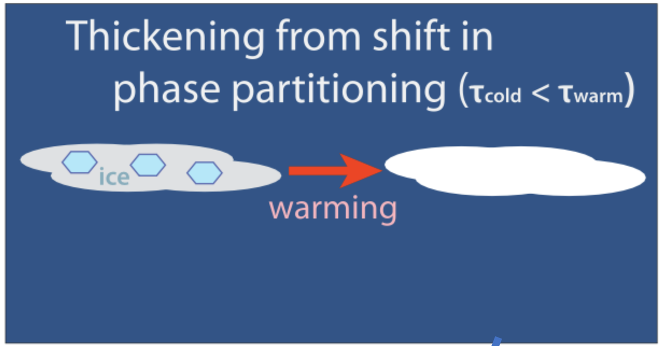




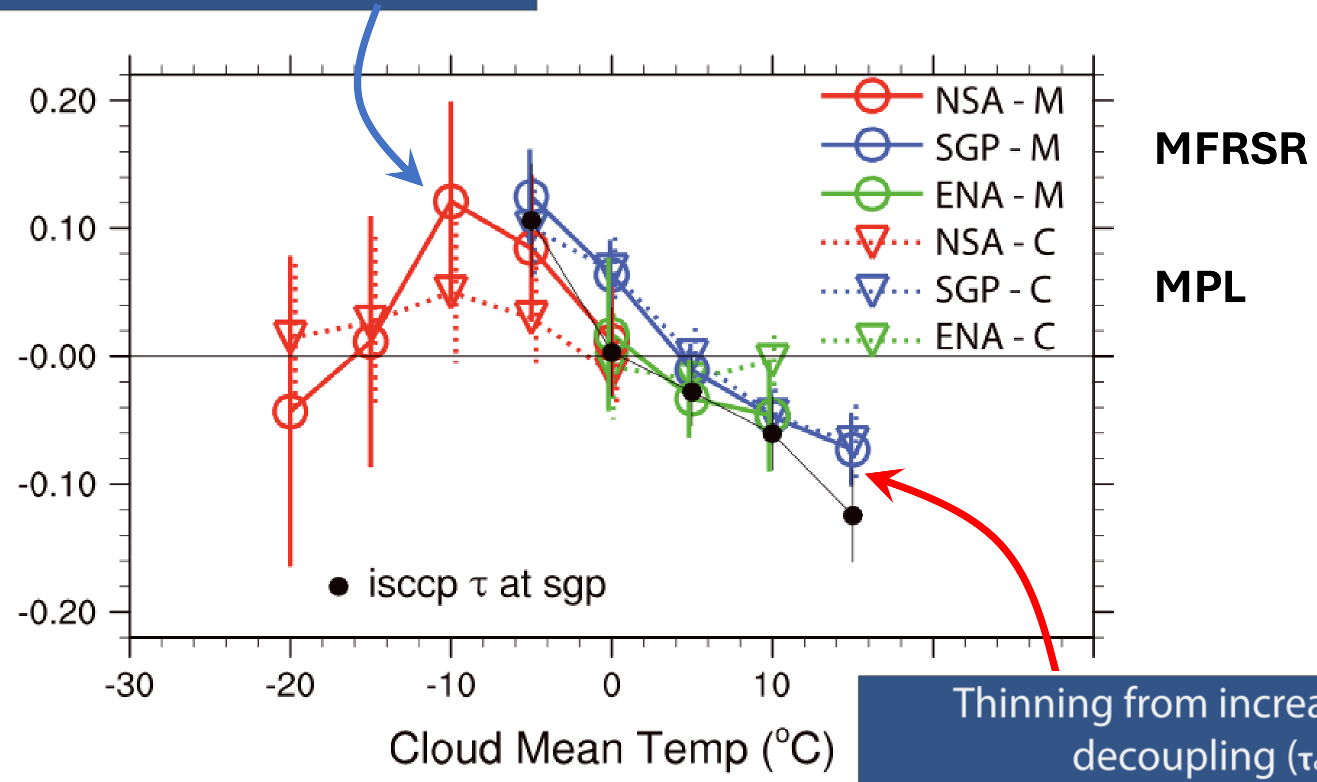
Varble, A. C., Ma, P.-L., Christensen, M. W., Mülmenstädt, J., Tang, S., & Fast, J. (2023). Evaluation of liquid cloud albedo susceptibility in E3SM using coupled eastern North Atlantic surface and satellite retrievals. *Atmos. Chem. Phys.*, **23**, 13523–13553.

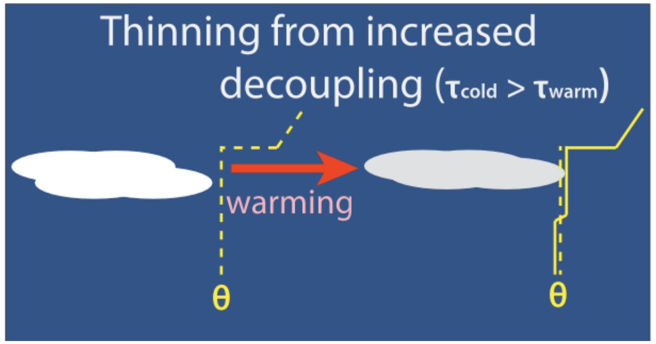
Zheng, X., Klein, S. A., Ma, H.-Y., Bogenschutz, P., Gettelman, A., & Larson, V. E. (2016). Assessment of marine boundary layer cloud simulations in the CAM with CLUBB and updated microphysics scheme based on ARM observations from the Azores. *J. Geophys. Res.*, **121**, 8472–8492.

Cloud Feedbacks



- Retrievals show that cloud optical depth decreases or stays constant with increases temperature for warm clouds but increases for cold clouds
- LWP path sensitivity to warmi explains the optical depth sensitivity at all sites.



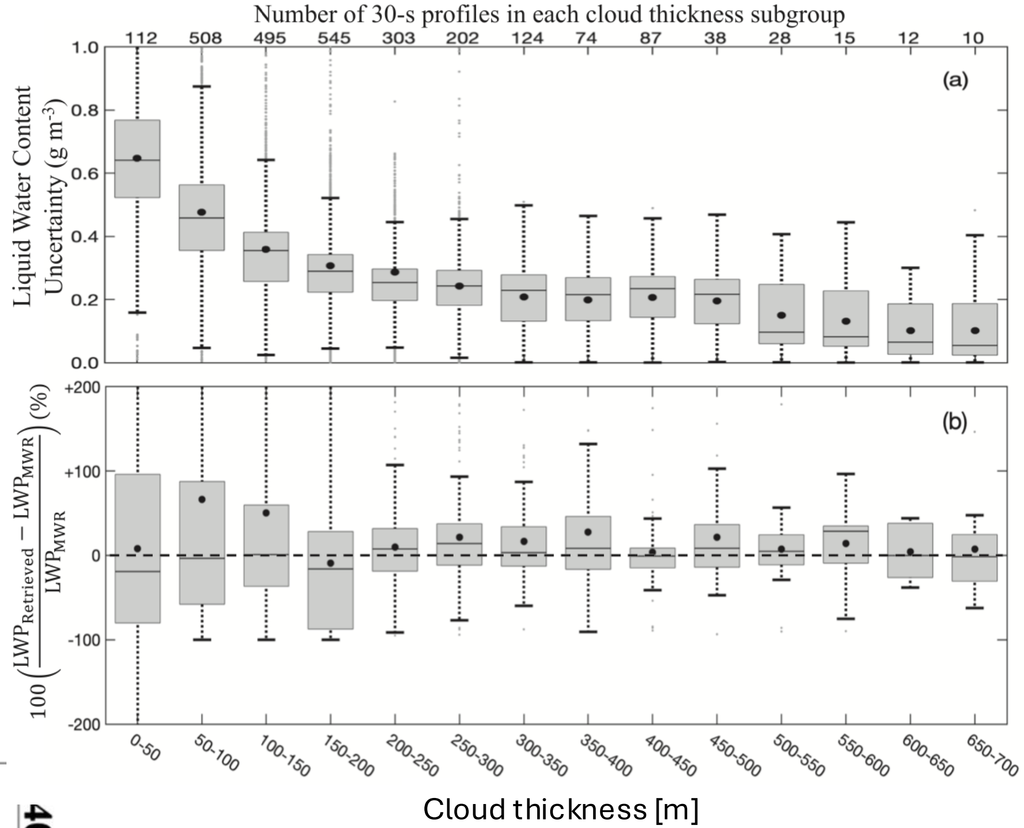


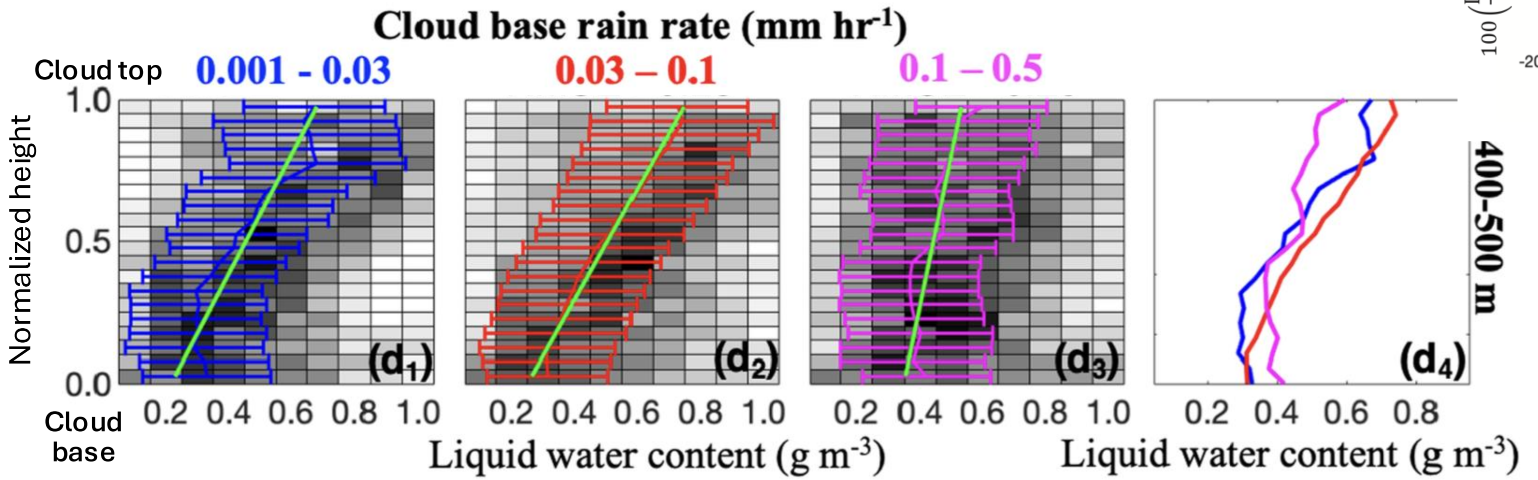
Terai, C. R., Zhang, Y., Klein, S. A., Zelinka, M. D., Chiu, J. C., & Min, Q. (2019). Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations. Journal of Geophysical Research: Atmospheres, 124(4), 2127–2147. https://doi.org/10.1029/2018JD029359

ENAbling Technology and Retrieval Development

DUAL FREQUENCY RADAR LIQUID WATER CONTENT PROFILES

- W band (94-GHz) and Ka band (35-GHz), beam matched (0.3°)
- Remove cloud profiles containing segments that have a 35 - 94 GHz difference in Doppler velocity at >0.1 m/s
- Uncertainty in LWC large for cloud thickness < 150 m but decreases to ~0.2 g m^{-3} for thicker clouds





Zhu, Z., Lamer, K., Kollias, P., & Clothiaux, E. E. (2019). The Vertical Structure of Liquid Water Content in Shallow Clouds as Retrieved From Dual-Wavelength Radar Observations. *J. Geophys. Res.*, **124**, 14184–14197.

Summary

- Data from the ENA Atmospheric Observatory (and attendant IOPs) has helped catalyze a decade of new scientific discoveries, particularly for marine boundary layer clouds, aerosols, and their interactions

- ENA investigators and the science resulting from the site has only been made possible because of the dedication of the ARM site managers (Heath Powers and Juarez Viegas) and infrastructure team, the site technicians (Silva. Bruno Cunha and Tercio Silva), numerous ARM mentors, developers, and translators for both the ENA site and the ARM Aerial Facility. Special thanks to Eduardo Azevedo at the University of the Azores.