Using A Phase Space of Environmental Variables to Drive an Ensemble of Cloud-resolving Simulations of Low Marine Clouds

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1. Background

- Low marine clouds are a major source of uncertainty in cloud feedbacks across climate models and in forcing by aerosol-cloud interactions (IPCC 2013).
- The evolution of these clouds and their response to aerosols are sensitive to ambient environmental conditions (Erfani et al., 2022), so it is important to determine different responses over a representative set of conditions.
- Here, we propose a novel approach to encompassing the broad range of conditions present in low marine cloud regions, by building a library of observed environmental conditions.
- The approach can be used, for example, to select a representative set of cases for process model studies (e.g., Large Eddy Simulations or LES).

2. Methodology

Data

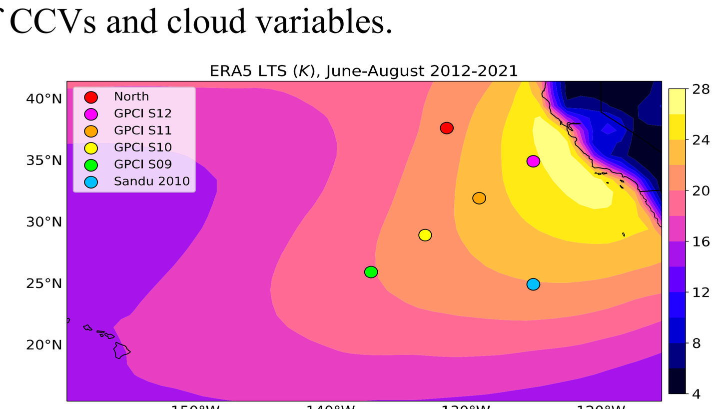
- ERA5 reanalysis and satellite observations are used to extract and derive macrophysical and microphysical cloud-controlling variables (CCVs) and cloud variables.
- **CCVs:** sea-surface temperature (SST), lower tropospheric stability (LTS), surface wind speed (WS), free-tropospheric (FT) moisture (q), FT subsidence (ω), and surface pressure (P).
- Cloud variables: low cloud fraction (CF), liquid water path (LWP), cloud-top height (CTH), and cloud droplet number concentration (N_d).

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	Two times per day*	Two times per day*	Two times per day*	Two times per day*
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

* 01:30 and 13:30 LT

Locations

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



PCA

Principal Component Analysis (PCA) is applied to reduce the dimensionality and to select a reduced set of **principal components (PCs)**.

Removing seasonality → Standardization → PCA

$$V'_n = V_n - \langle V_n \rangle$$

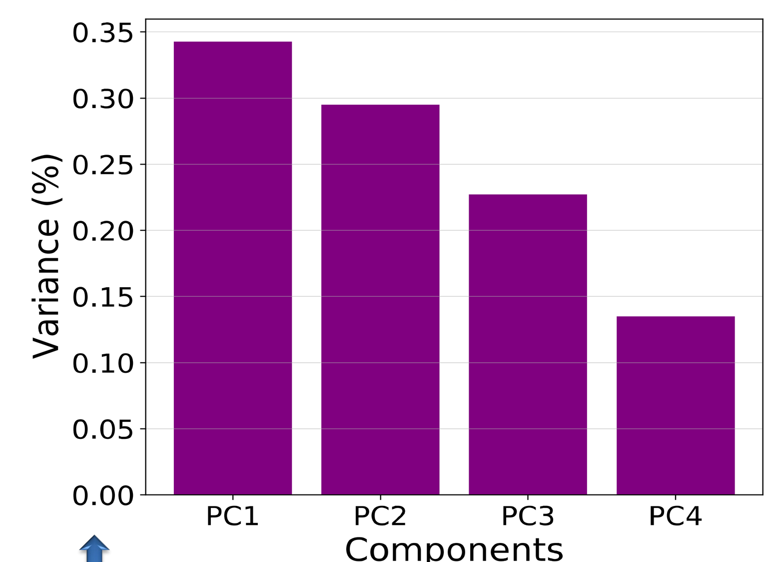
n: n[th] day since June 1[st]
V_n: V for day n of a year
$\langle V_n \rangle$: time-mean V for day n of 2012-2021

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

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

3. PCA & Phase Space

Percentage of variance explained by each PC

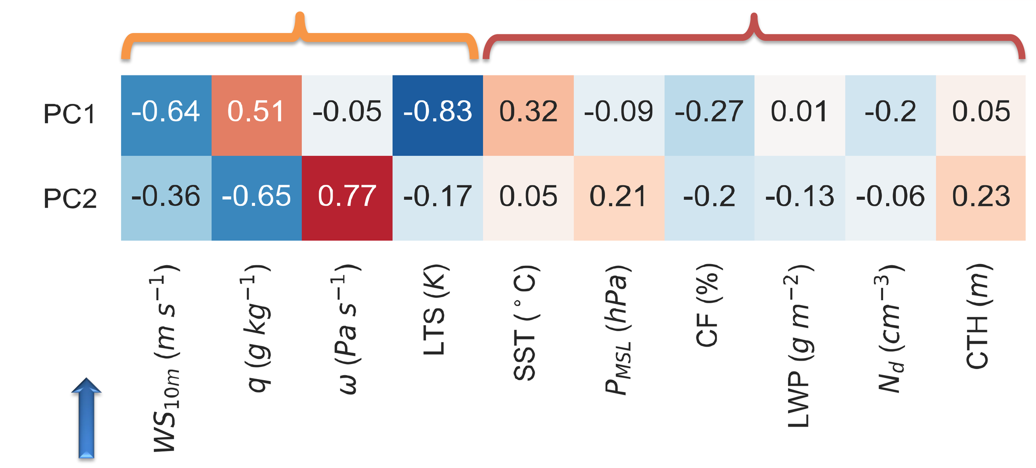


- We conduct one PCA based on 4 CCVs for all 6 locations and all days in JJA 2018-2021 (a total of 2208 data points).
- Most (**65%**) of the information is compressed into PC1 and PC2.

Correlation (R) between PCs, CCVs, and cloud variables

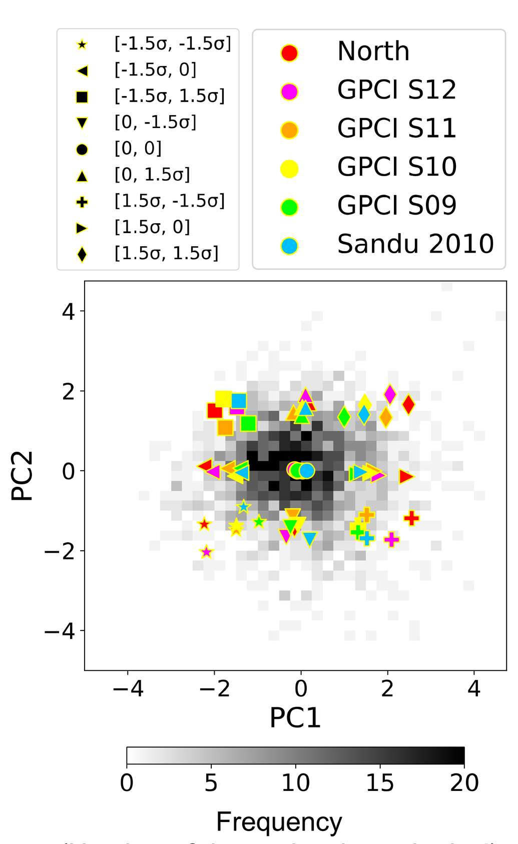
4 CCVs (WS, q, ω, and LTS) are used as inputs for PCA.

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

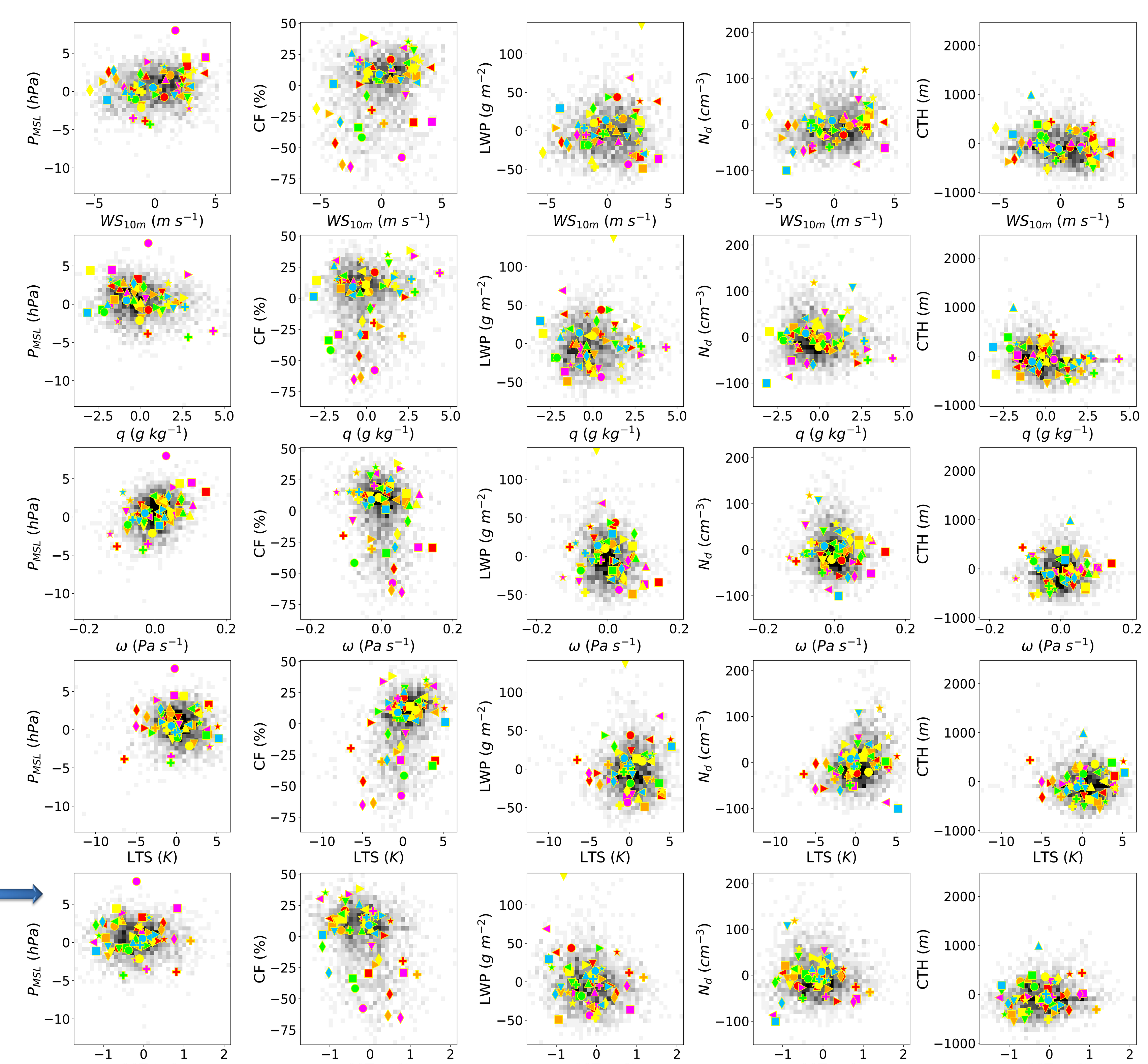


- Here, the relationships between PCs and all variables are shown.
- LTS contributes the most to PC1 and ω contributes the most to PC2.
- An R-value of 0.1 or higher is statistically significant since it leads to a p-value smaller than 0.05 for non-directional conditions.

Phase Space

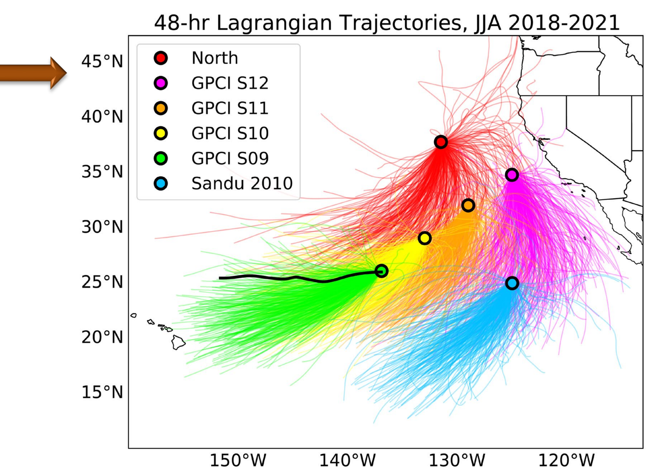


- For each location, 9 points are selected to represent **(-1.5σ, 0, 1.5σ)** in PC1-PC2 space (points shown by different markers).
- It is seen that selected data points in PC1-PC2 space successfully represents the observed spectrum of CCVs and cloud variables.



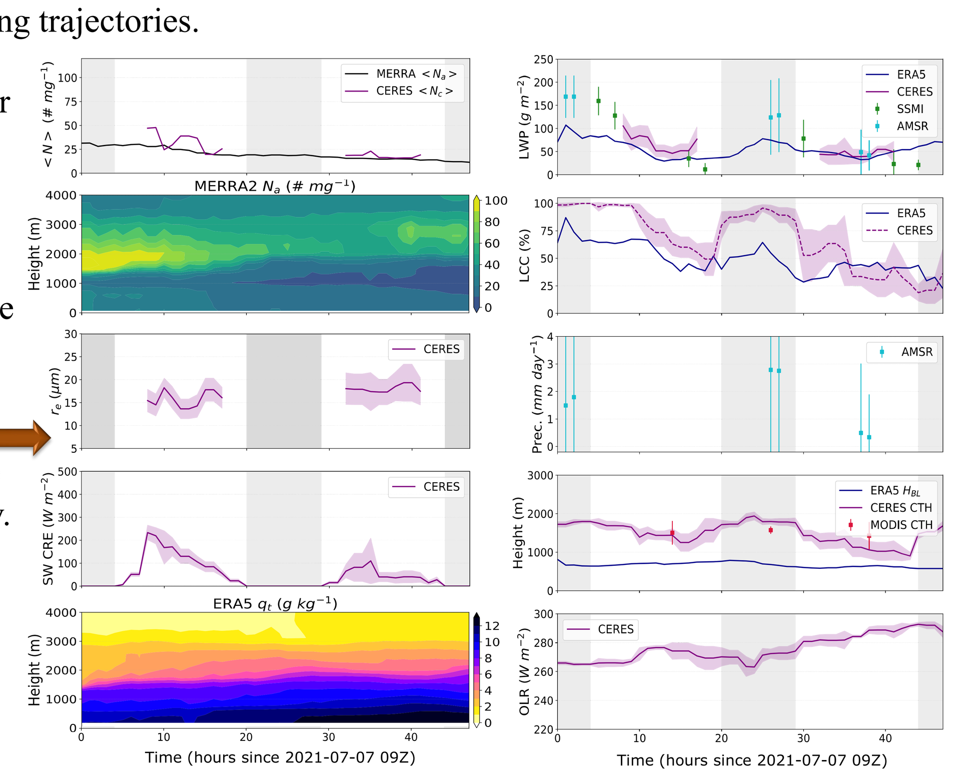
4. Trajectories

- 2208 Lagrangian forward trajectories are created isobarically from an initial level of 950 hPa for 72 hours, using ECMWF ERA5 winds and trajectory code developed at UW.
- Those will serve as forcing for 10s of LES cases (will be selected from the phase space) and will provide a tool for comparison of LES and observations.



Compiling variables along trajectories

- We use the Python package "uw-trajectory" developed at UW for compiling reanalysis and satellite data along trajectories.
- The accumulated-mode aerosol number concentration (N_a) is calculated using the MERRA2 mass of aerosol species and their assumed particle size distribution (Erfani et al., 2022).
- Just one example is shown here for the thick black trajectory.
- The starting location of this trajectory corresponds to green circle marker in the phase space.



5. Conclusions

- Applying PCA reduces the dimensionality of the data needed to cover cloud field variability, and two PCs explain 65% of the variability among CCVs. PCA is useful in efficiently selecting LES cases that encompass the observed CCV phase space.
- A large number of Lagrangian trajectories are developed and reanalysis and satellite variables are compiled along each trajectory. From them and based on the phase space, 10s of cases with distinct environmental conditions will be selected and used to initialize 2-day LES modeling to provide a spectrum of aerosol-cloud interactions and Sc-to-Cumulus transition under observed ambient conditions.
- Such a large number of simulations will help create statistics to assess how well the LES can simulate the cloud lifecycle when constrained by the 'best estimate' of the environmental conditions, and how sensitive the modeled clouds are to changes in these driving fields. Ultimately this analysis will be useful for assessing the efficacy of intentional Marine Cloud Brightening (MCB) under a range of representative conditions.

Acknowledgment

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References

- Doelling, D. R., et al. (2016), Advances in geostationary-derived longwave fluxes for the CERES synoptic (SYN1deg) product. *J. Atmos. Oceanic Tech.*, 33 (3), 503–521.
- Eastman, R., Wood, R. & O, K-T. (2017), The subtropical stratocumulus-topped planetary boundary layer: A climatology and the Lagrangian evolution. *J. Atmos. Sci.*, 74, 2633-2656.
- 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.
- 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. https://doi.org/10.1029/2022JD037258
- Gelaro, R., et al. (2017). Modern-era retrospective analysis for research & applications, version 2 (MERRA-2). *J. Clim.*, **30**(14), 5419–5454.
- Hersbach, H., et al. (2020), The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, 146 (730), 1999–2049.
- IPCC. (2013). In T. F., Stocker et al. (Eds.), *Climate change 2013: The physical science basis*, (p. 1535). Cambridge University Press.
- 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.