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Building a comprehensive library of cloud-resolving simulations to study MCB across a spectrum of environmental conditions

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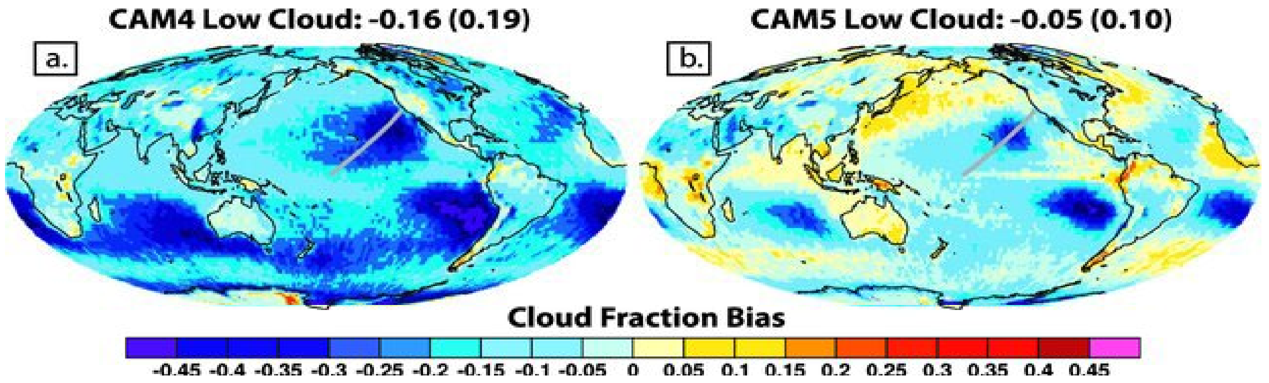
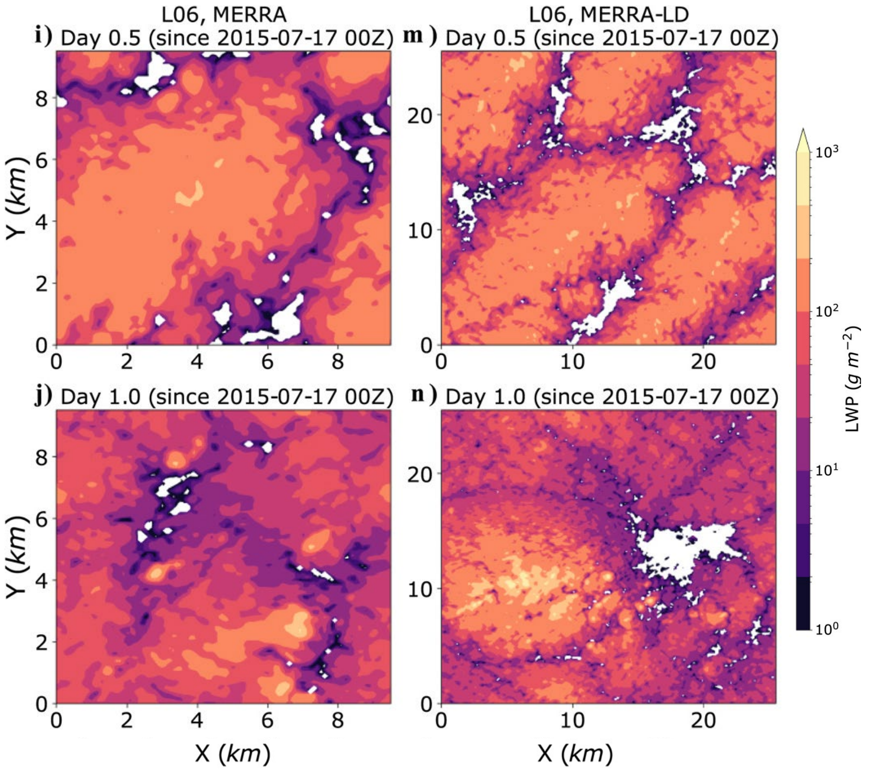
Introduction

- Weather and climate models **underestimate low marine clouds** over the eastern subtropical oceans because of the complex set of under-resolved physical mechanisms.

- **Large-eddy simulation (LES)** is a useful tool for studying low marine clouds due to its ability to represent turbulence, aerosol and cloud processes in the marine boundary layer (MBL) (Erfani et al., 2022).



Kay et al. (2012)

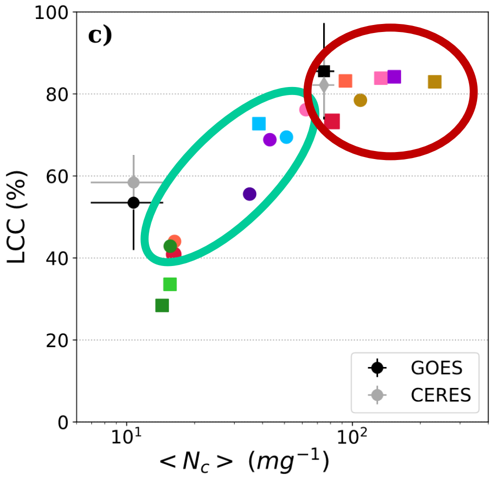


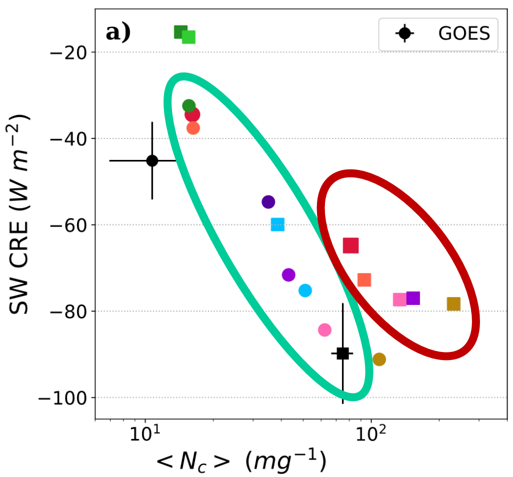
Erfani et al. (2022)

Introduction

- Previously, we used cloud, aerosol, and meteorological aircraft measurements from CSET field campaign to initialize LES for two trajectories:
  - **Case 1: Clean and precipitating**
  - **Case 2: Polluted and non-precipitating**
- These clouds' evolution and their response to aerosols are **sensitive to ambient environmental conditions** (Erfani et al., 2022).

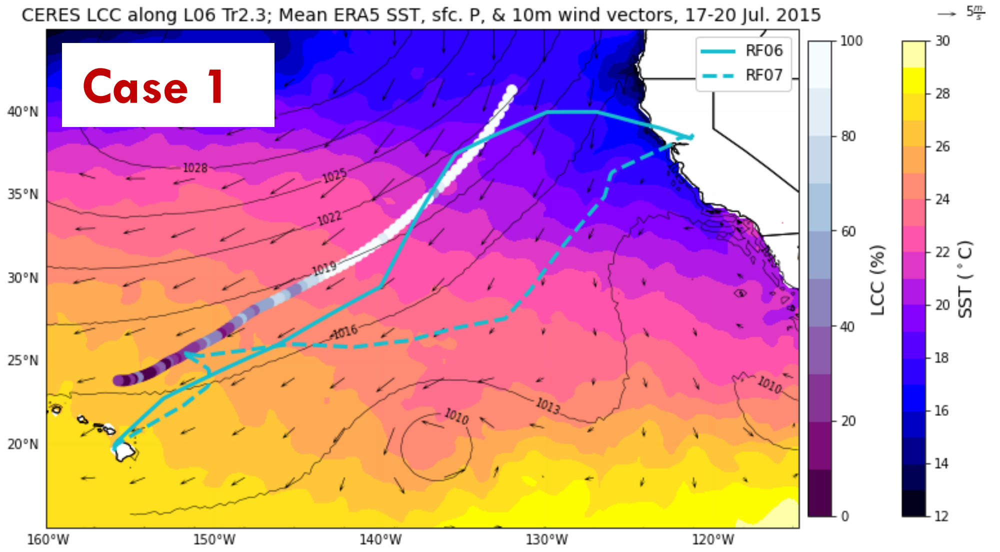
Low cloud cover

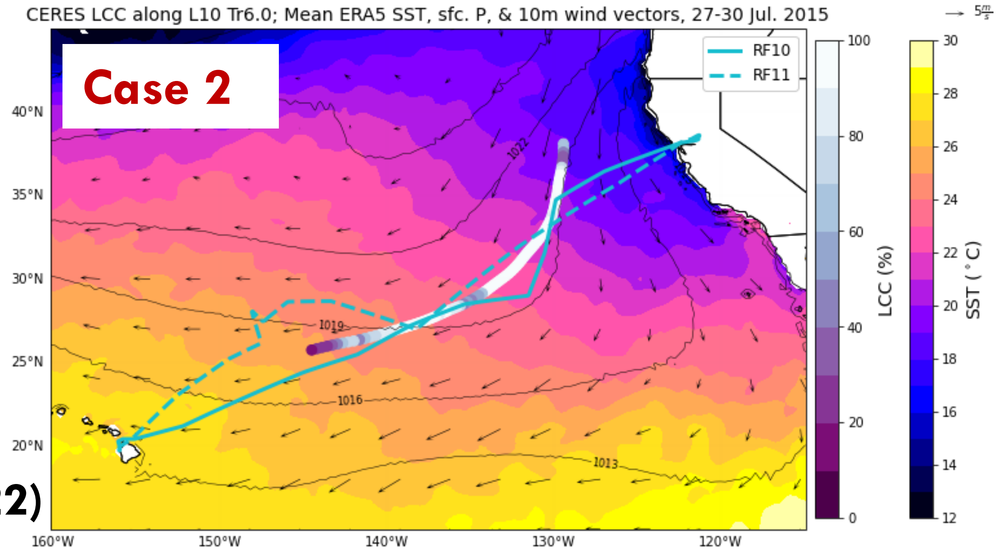




Cloud radiative effect

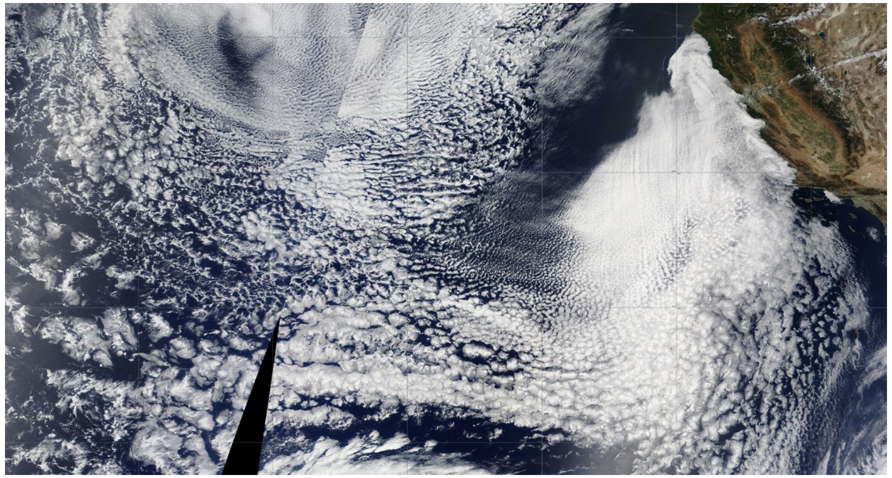
Erfani et al. (2022)

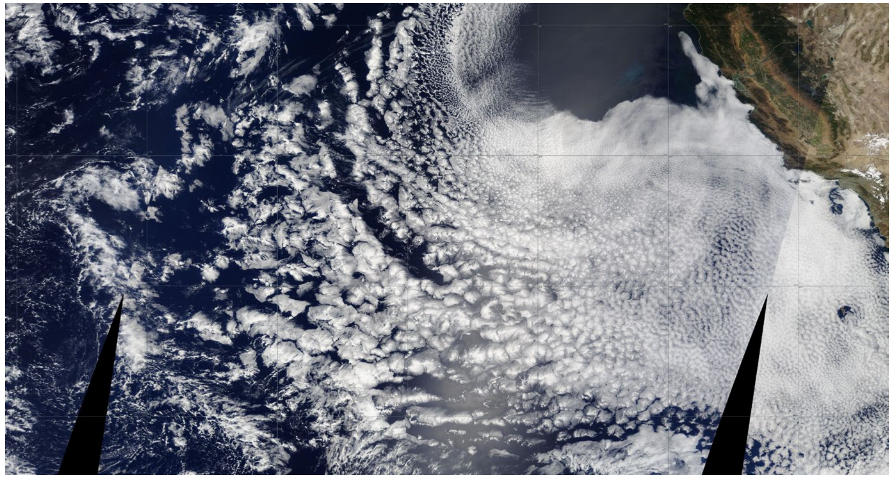




Goals

- Creating **a comprehensive library** of Lagrangian observations in order to represent **a full spectrum of environmental conditions** common in low marine cloud regions, where MCB would be most efficient.
- Developing a methodology **to routinely initialize and force realistic LES with satellite and reanalysis data**, rather than occasional aircraft measurements.
  - LES runs with normal and perturbed aerosols to represent MCB





Data

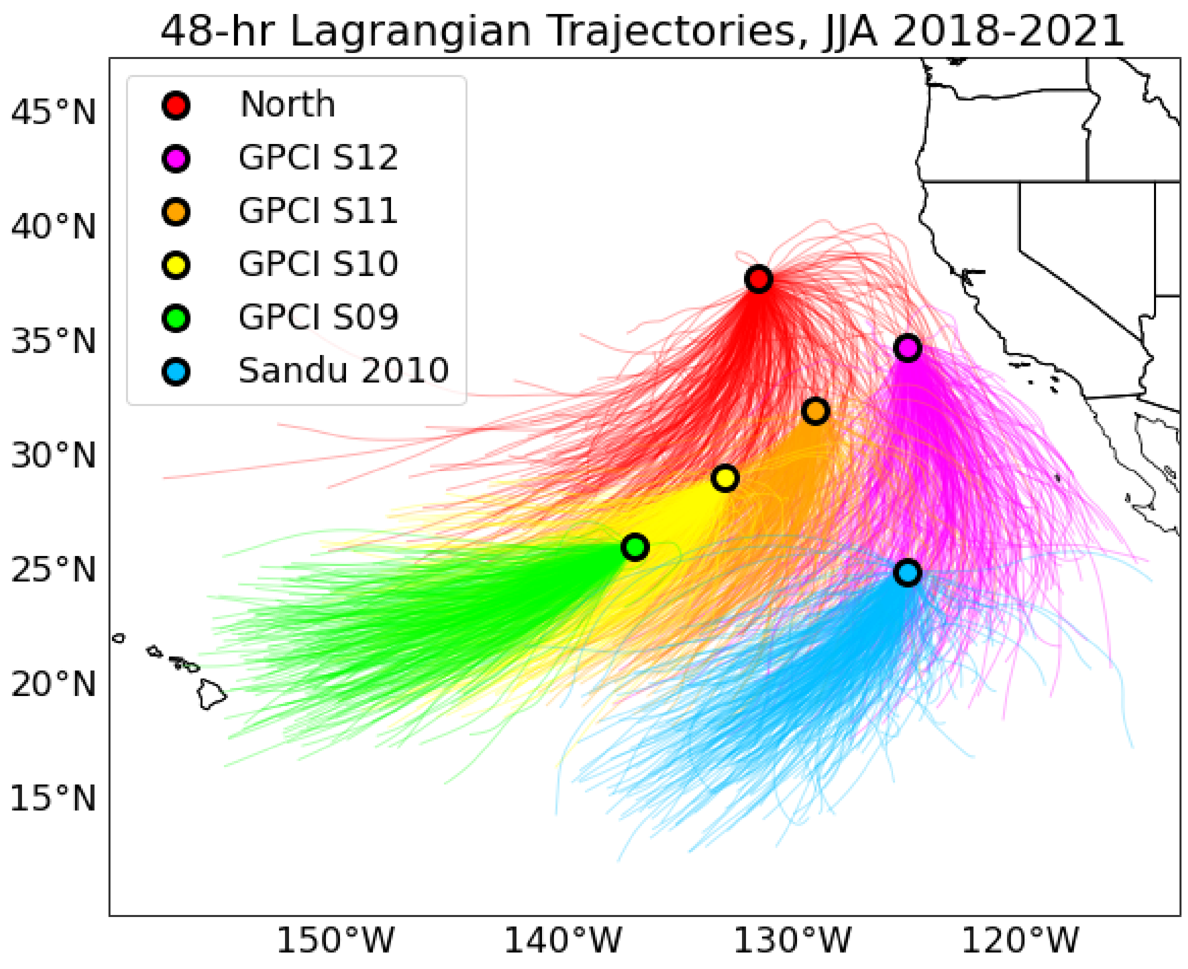
- **Cloud-controlling variables (CCVs):** ***extracted from ECMWF ERA5 reanalysis data.***
  sea-surface temperature (SST), Estimated inversion strength (EIS), surface wind speed (WS), free-tropospheric (FT) moisture (q), FT subsidence (ω), and mean sea level pressure (P_{MSL})
- **Cloud variables:** ***extracted from various satellite observations.***
  low cloud fraction (CF), liquid water path (LWP), cloud-top height (CTH), precipitation, and cloud droplet number concentration (N_d)
- **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 (surface & pressure levels)	MERRA2 M2I3NVAER (aerosol variables)	CERES SYN L3 (cloud variables)	SSMI V08 L3 (LWP)	AMSR-2 V08 L3 (LWP)	AMSR-2 V08 L3 (rain rate)	MODIS (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	01:30 LT 13:30 LT	01:30 LT 13:30 LT	01:30 LT 13:30 LT	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°	from 5×3 to 62×35 km	1 km at nadir

Trajectories

- A few locations in the **stratocumulus (Sc) deck region** of the Northeast Pacific during JJA 2018-2021 are selected to **fill out a phase space of CCVs 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.



We exclude 3% of trajectories that pass close to the coast or over land.

Principal Component Analysis (PCA)

Using **PCA** to reduce the **dimensionality** & to select a reduced set of **principal components (PCs)**.

Removing seasonality → **Standardization** → **PCA**

$$V'_n = V_n - \langle V_{(n-15:n+15)} \rangle$$

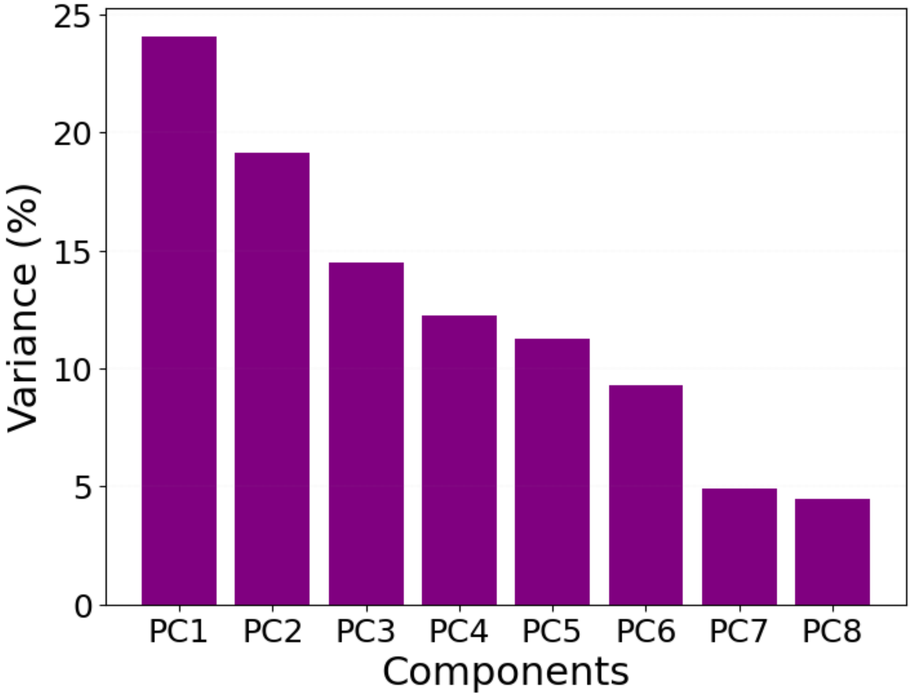
n: n-th day since June 1st
V_n: V for day n of a year
$\langle V_{...} \rangle$: time-mean V for days n-15 to n+15 of 2018-2021

$$V_{standardized} = \frac{(V - \bar{V})}{\sigma_V}$$

$\bar{V}$: time-mean V
σ_V: standard deviation of V

- We conducted **one PCA based on 8 variables** (along-trajectory **means**, & **differences** between beginning & end of the trajectory for CCVs: **EIS, *q* , *ω*,** & **WS.**
- Included all 6 initial locations and all days in JJA 2018-2021 excluding trajectories with ice clouds that have a large ice content (a total of 1663 trajectories were used).
- **43% of the information** is compressed into PC1 and PC2.

Percentage of variance explained by each PC



Relationships between PCs and variables

- Δ **EIS** contributes the most to PC1 and mean **EIS** contributes the most to PC2.
- Here, an **R-value of 0.1** or higher is statistically significant since it leads to a p-value smaller than 0.05 for non-directional conditions.

PCA inputs: 8 variables (along-trajectory **means**, & **differences** between beginning & end of the trajectory for CCVs: **WS, q, ω,** & **EIS**

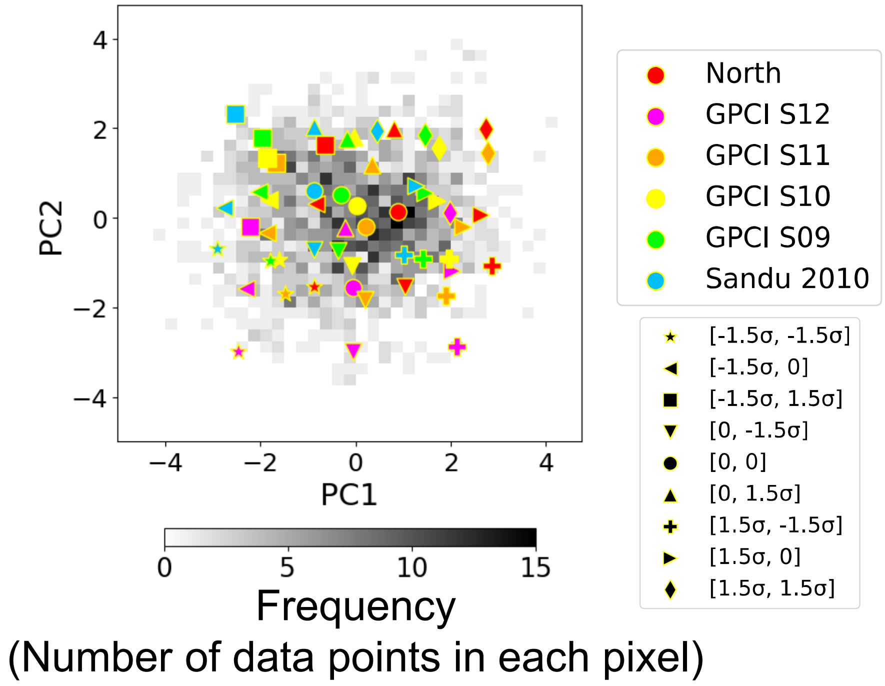
2 CCVs (SST and P_{MSL}) and cloud variables are excluded from PCA.

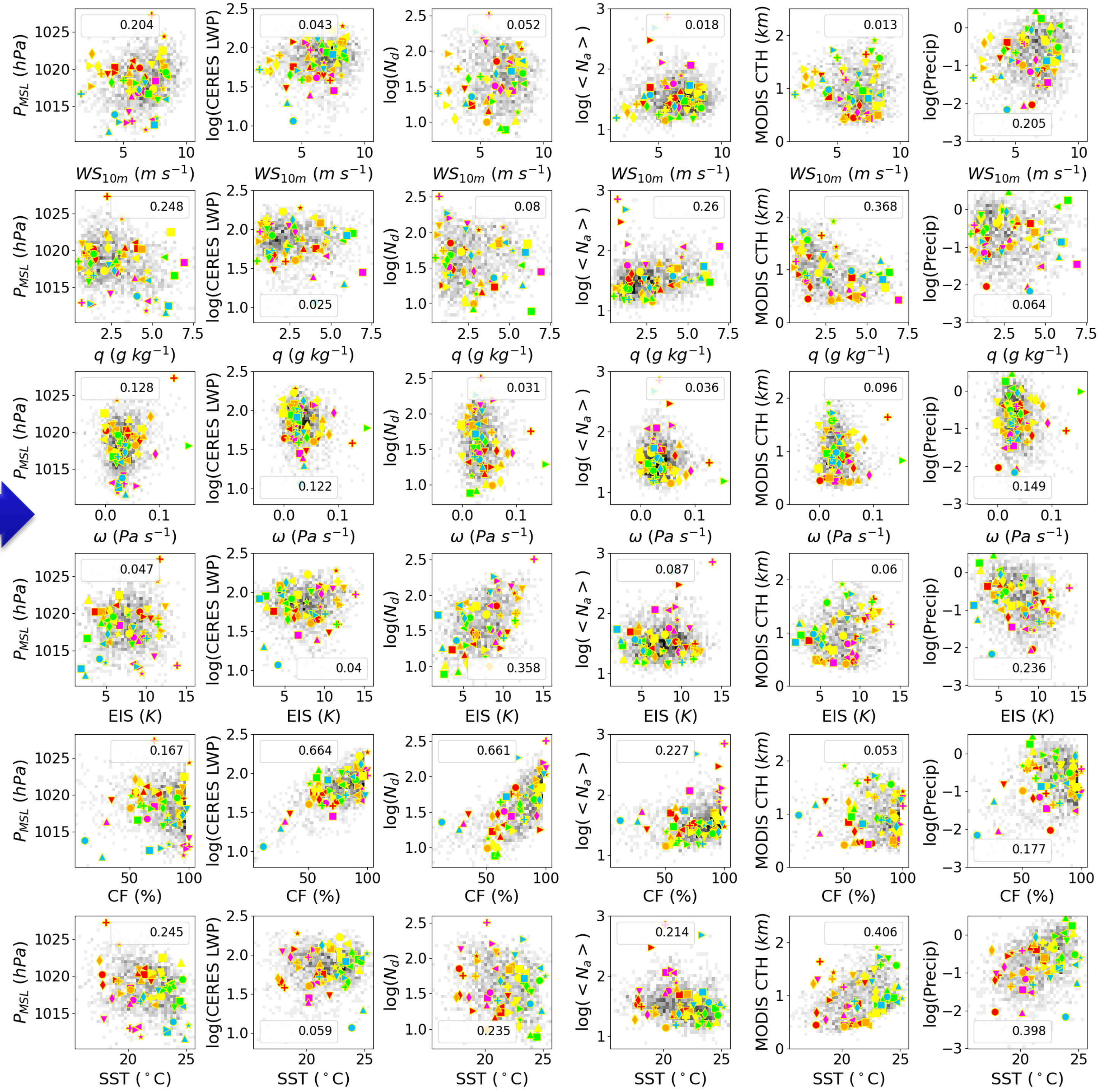
Relationships between PCs and all variables

	ΔWS_{10m} ($m\ s^{-1}$)	Δq ($g\ kg^{-1}$)	$\Delta \omega$ ($Pa\ s^{-1}$)	Δ EIS (K)	WS_{10m} ($m\ s^{-1}$)	q ($g\ kg^{-1}$)	ω ($Pa\ s^{-1}$)	EIS (K)	CF (%)	SST ($^\circ C$)	P_{MSL} (hPa)	log(CERES LWP)	log(N_d)	log($<N_a>$)	MODIS CTH (km)	log(Precip)
PC1	-0.03	-0.38	0.02	0.78	-0.43	-0.72	0.48	0.48	-0.07	-0.47	0.21	-0.04	-0.06	-0.17	0.15	-0.1
PC2	0.6	-0.56	0.23	0.39	-0.15	0.29	0	-0.74	-0.34	0.38	0.12	-0.05	-0.37	-0.19	0.02	0.19

Phase Space

- For each initial location, 9 points are selected to represent **(-1.5σ, 0, 1.5σ)** in PC1-PC2 space *(bottom left)*.
- The 54 selected data points in PC1-PC2 space **successfully represent observed spectrum** of CCVs & cloud variables.

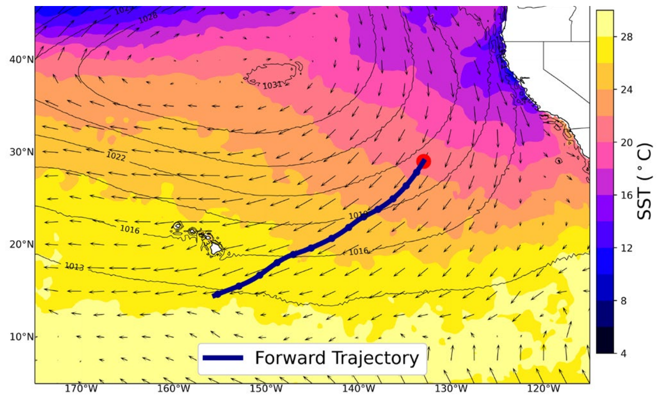




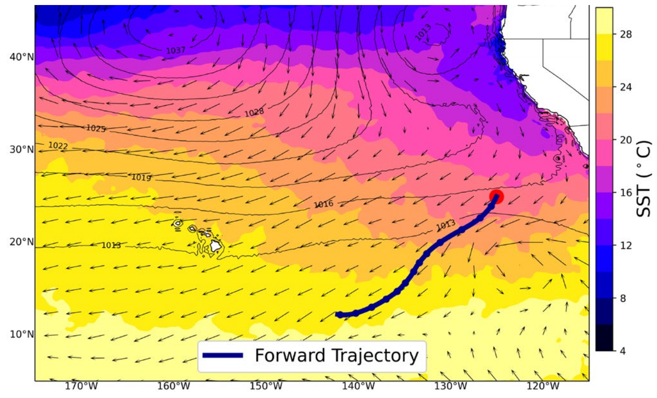
Large-Eddy Simulations (LES)

- 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 two sample trajectories** are shown, including additional runs with perturbed initial MBL aerosols.

Trajectory start: **GPCI S10, 2018-07-31**



Trajectory start: **Sandu2010, 2018-07-04**



Experiments (for each trajectory):

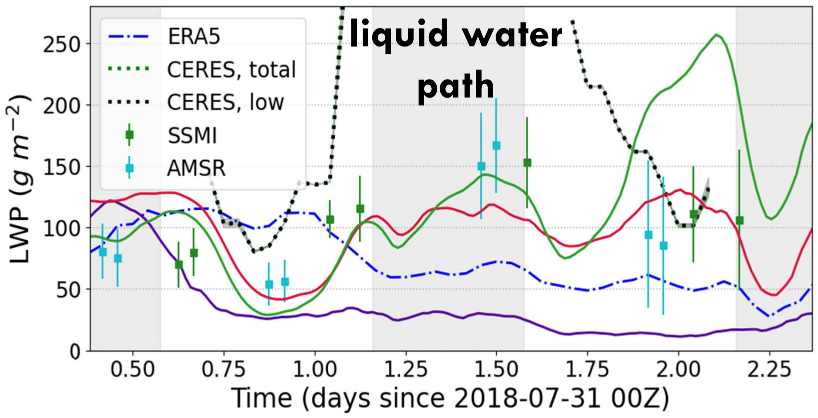
Run Name	Initial MBL N_a	FT N_a	Run Time	Horizontal resolution	Domain size	Vertical level #
ctrl	MERRA	MERRA	48 hrs.	100×100m	50×50km	260
N_a×3*	MERRA×3	MERRA	48 hrs.	100×100m	50×50km	260
N_a×9	MERRA×9	MERRA	48 hrs.	100×100m	50×50km	260

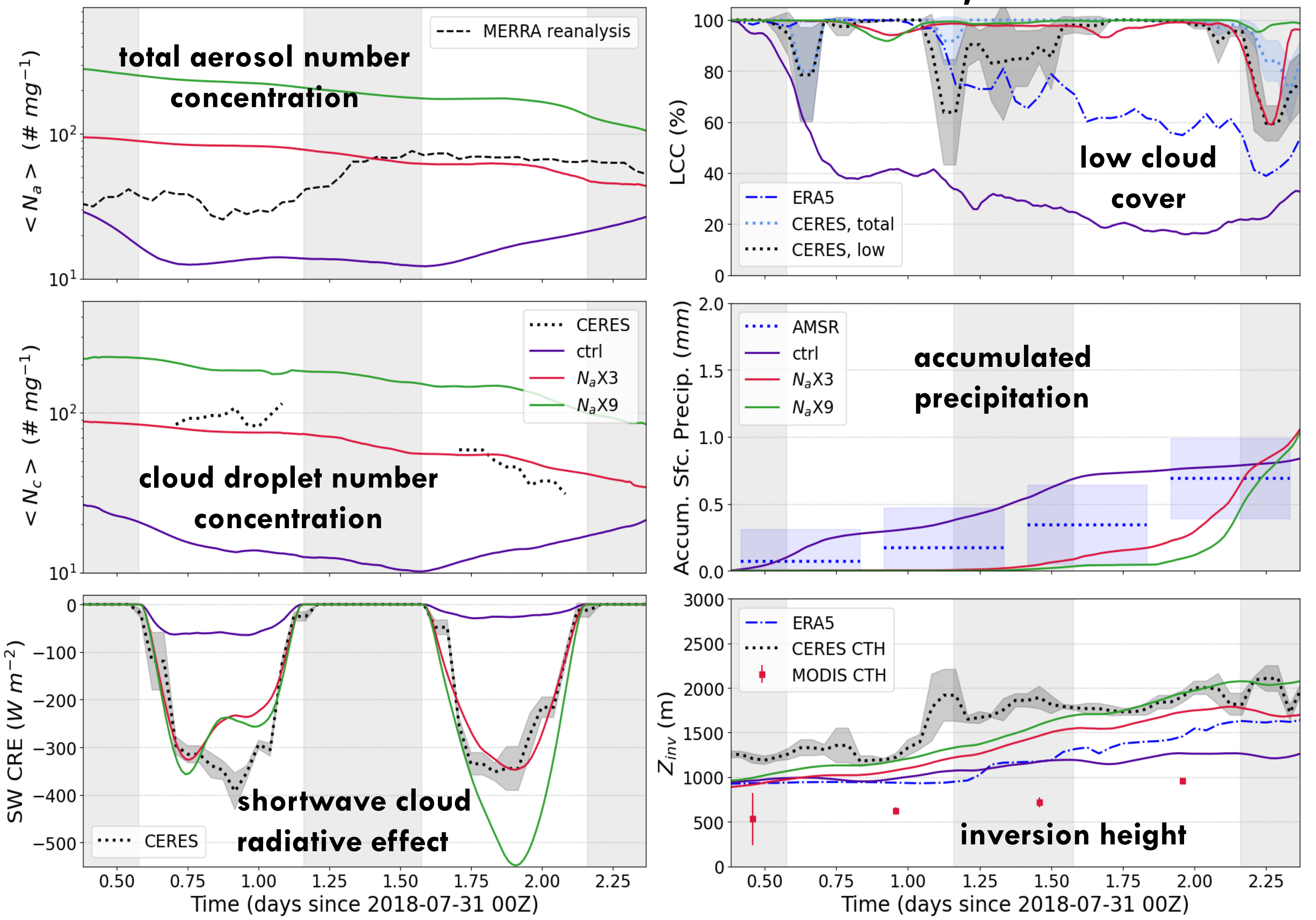
* Run initialized by MERRA MBL aerosol concentration multiply by 3

LES Results for Trajectory 1

Start: GPCI S10, 2018-07-31

- $N_a \times 3$ run simulates LCC, LWP, N_d, and SW CRE **close to observations.**
- Perturbed aerosols **enhance SW CRE and delay the cloud breakup.**
- $\boldsymbol{d(\mathrm{SW\ CRE})/d(N_d)}$ **is nonlinear,** with a bigger increase from ctrl run to $N_a \times 3$ run than from $N_a \times 3$ run to $N_a \times 9$ run.

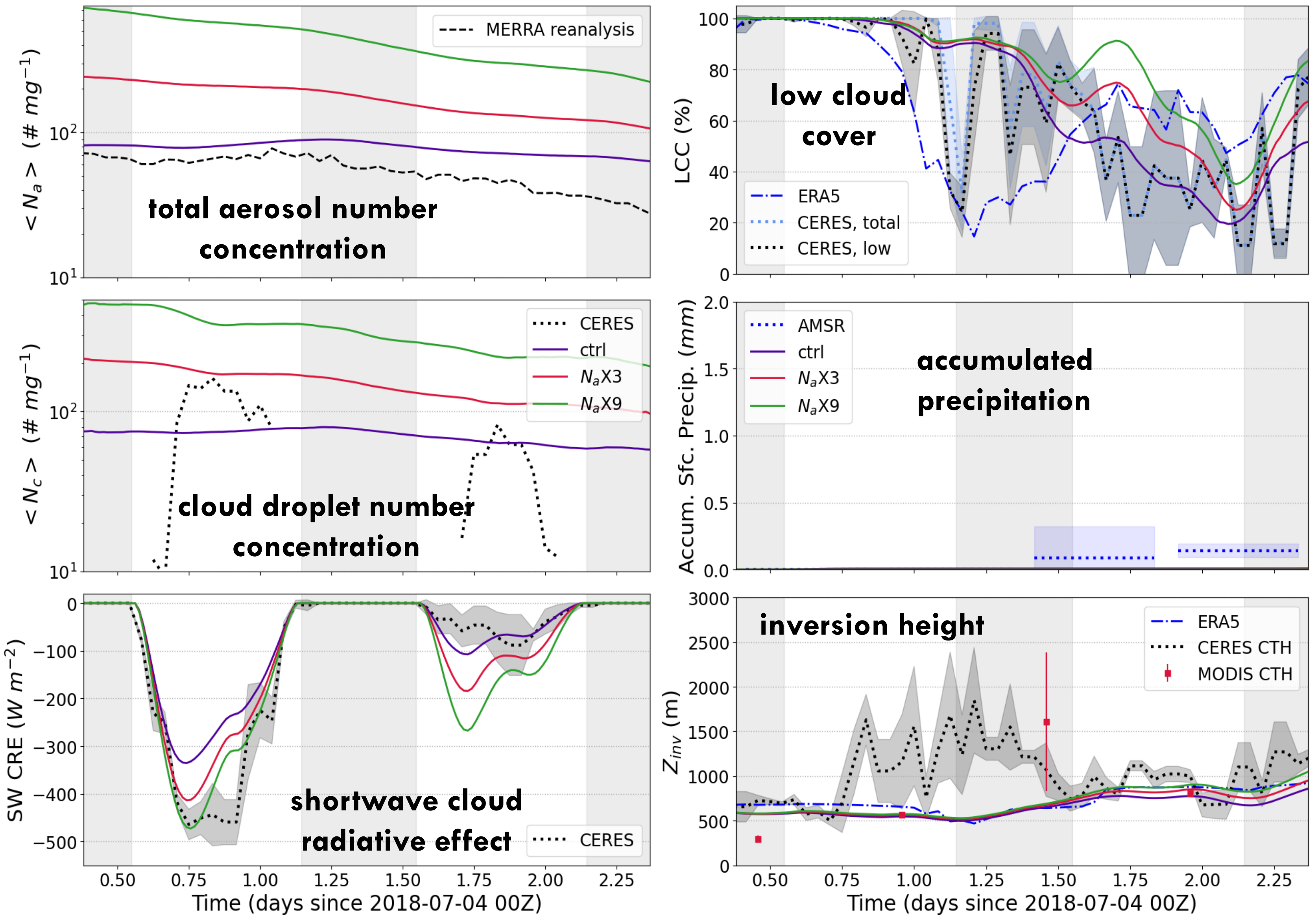


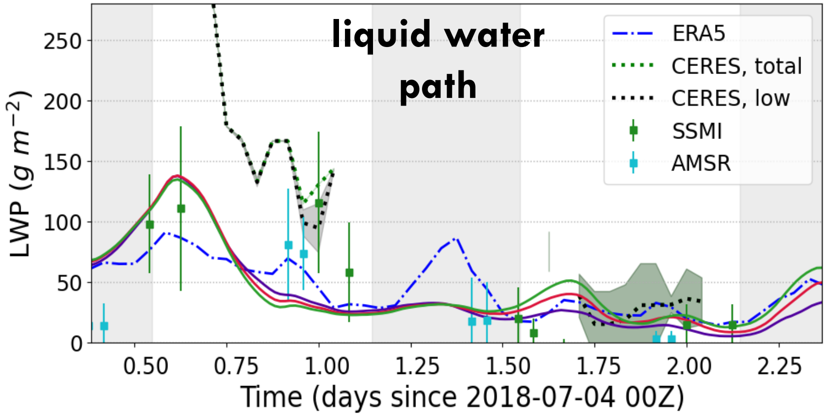


LES Results for Trajectory 2

Start: Sandu2010, 2018-07-04

- **ctrl** run agrees well with **observations** regarding LCC, N_d, and SW CRE.
- **Lack of precipitation** limits the impact of perturbed aerosols on **SW CRE,** and **cloud breakup.**
- In this case, **SW CRE** is more sensitive to $\boldsymbol{N_a}$ for **perturbed**





Conclusions

- More than **2000 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 CCV 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 realistic, high-resolution, large-domain LES experiments**, thereby **simulating a spectrum of aerosol-cloud interactions** under observed as well as perturbed aerosol conditions.
- The results for a few runs along two trajectories reveals the **effect of perturbed aerosols in enhancing cloud radiative effect and delaying cloud breakup** thereby **increasing cloud cover and cloud lifetime.** Precipitation plays a key role in regulating the sensitivity to aerosols.
- The final outcomes will contribute to **advancing our understanding of MCB's potential** impact as a climate intervention method. The large number of simulations will enable us to synthesize valuable statistics to assess **how well LES can simulate cloud lifecycle** under the 'best estimate' environmental conditions, and **how sensitive the simulated clouds are to changes in these driving fields.**

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Thank you very much!

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References

- Eastman, R., Lebsock, M., & Wood, R. (2019), Warm Rain Rates from AMSR-E 89-GHz Brightness Temperatures Trained Using CloudSat Rain-Rate Observations. *J. Atmos. Oceanic Tech.*, 36(6), 1033–1051. https://doi.org/10.1175/JTECH-D-18-0185
- Erfani, E., Blossey, P., Wood, R., Mohrmann, J., Doherty, S., Wyant, M., & O, K. (2022), Simulating aerosol lifecycle impacts on the subtropical stratocumulus-to-cumulus transition using large-eddy simulations. *J. Geophys. Res.*, 127, e2022JD037258.
- Gelaro, R., et al. (2017). Modern-era retrospective analysis for research & applications, version 2 (MERRA-2). *J. Clim.*, **30**(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758
- Hersbach, H., et al. (2020), The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, 146 (730), 1999–2049.
- Wentz, F. J.,et al. (2014), Remote Sensing Systems DMSP SSM/I Daily Environmental Suite on 0.25 deg grid, Version 7. Remote Sensing Systems, Santa Rosa, CA.

Building a comprehensive library of cloud-resolving simulations to study marine cloud brightening across a spectrum of environmental conditions

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Research on Marine Cloud Brightening (MCB) shows the potential to cool the planet, yet uncertainties exist in predicting its efficacy within global climate models (GCMs), largely due to limitations in capturing complex low marine cloud mechanisms and associated aerosol-cloud interactions. As these clouds' evolution and their response to aerosols are sensitive to ambient environmental conditions, it becomes imperative to determine different responses across a spectrum of conditions. In this study, we introduce an innovative approach aimed at encompassing the wide array of conditions prevalent in low marine cloud regions through the creation of a comprehensive library of observed environmental conditions. This approach is subsequently employed to select a representative selection of cases for process model studies, such as Large Eddy Simulations (LES).

Utilizing European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis, version 5 (ERA5) wind data, we generate over 2000 Lagrangian isobaric (950 hPa) boundary layer forward trajectories for specific locations within the Northeast Pacific Ocean's stratocumulus deck region during the summer seasons of 2018 to 2021. Thereafter, meteorological, cloud, and aerosol variables from reanalysis and satellite data are compiled along the trajectories. By using critical cloud-controlling variables (CCVs) (e.g., along-trajectory means, and differences between the beginning and end of the trajectory for wind speed, mixing ratio, subsidence, and estimated inversion strength), we employ Principal Component Analysis (PCA) to reduce the dimensionality of the data. This technique illustrates that three principal components capture 62% of the variability among CCVs. Notably, PCA facilitates the efficient selection of LES cases that span the observed CCV, aerosol, and cloud phase space.

Utilizing the PCA results, we identify more than 50 distinct cases representing a diverse array of environmental conditions. These cases will be used to initiate 2-day realistic, high-resolution, large-domain LES experiments, thereby simulating a spectrum of aerosol-cloud interactions under observed as well as perturbed aerosol conditions. Our LES incorporates a prognostic aerosol scheme, accounting for aerosol budget tendencies such as coalescence and interstitial scavenging, surface sources, and entrainment from the free troposphere. The LES is forced with meteorological data as well as an accumulation-mode aerosol number concentration calculated from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) masses of aerosol species and their assumed particle size distributions. Such a large number of simulations will enable us to synthesize valuable statistics to assess how well LES can simulate the cloud lifecycle under the 'best estimate' environmental conditions, and how sensitive the simulated clouds are to variations in these driving fields. This ongoing procedure holds the promise of enhancing our ability to evaluate the efficacy of intentional MCB under a range of representative conditions. As we continue to conduct LES experiments, its outcomes will contribute to advancing our understanding of MCB's potential impact as a climate intervention method.

References:

- Eastman, R., Lebsock, M., & Wood, R. (2019), Warm Rain Rates from AMSR-E 89-GHz Brightness Temperatures Trained Using CloudSat Rain-Rate Observations. *J. Atmos. Oceanic Tech.*, 36(6), 1033–1051. https://doi.org/10.1175/JTECH-D-18-0185

- Erfani, E., Blossey, P., Wood, R., Mohrmann, J., Doherty, S. J., Wyant, M., & O, K. T. (2022). Simulating Aerosol Lifecycle Impacts on the Subtropical Stratocumulus-to-Cumulus Transition Using Large-Eddy Simulations. Journal of Geophysical Research: Atmospheres, 127(21), e2022JD037258.

- Gelaro, R., et al. (2017). Modern-era retrospective analysis for research & applications, version 2 (MERRA-2). *J. Clim.*, **30**(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758

- Kawanishi, T., et al. (2003), The Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), NASDA's contribution to the EOS for global energy and water cycle studies. *IEEE Trans. Geosci. Remote. Sens.*, *41*(2), 184-194.

- Wentz, F. J., et al. (2014), Remote Sensing Systems DMSP SSM/I Daily Environmental Suite on 0.25 deg grid, Version 7. Remote Sensing Systems, Santa Rosa, CA.