Simulating Low Cloud Evolution by Building a Comprehensive Library of Observed Lagrangian Trajectories

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1. Background

Challenges:

- Significant **uncertainties** exist in regional and global modeling of **marine low clouds** over the eastern subtropical oceans because those models do not resolve many of the **complex physical processes** including aerosol-cloud interactions.
- The evolution of these clouds and their response to aerosols are **sensitive** to ambient **environmental conditions**.

Objectives:

- Creating a **comprehensive library** of Lagrangian observations in order to represent **a full range** of environmental conditions common in marine low cloud regions.
- Developing a methodology **to routinely initialize and force detailed LES with satellite and reanalysis data**, rather than in-situ measurements, which are rare over remote oceans.

2. Methodology

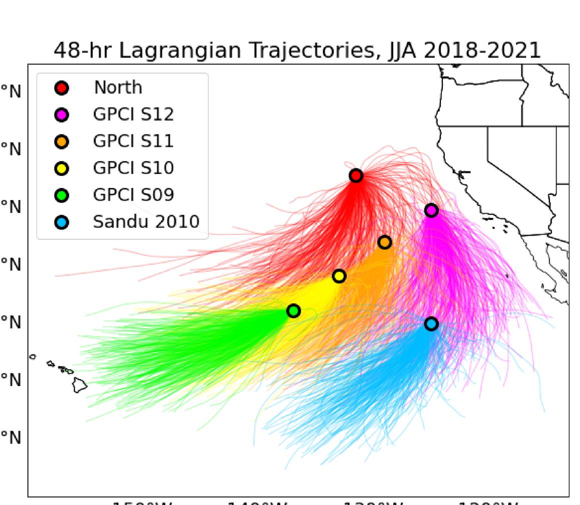
Data

- **Cloud-controlling factors (CCFs):** ***extracted from ECMWF ERA5 reanalysis data.*** sea-surface temperature (SST), Estimated inversion strength (EIS), surface wind speed (WS), free-tropospheric (FT) moisture (q), FT subsidence (ω), mean sea level pressure (P_{MSL}), and inversion height (Z_{inv}).
- **Cloud and radiation variables:** ***extracted from various satellite observations.*** low cloud fraction (CF), liquid water path (LWP), cloud-top height (CTH), precipitation, cloud droplet number concentration (N_d), and effective radius (r_e).
- **Aerosol variables:** marine boundary layer (MBL)-averaged accumulation-mode **aerosol number concentration (<N_a>)** calculated from NASA MERRA2 **masses of aerosol species** and their assumed **particle size distributions** (Erfani et al., 2022).

Dataset	ERA5 (meteorology)	MERRA2 (aerosol)	CERES SYN L3 (cloud)	SSMI V08 L3	AMSR-2 V08 L3	AMSR-2 V08 L3	MODIS
Important Variables	WS, P, T, q, ω, EIS, SST, Z_{inv}, w_e, CF, LWP	N_a	CF, LWP, CTH, N_d, r_e, τ_c, OLR, CRE	LWP	LWP	rain rate	CTH
Reference	Hersbach et al. (2020)	Gelaro et al. (2017)	Doelling et al. (2016)	Wentz et al. (2012)	Kawanishi et al. (2003)	Eastman et al. (2019)	Eastman et al. (2017)
Temporal Resolution	Hourly	3-hourly	Hourly	Two times per day	Two times per day	Two times per day	01:30 LT 13:30 LT
Spatial Resolution	0.25×0.25°	0.5×0.625°	1×1°	0.25×0.25°	0.25×0.25°	0.25×0.25°	1×1°

Trajectories

- A few locations in the **stratocumulus deck** region of the Northeast Pacific during JJA 2018-2021 were selected to **fill out a phase space** of CCFs and cloud variables.
- UW trajectory codes were employed to generate **2208 Lagrangian** isobaric (950 hPa) forward **trajectories** for 82 hours, **incorporating** meteorological, cloud, and aerosol **variables** obtained from reanalysis and satellite data.



Excluded are the 4% of the trajectories that pass close to the coast or over land.

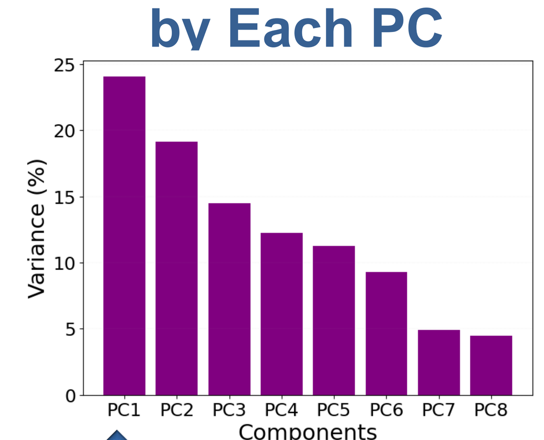
PCA

- **Principal Component Analysis** (PCA) was applied to **reduce** the **dimensionality** and to select a reduced set of **principal components (PCs).**
- We included all 6 initial locations and all days in JJA 2018-2021, **excluding** trajectories with clouds that have a **large ice content** (a total of **1663** trajectories were used).

Standardization $V_{standardized} = (V - \bar{V})/\sigma_V$; $\bar{V}$: time-mean V; σ_V: standard deviation of V → **PCA**

3. PCA and Phase Space

Percentage of Variance Explained by Each PC

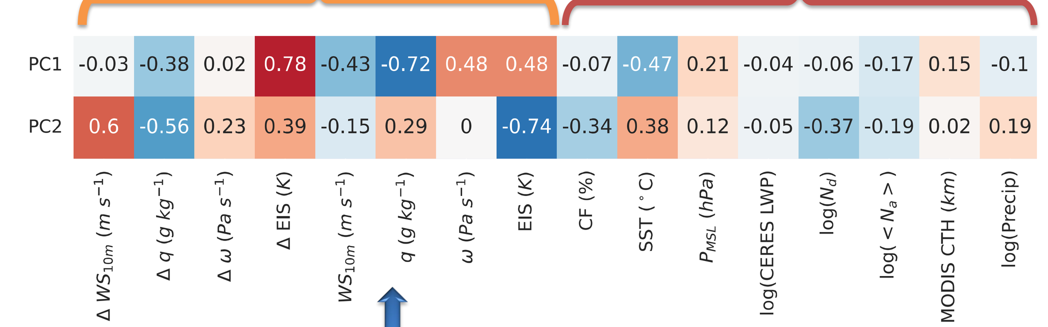


- We conducted **one PCA** based on 8 variables (**differences** between beginning and end of the trajectory, and along-trajectory **means** for CCFs: **EIS**, q, ω, and **WS**).
- **43%** of the information is compressed into **PC1** and **PC2**.

Relationships Between PCs and Variables

PCA inputs: 8 variables (**differences** between beginning and end of trajectory, and along-trajectory **means** for CCFs: **WS**, q, ω, and **EIS**)

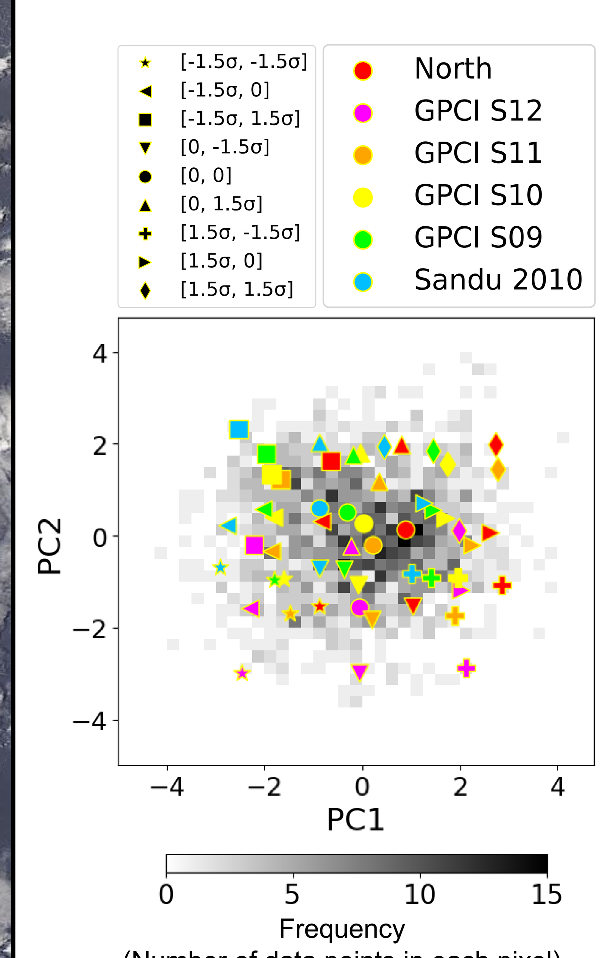
2 CCFs (**SST** and P_{MSL}) and **cloud** variables are **excluded** from PCA.

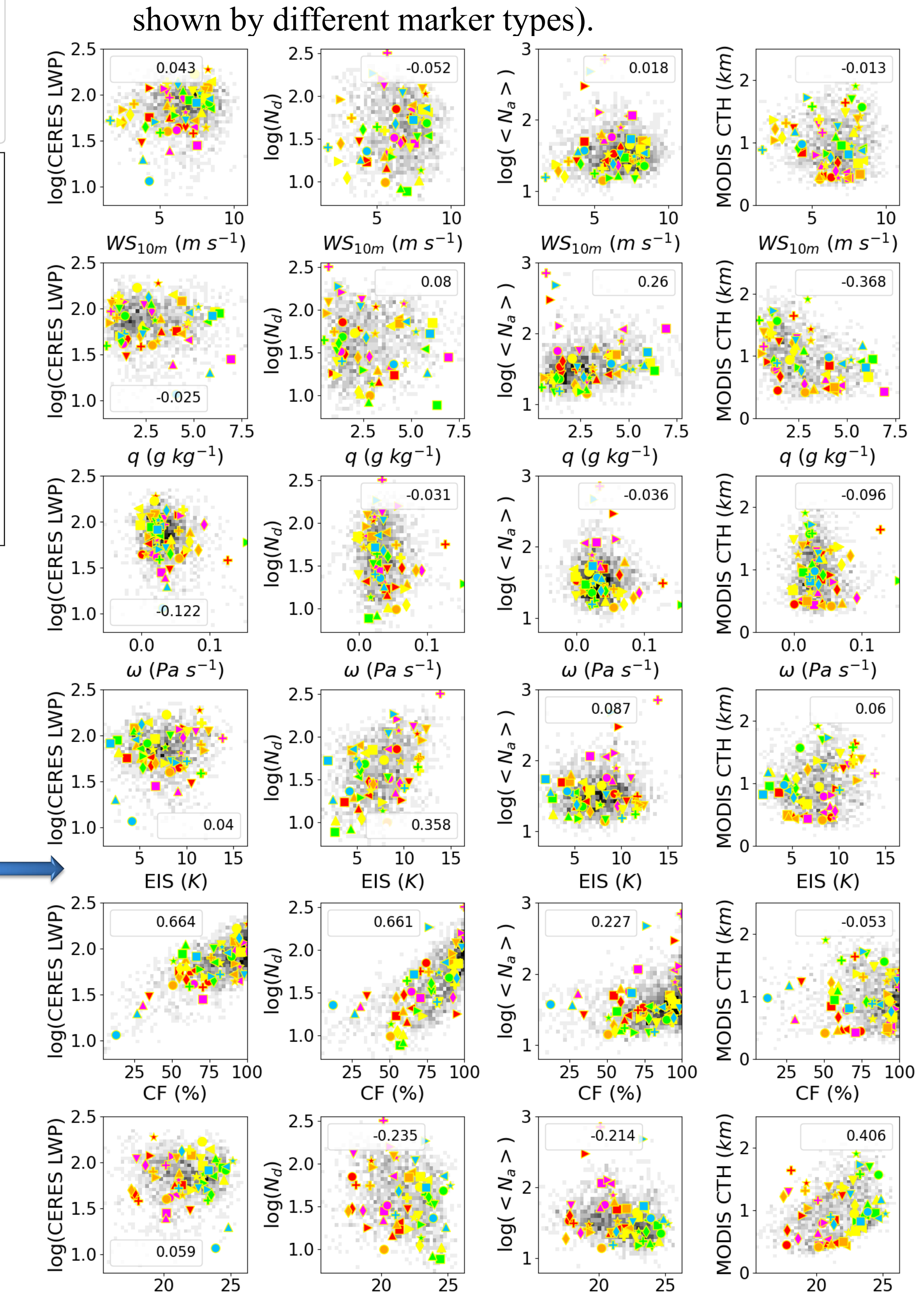


- The **Correlations (R-values)** between PCs and all variables
- **ΔEIS** and mean q contribute the most to PC1 and mean **EIS** and **ΔWS** contribute the most to PC2.
- Here, an absolute **R-value of 0.14** or higher is statistically significant since it leads to a p-value smaller than 0.05 for non-directional conditions.

Phase Space

For each initial location, 9 points are selected to represent **(-1.5σ, 0, 1.5σ)** in PC1-PC2 space (points shown by different marker types).





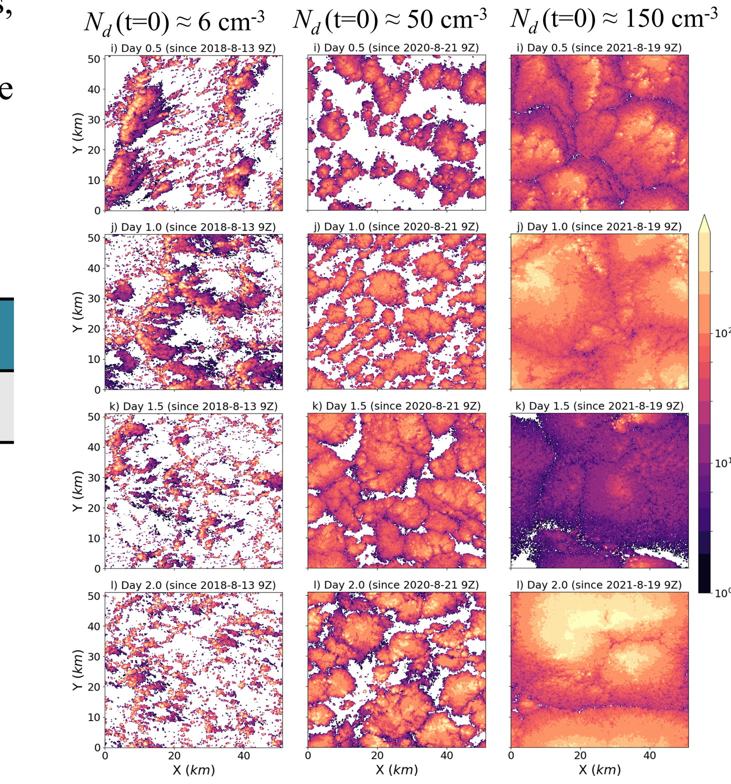
- Each marker shows a variable **averaged** along a trajectory.
- The **correlation** for each pair of variables is provided in the text box.
- The 54 selected data points in PC1-PC2 space (colorful markers) **successfully represent the observed spectrum** of CCFs and cloud variables (Erfani et al., 2024; EGUsphere).

4. Large-Eddy Simulations

- System for Atmospheric Modeling (**SAM**)
- **Coupled** to Berner aerosol scheme: calculates **MBL aerosol tendencies** due to accretion, autoconversion, interstitial scavenging, surface sources, sedimentation, and entrainment from the FT.
- LES is forced by **meteorological** and **aerosol** variables compiled along the trajectory.
- Here, such simulations along **15 sample trajectories** are analyzed.

Cloud Morphology for 3 Select Runs

1. Clean N_d(t=0) ≈ 6 cm^{-3} **2. Moderate** N_d(t=0) ≈ 50 cm^{-3} **3. Polluted** N_d(t=0) ≈ 150 cm^{-3}



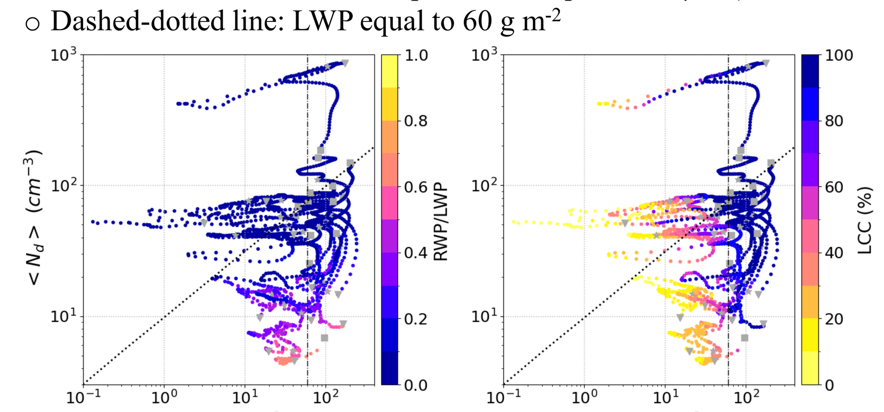
Experiments:

# of cases	Initial MBL N_a	FT N_a	Run Time	Horizontal resolution	Domain size	Vertical level #
15	CERES-corrected MERRA2	MERRA2	48 hrs.	100×100 m	51.2×51.2 km	260

Evolution of 15 Runs in LWP–N_d State Space:

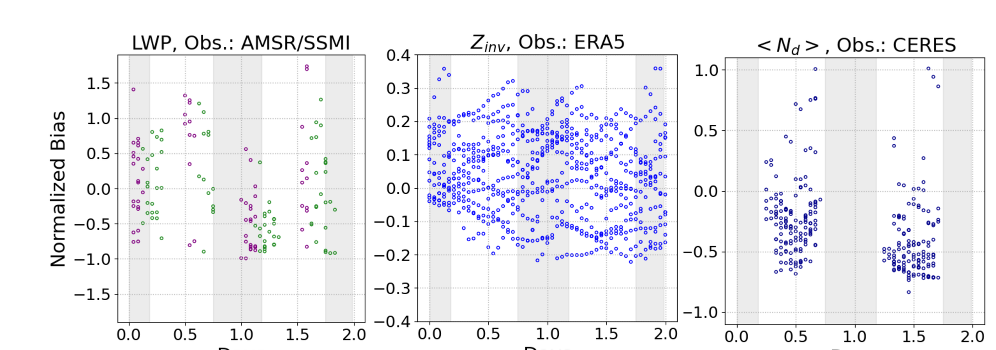
- Theoretically, the **precipitation** onset is quantified by **critical radius** ≈ 12 μm (Glassmeier et al., 2019). For r > 12 μm, cases show either initially-low N_d or a rapid decrease in N_d (bottom right part of left panel).
- Almost all instance of **cloud breakup** (e.g., LCC < 50%) occurs when **LWP** is smaller than 60 g m^{-2} (right panel).

○ Gray symbols: start (square), middle (star), and end (triangle) of simulations.
○ The shades on small markers show RWP/LWP (left), and LCC (right).
○ Dotted line: volume-mean droplet radius equal to 12 μm (critical radius)
○ Dashed-dotted line: LWP equal to 60 g m^{-2}



Evolution of Errors for 15 runs:

Normalized bias = (LES – "Obs.")/"Obs."



5. Conclusions

- More than **2200 Lagrangian trajectories** are developed, and then meteorological, cloud, and aerosol variables from **reanalysis** and **satellite** data **are compiled** along each trajectory.
- Employing **PCA reduces the dimensionality** of the data needed to cover cloud field variability. PCA is useful in **efficiently selecting LES cases** that encompass the observed CCF phase space.
- Based on the PCA and phase space analysis, we identify more than **50 distinct cases representing a diverse array of environmental conditions**. These cases are used to **initiate 2-day detailed, high-resolution, large-domain LES** experiments.
- We employ **SAM**, which is coupled with a **prognostic aerosol scheme** that accounts for **aerosol budget tendencies** such as coalescence and interstitial scavenging, surface sources, and entrainment from the free troposphere.
- LES results for some cases demonstrate SAM's capability to **simulate observed conditions** and show the **sensitivity** of simulated cloud properties to **variations in environmental conditions**.
- The final LES simulations will enhance our understanding of **aerosol-cloud interactions** under a **spectrum of representative conditions**.

Acknowledgment

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