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ASR Atmospheric System Research

Using ARM Data and Multiscale Models to Advance the Understanding of Liquid-Phase Cloud Response to Aerosol Perturbation over Ocean and Land

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Organization	Office of Biological and Environmental Research
Program Manager	Drs. Sally McFarlane, Shaima Nasiri and Jeff Stehr
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Budget Period	FY2023

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Scientific Objectives

This project aims to study the response of liquid-phase clouds to aerosol perturbation and reduce the related uncertainty in the DOE Earth system model. Specific objectives include:

Objective 1: Quantify the aerosol indirect effect on liquid-phase clouds using ARM observations and satellite retrievals while constraining the confounding large-scale conditions.

Objective 2: Harness LES case studies, untangle the confounding meteorological impacts on the observed aerosol indirect effect, and identify key cloud processes controlling the net radiative forcing of aerosol-cloud interactions at different spatiotemporal scales.

Objective 3: Evaluate the aerosol indirect effect on liquid-phase clouds with process-level understanding in E3SM multiscale model configurations.

Accomplishments

In this fiscal year, we studied marine warm boundary layer clouds, aerosols, and aerosol-cloud interaction (ACI) in the Eastern North Atlantic (ENA) region with ARM observations, geostationary satellite retrievals, and reanalysis data (Objective 1).

Diurnal variation of aerosol indirect effect

Using cloud droplet number concentration (N_d) as an intermediary variable, we investigated ACI in warm boundary layer clouds and its diurnal variation over the ENA region centered at the ARM ENA site with half-hourly and 3-km cloud property retrievals from SEVIRI on Meteosat-11 (Qiu *et al.*, submitted). Our results revealed a significant "U-shaped" daytime cycle in susceptibilities of cloud liquid water path (LWP), cloud albedo, and cloud fraction to changes in N_d. (black lines in Fig. 1). The backward tracking analyses found evidence that the diurnal cycle in LWP and albedo susceptibilities for non-precipitating clouds is influenced by a combination of the transition between non-precipitating thick and thin clouds and the "lagged" cloud responses to N_d perturbations. Furthermore, by decomposing the contribution to the diurnal cycle of cloud susceptibilities (blue lines vs. red lines in Fig. 1), our results imply that polar-orbiting satellites with overpass time at 1330LST might underestimate the daytime mean value of cloud susceptibility in the eastern North Atlantic, as they observe susceptibility daily minima. This study highlights the importance of considering the diurnal cycle of cloud susceptibilities when quantifying ACI and its impact on clouds and radiation.

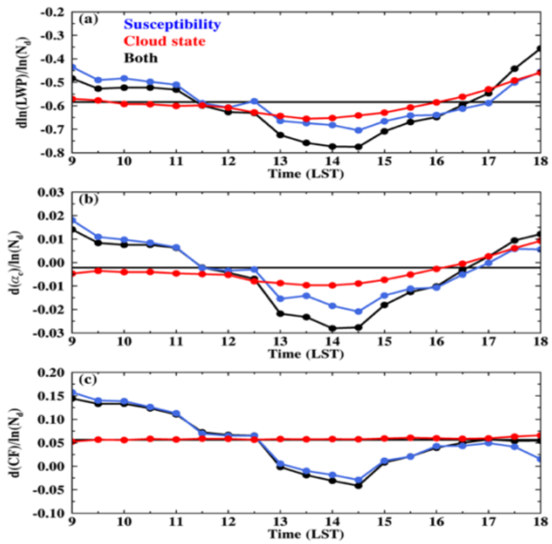

Figure 1. Daytime variation in cloud susceptibility contributed from the variability in the intensity of susceptibility (blue lines with symbols), variability in cloud state (red lines with symbols), and from both (black lines with symbols). (a) cloud LWP susceptibility, (b) cloud albedo susceptibility, (c) cloud fraction susceptibility. The black solid lines without symbols in (a)-(c) are the daytime mean susceptibility. (Qiu *et al., submitted*)

Deep Spatiotemporal Clustering (DSC) models

To simultaneously constrain multiple large-scale conditions through clustering, we developed DSC models with deep learning-based unsupervised clustering algorithms (Faruque et al., 2023). Inspired by the U-net architecture, DSC utilizes an autoencoder integrating Convolution Neural Network (CNN) and Long Short-Term Memory (LSTM) layers to learn latent representations of the spatiotemporal data. DSC also includes a unique layer for cluster assignment on latent representations that uses the student's *t*-distribution. Extensive experiments by Faruque *et al.* (2023) demonstrated the proposed approach outperforms both conventional and previous deep learning-based unsupervised clustering algorithms. Additionally, we created its various variants (CNN encoder, CNN autoencoder, CNN-LSTM encoder, CNN-LSTM autoencoder, etc.) to get insight into using both the CNN and LSTM layers in the autoencoder.

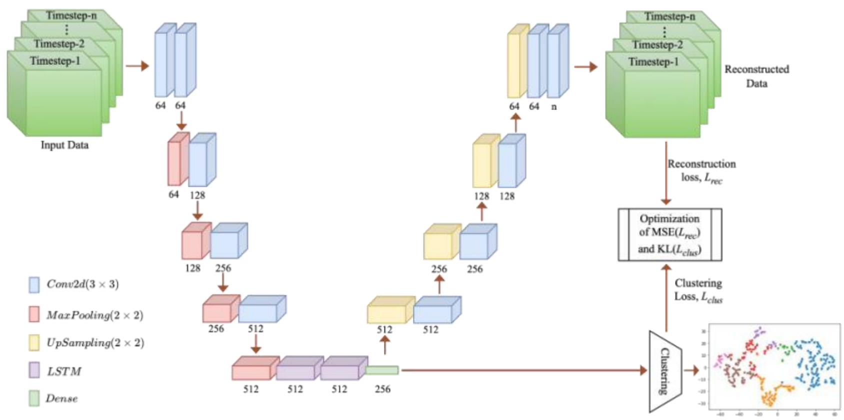

Figure 2. Illustration of the proposed deep spatiotemporal clustering model architecture. The number at the bottom of each block means the number of feature layers (Faruque et al., 2023).

Aerosol and warm marine boundary layer cloud variability in different synoptic regimes

During this fiscal year, we conducted an analysis using ARM ENA observations in conjunction with Meteosat-11 cloud retrievals around the ENA site for the period spanning June, July, and August (JJA) from 2016 to 2021. Through this analysis, we identified more than 120 days with available ARM cloud, PBL, and surface CCN measurements, representing typical ENA warm boundary layer cloud cases. Among these cases, 30 were classified as high surface CCN days (CCN at 0.2% > 300 cm^{-3}). Additionally, we further selected approximately 10 cases within four synoptic regimes for marine boundary layer clouds, which we plan to utilize for future LES simulations.

To investigate the influence of different synoptic conditions on aerosol and cloud variability over the ENA region, we utilized ERA5 daily 2D maps of multiple variables (500-hPa Geopotential height, Sea-level pressure, 10-m U, and 10-m V) for JJA from 2016 to 2021 as input data for the DSC model. This allowed us to classify the synoptic regimes (Fig. 3 top) that exhibited strong correlations with different cloud conditions (e.g., boundary layer cloud condition, Fig. 3 bottom). By characterizing and comparing aerosol and cloud variability using ARM ENA observations, aerosol reanalysis data, and satellite retrievals across different synoptic regimes, our analyses suggest that the differences in cloud macro and micro properties among these regimes are more significant than the changes observed in most aerosol properties (Zheng et al., *in prep.*).

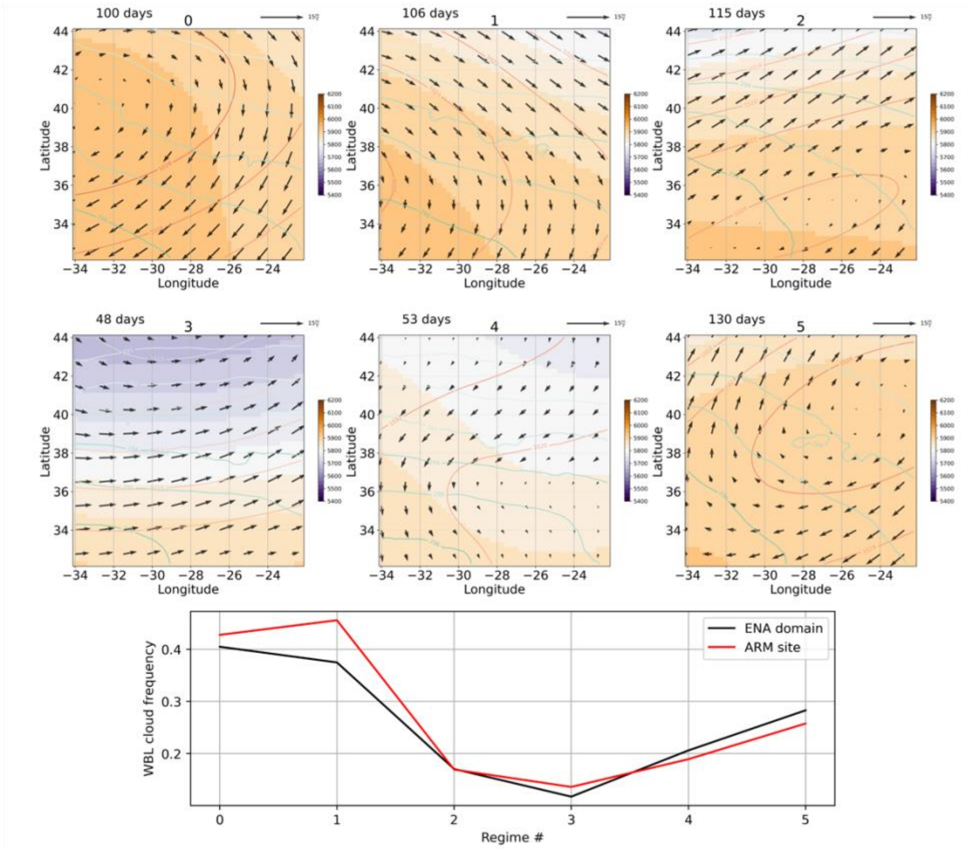

Figure 3. Composite large-scale conditions for six synoptic regimes over the ENA region for JJA from 2016 to 2021 based on the Deep Spatiotemporal Clustering model (top). The frequency of occurrence of warm boundary layer clouds from satellite retrievals over the whole ENA region (black line) and over the 1°x1° area centered at the ARM site (red line) for each synoptic regime for JJA, 2018-2021 (bottom).

Opportunities for training and professional development

This project funded a postdoctoral researcher, Dr. Shaoyue Qiu at LLNL and supported a Ph.D. graduate student, Omar Faruque, and a master's student, Rohan Salvi, at the Department of Information Systems, University of Maryland Baltimore County through a subcontract. Additionally, it also provided PI with opportunities for mentorship, co-advising graduate students, research collaboration, project management, and subcontract management.

Plan for Next Year

Firstly, we intend to complete the publication of the diurnal variation of aerosol indirect effect for ENA clouds work (Qiu *et al.*, submitted), as well as the work on ENA aerosol and warm marine boundary layer cloud variability in different synoptic regimes (Zheng *et al.*, in prep.). Once these papers are published, we will make all the related data analysis products available through NERSC Science Gateways.

Moving on to Objective 2, we plan to conduct the ENA case study using WRF nested domain LES simulations. These ENA simulations have already been built and initially tested on NERSC and LC. Additionally, in response to our collaboration with the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) project, we aim to conduct a California stratocumulus case study. This study will involve using EPCAPE observations and conducting LES simulations to investigate the Canonical stratocumulus cases that are directly affected by the local meteorology and continental sources of aerosols.

To facilitate the ENA and EPCAPE case studies, we have begun the process of recruiting a postdoctoral researcher with numerical modeling skills. The recruited postdoctoral researcher will work with the PI on the ENA and EPCAPE case studies in the coming year.

Publications

Faruque, O., F. N. Nji, M. Cham, R. M. Salvi, **X. Zheng**, J. Wang, 2023: Deep Spatiotemporal Clustering: A Temporal Clustering Approach for Multi-dimensional Climate Data, Machine Learning (cs.LG), eprint arXiv:2304.14541, https://doi.org/10.48550/arXiv.2304.14541

Qiu, S., **X. Zheng**, D. Painemal, C. R. Terai, and X. Zhou, 2023: Diurnal variation of aerosol indirect effect for warm marine boundary layer clouds in the eastern north Atlantic estimated from geostationary satellite retrievals, *Atmospheric Chemistry and Physics*, submitted.

Zheng, X., S. Qiu, O., Faruque, 2023: Variability of Eastern North Atlantic Aerosols and Warm Marine Boundary Layer Clouds Across Different Synoptic Regimes, *Journal of Geophysical Research: Atmospheres*, in preparation.

Intellectual property

Deep Spatiotemporal Clustering (DSC) models: These models are based on deep learning-based unsupervised clustering algorithms and include statistical evaluation metrics to measure the performance of the clustering results.

Python Notebook package: This package is capable of generating daily composite meteorological conditions, regional cloud and aerosol properties, and ARM cloud and aerosol properties for given synoptic regimes and observational data set.

Data analysis products

ARM data analysis: identified typical ENA warm boundary layer cloud days with available ARM cloud and surface CCN measurements in different synoptic regimes.

Satellite retrieval analysis: refined cloud properties and cloud susceptibility data set for warm boundary layer cloud only cloud objectives over the ENA region for JJA from 2018 to 2021. To minimize the retrieval uncertainties and focus on ACI in marine boundary layer clouds, this daytime dataset excludes cloud edges and low clouds that are embedded in deeper cloud layers.

Conference Presentations

Zheng, X., Observational Study of Warm Cloud Response to Aerosol Perturbation over the Northeastern Atlantic Ocean, AMS Annual Meeting (Oral presentation), Jan. 2023.

Qiu, S., et al., Aerosol indirect effect on summertime boundary-layer clouds in the northeastern Atlantic (Poster presentation), AGU Fall Meeting, Dec. 2022.

Zheng, X., ENA Warm Boundary Layer Clouds from ARM Observations and Geostationary Satellite Cloud Retrievals (Oral presentation), Joint ARM User Facility and ASR PI Meeting, Oct. 2022.

Qiu, S., et al., Aerosol indirect effect in northeastern Atlantic estimated from satellite cloud retrievals and ARM ground-based observations (Poster presentation), Joint ARM User Facility and ASR PI Meeting, Oct. 2022

Participants

- PI Xue Zheng contributed ~0.4 FTE to this project. In addition to project management and subcontract management, Xue Zheng provided mentorship to the postdoc and co-advised graduate students. Xue Zheng also evaluated the DSC model in comparison with other clustering models and conducted an observational study on summertime aerosol and warm marine boundary layer cloud variability in different synoptic regimes in the ENA region.
- Dr. Shaoyue Qiu, the postdoctoral researcher, dedicated full-time work to the project during the past fiscal year. Shaoyue Qiu completed and submitted a research paper that focused on the diurnal cloud variability and the susceptibility of clouds to changes in cloud droplet number concentrations over the ENA region using geostationary satellite retrievals. Additionally, she was responsible for collecting, preprocessing ARM observational data, and identifying warm boundary layer cloud days over the ENA region.

There was no international collaboration and travel during this reporting period.

Collaborations

- Collaboration with Dr. Xiquan Dong from the University of Arizona and Dr. Virendra Ghate from Argonne National Laboratory for ENA aerosol, cloud, precipitation and PBL properties derived from ARM ground-based measurements.
- Collaboration with Dr. David Painemal from NASA Langley Research Center for satellite retrieval analyses.
- Communication Dr. Lynn Russell from University of California, San Diego: Discussions were initiated with Dr. Lynn Russell regarding EPCAPE case studies. PI Xue Zheng has an invited talk to the EPCAPE breakout session in the upcoming ARM/ASR PI meeting in August 2023. The talk will likely be proposing new modeling work with EPCAPE cases.

Carryover amount

The carryover from FY2022 into FY2023 was $644K. FY2023 funding is $500K. The estimated carryover at the end of FY2023 should be ~$680K.