

Spring-summer atmospheric circulation and boundary layer processes modulating aerosol and cloud characteristics over the coastal Northeast Pacific during EPCAPE

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Abstract. Observations collected during the ARM Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) for the period spanning April to September 2023 (spring and summer) at Scripps Pier in La Jolla, California (32.8663°N, 117.2546°W) were used to investigate the regional-scale atmospheric factors that control the variability of predominant marine low clouds and aerosols in the coastal boundary layer. Using Self-Organizing Maps (SOMs) applied to ERA5 sea level pressure and near-surface wind fields, we classify the synoptic evolution of the subtropical anticyclone into 9 regimes. This regime categorization highlights the following dominant features in Northeast Pacific: 1) regimes that capture the evolution of the anticyclone in terms of magnitude (strong vs weak) and location (coastal vs offshore), with their corresponding transitions in boundary layer wind strengthening and large-scale subsidence (regimes: 1-3 vs 6-8), 2) a second dominant feature characterized by an anticyclone with its core at the northwestern edge of the domain, resulting in modest sea level pressure changes near Scripps Pier (regimes 6-8), 3) patterns with a weakened subtropical anticyclone south of Scripps Pier and a midlatitude cyclone further north (regimes 4 and 5), and 4) an additional regime that captures anomalies that minimally depart from the climatological mean (regime 9). GOES-18 satellite cloud retrievals reveal that regimes associated with an anticyclone core closer to the EPCAPE coastal site (regimes 1-4) is associated with reduced low-cloud fraction, shallower clouds, and low liquid water path

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(LWP) along the shoreline; whereas regimes with a west/north-westward-displaced anticyclone combined with a weak coastal inland low-pressure feature (regimes 6-8) that support extensive stratocumulus with higher LWP and elevated cloud tops. Variability in the aerosol distribution is also controlled by the synoptic scale processes. Regimes with a relatively weak anticyclone centered adjacent to the Scripps Pier (regime 4) generally feature the highest concentrations of particles with diameter $\leq 0.1 \mu\text{m}$, associated with a stable boundary layer and stagnation under weak winds. Regimes with anticyclone strengthening farther offshore (regimes 6-8) have relatively lower aerosol concentrations. The partial inconsistency in the evolution of the cloud droplet number concentration (Nd) and aerosol concentration indicates that the variability in boundary layer turbulence is a critical component that explains the aerosol activation into Nd.

1. Introduction

The Northeast Pacific (NEP) stratiform cloud regime is a key climatological feature over the subtropics, playing a central role on the Earth's radiation budget (Hartmann et al., 1992; Wood, 2012) and exerts a climate feedback with the large-scale sea surface temperature and atmospheric circulation (e.g., Clement et al., 2009). Coastal Southern California experiences diverse synoptic weather patterns driven by the coastal topography and large-scale circulation. The subtropical high dominates in spring and summer, generating strong onshore flow that enhances marine layer clouds and coastal cooling (Raphael, 2003; Clemesha et al., 2017). In contrast, fall and winter witness a wider range of weather patterns, with frequent synoptic-scale transitions of anticyclonic and cyclonic circulation of varying extent and magnitude. These changes dramatically modulate cloud variability, giving rise to convective systems especially in frontal regions, and synoptically forced stratocumulus clouds under conditions with strong post-cyclonic subsidence (Weaver and Ramanathan, 1994). These circulation shifts generate stark contrasts in coastal meteorology, pollutant dispersion, and cloud variability (Lu and Turco, 1994, 1995). Furthermore, the diurnal land-sea breeze interacts with the synoptic forcing. Weak synoptic forcing allows land-sea breezes to dominate, while katabatic winds originated from a high-pressure system (Santa Ana winds) disrupt these cycles, enhancing offshore pollutant transport and reducing cloud coverage (Abel and Hall, 2010). In contrast, low-pressure conditions strengthen the offshore flow, deepen the marine atmospheric boundary layer (MBL), and increase the cloud cover (Lebassi-Habtezion et al., 2011).

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98 The coastal southern California is particularly impacted by transport of polluted air from
 99 industrial regions like Los Angeles and Long Beach (Husar and Patterson, 1980; Husar et al.,
 100 1977). Moreover, pollution transport extends offshore over the stratocumulus cloud-topped marine
 101 atmospheric boundary layer during Santa Ana wind events (Abel and Hall, 2010), directly
 102 affecting the marine stratocumulus clouds. Conversely, synoptic onshore flow brings pristine
 103 marine aerosols inland, dramatically changing the local aerosol composition (Maneenoi et al.,
 104 2025; Han et al., 2025). The diversity in chemical composition and wide range of aerosol
 105 variability makes this region a unique observatory for investigating aerosol pathways and modes
 106 of variability over a coastal region situated next to densely urbanized areas. Moreover, advection
 107 of continental aerosols over the adjacent ocean can potentially impact the evolution and radiative
 108 properties of the [NEP](#) stratocumulus cloud deck. In this respect, a fundamental mechanism of
 109 aerosol-cloud interaction is through an increase in cloud droplet number concentration (N_d)
 110 mediated by an increase of cloud condensation nuclei (CCN) under conditions of enhanced aerosol
 111 loading (Bellouin et al., 2020 and references therein). The positive correlation between CCN and
 112 N_d have been observed in several studies (e.g., Sorooshian et al., 2019; Painemal et al., 2017), with
 113 the radiative implications manifested in an increase of albedo at the top of the atmosphere
 114 documented from satellite observations (Painemal, 2018). It has been hypothesized that changes
 115 in N_d can trigger multiple feedbacks and rapid cloud adjustments that can alter the cloud properties
 116 (precipitation, water content, thickness, among other); however, their magnitudes remain highly
 117 uncertain (Bellouin et al., 2020).

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118 An important factor contributing to uncertainties in the quantification of the aerosol
 119 indirect effect is the fact that clouds primarily respond to changes in the local atmospheric state,
 120 which in turn also modulate the microphysical interactions between aerosol and clouds. Indeed,
 121 Chen et al. (2014) and Zhang et al. (2022) highlight the importance of accounting for
 122 meteorological factors for assessing aerosol-cloud interactions (e.g., atmospheric stability and
 123 humidity). For the [NEP](#), data collected during the MAGIC campaign (Lewis, 2016) along with
 124 reanalyzed meteorological fields show [that](#) the coastal California low-level jet as a key mechanism
 125 transporting aerosols from North American continent to the northeast Pacific. Furthermore,
 126 Painemal et al. (2015) found a negative correlation between 1000 hPa zonal wind and N_d ,
 127 underscoring the influence of large-scale meteorology in transporting aerosol from coastal regions
 128 to the open ocean in the [NEP](#).

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133 Cognizant of the knowledge gaps in the characterization of clouds and aerosols in the
134 atmospheric boundary layer of coastal California, the Department of Energy's Atmospheric
135 Radiation Measurement (ARM) program deployed the ARM Mobile Facility at Scripps Pier
136 (32.8663°N, 117.2546°W) in La Jolla (California) during the Eastern Pacific Cloud Aerosol
137 Precipitation Experiment (EPCAPE; Russell et al., 2025). This year-long field campaign,
138 conducted from mid-February 2023 to mid-February 2024, provided comprehensive high-
139 resolution observations of aerosols, clouds, precipitation, and atmospheric state. Being a
140 downwind coastal site, Scripps Pier is ideally situated to observe the interactions between
141 continental and marine air masses, and boundary layer clouds in the [NEP](#).

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142 Here, we describe the synoptic regimes that modulate cloud variability and aerosol
143 characteristics over the coastal Southern California for the period spanning April through
144 [September, 2023](#) corresponding to [Southern California spring \(April-June\) and summer \(July-](#)
145 [September\)](#), a period characterized by the frequent presence of stratocumulus clouds. To this end,
146 we employ self-organizing maps (SOM) – an unsupervised neural network method – to categorize
147 meteorological regimes using fields from the Fifth Generation ECMWF reanalysis (ERA5). In
148 addition, [Satellite CLOUD and Radiation Property retrieval System \(SatCORPS\) cloud products](#)
149 [derived](#) from the 18th Generation Geostationary Operational Environment Satellite (GOES-18) and
150 ground-based in-situ and remote sensing measurements for the study period from the EPCAPE
151 campaign at Scripps Pier are combined to analyze the factors that link the atmospheric circulation
152 with cloud and aerosol characteristics. By leveraging EPCAPE observations, this research provides
153 a novel approach to linking large-scale weather patterns with localized atmospheric processes. The
154 paper is structured as follows: Section 2 outlines the EPCAPE in-situ and remote measurements,
155 satellite cloud observations, and reanalysis data. Section 3 covers atmospheric regime
156 classification using SOM. Section 4 describes meteorological, cloud, and aerosol properties within
157 these atmospheric regimes. Section 5 outlines the summary and discussion.

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159 2. Datasets and methodology

160 The key dataset for this study was collected by the ARM's Mobile Facility deployed at
161 Scripps Pier during EPCAPE. ERA5 and SatCORPS GOES-18 are primarily used for describing
162 the regional scale context of the EPCAPE observations. In the following, we describe the dataset
163 used in our study.

2.1. ARM observations and products

Cloud boundaries

Cloud base height (CBH) is estimated from a laser ceilometer Vaisala CL31 (CEIL; Morris, 2016), with a 16-s sampling and a vertical resolution of 10 m. The typical accuracy of CBH measurements is within ± 30 meters for low clouds, though uncertainties increase at higher altitudes or in the presence of fog, aerosols, or precipitation. Ceilometer data were also used to estimate the hourly cloud occurrence frequency for low altitude clouds, hereafter referred to as cloud frequency fraction (CFF) and computed by counting the number of cloudy observations relative to the total sampling in an hour.

The vertically pointing Ka-band ARM Zenith Radar (KAZR, Widener et al., 2012; Feng et al., 2024), provided cloud top height (CTH) measurements throughout the campaign. We used the KAZR Active Remote Sensing of Clouds (KAZRARSCL) Value Added Product (VAP) for determining the cloud height, with the vertical resolution of 30 m and a 4-s sampling.

Liquid water path and cloud optical thickness

The 3-channel Microwave Radiometer (MWR3C) provided LWP retrievals at 1-second interval throughout the campaign. MWR3C measures brightness temperatures at three frequencies (23.8 GHz, 30 GHz, and 89 GHz) which are sensitive to atmospheric water vapor and liquid water.

The LWP is retrieved using the updated Microwave Radiometer RETrieval (MWR3RET) algorithm which follows the physical retrieval method developed by Turner et al. (2007) and Gaustad and Turner (2009) and is provided as ARM VAP. The inclusion of the 89 GHz channel,

with its enhanced sensitivity to low liquid water content, improves retrievals for clouds with small LWP. We limit the sampling to boundary layer clouds by only retaining observed clouds with KAZR cloud tops below 2 km. The occurrence of thin clouds is minimized by removing samples with $LWP < 5 \text{ g m}^{-2}$ and $CFF < 20\%$. To reduce the retrieval and measurements uncertainty, we evaluate non-precipitating clouds, by filtering out the measurements during surface precipitation events, (excluded datasets with rain fraction > 0), which accounted $< 1\%$ of total. This filtering effectively eliminates periods of substantial surface precipitation while retaining cases of light drizzle aloft that evaporate before reaching the ground (this behavior is frequently observed in subtropical marine stratiform clouds) and remain part of the dataset. Finally, to ensure

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comparability across instruments with different sampling intervals, all cloud and aerosol datasets for the Scripps Pier are aggregated onto a common 1-hour time grid.

Ground-based ARM N_d is computed from the ARM Cimel Sunphotometer (CSPHOT, Chiu et al., 2010, 2012) cloud optical thickness (τ) and MWR3RET LWP following Painemal et al. (2017), enabling robust analysis of cloud microphysical properties from ground-based data. A second ground-based ARM N_d utilized here is NDROP N_d available as ARM VAP product (McComiskey et al. 2009) calculated using Multifilter Rotating Shadowband Radiometer derived τ and MWR3RET LWP following Boers and Mitchell (1994).

Deleted: → Cloud optical thickness (τ) is estimated from the ARM Cimel Sunphotometer (CSPHOT), a multi-channel automatic sun-and-sky scanning radiometer that measures direct solar irradiance and sky radiance at the surface during daylight hours. The retrieval algorithm employs non-absorbing zenith radiances at 440–870 nm for determining τ , and is available as Cloud Mode VAP (Chiu et al., 2010, 2012). Ground-based ARM N_d is computed from CSPHOT τ

Aerosol observations

Continuous range of aerosol number concentration (N_a) and particle size distribution are obtained from merged Scanning Mobility Particle Sizer (SMPS) and Aerodynamic Particle Sizer (APS) measurements, available as MERGEDSMPSAPS VAP (Beddows et al., 2010; Shilling and Levin, 2023). The SMPS measures the high-accuracy aerosol number size distribution, in the particle diameter range from 0.01 to 0.5 μm , by sizing particles based on their electrical mobility diameter using a differential mobility analyzer (DMA) and by counting particles using a condensation particle counter (CPC). The APS measures larger atmospheric particles in the diameter range of 0.5 to 20 μm , based on their aerodynamic diameter using the time-of-flight principle. Datasets are available for the entire EPCAPE time frame at 5-minutes except for a short duration (September 19 through October 23) of missing data.

Chemical composition and mass concentration of species aerosols such as organics, sulfate, nitrate, ammonium, and chloride are derived from Aerosol Chemical Speciation Monitor (ACSM: Shilling et al., 2024; Maneenoi et al., 2025) and are available at a 30 minute interval.

Cloud Condensation Nuclei

The cloud condensation nuclei (CCN) number concentration was measured on Scripps Pier by DOE ARM using a Cloud Condensation Nuclei Counter (CCN-200, DMT). The CCN counts aerosol particles after growing them at water supersaturations of 0.1 %, 0.2 %, 0.4%, 0.6 %, 0.8 %, and 1.0 % during a 1-hr cycle. This dataset is available for 25 May 2023 to 14 February 2024. A scaling factor of 1.67 (Berta et al., 2025) was applied to correct for a leak upstream of the instrument inlet that diluted CCN number concentrations with air from inside the air-conditioned

instrument van based on closure with composition and comparisons to the Mt. Soledad site (Dedrick et al., 2026). [This analysis focuses exclusively on CCN measurements at supersaturations \(SS\) of 0.1 % and 0.2 % because they are more representative of the environmental conditions at the Scripps Pier \(Dendrick et al., 2026\).](#)

Meteorological observations and models

The reanalyzed atmospheric dataset used in this study corresponds to ERA5 (Hersbach et al., 2020). ERA5 combines various observations from satellite and weather stations with advanced numerical weather prediction models to provide consistent and complete global records of atmospheric, oceanic, and land-surface conditions. Comprehensive atmospheric datasets are produced hourly at a horizontal resolution of 31 km (with spatial resolution of $0.25^\circ \times 0.25^\circ$) and 137 vertical levels extending from surface to 0.01 hPa. The hourly datasets, as well as daily and monthly mean are also available to download at [10.24381/cds.adbb2d47](https://cds.adbb2d47). The single-level products sea level pressure and sea surface temperature, as well as near-surface (975 hPa) winds, free-tropospheric (750 hPa) temperature, humidity, and winds from the vertical profiles are utilized in this study.

Backtrajectories are obtained from ARMTRAJ (Silber et al., 2025), an ARM VAP. ARMTRAJ consists of an ensemble of HYSPLIT forward and backward trajectories derived from hourly ERA5 [ensemble](#) reanalysis at 0.25° resolution for up to 10 days. ARMTRAJ is initialized at different levels, including surface (ARMTRAJ-SURF, 10 m), boundary layer top (ARMTRAJ-PBL), and cloud layer (ARMTRAJ-CLD). These trajectories provide information on the origin of air masses and are used to understand the source and transport path of aerosol and trace gas distributions. Here, we primarily utilize PBL [backtrajectories](#) to identify the possible transport processes for different atmospheric regimes at the Scripps Pier. ARM Eddy Correlation (ECOR) system provides half-hour measurements of the surface fluxes and carbon dioxide (Cook and Sullivan, 2025; Sullivan et al., 2025). The ECOR system deployed at the Scripps Pier include a fast-response, 3D wind sensor (sonic anemometer) to record the orthogonal wind components and the speed of sound, which is used to derive the air temperature, and an open-path infrared gas analyzer (IRGA) to obtain the water vapor density and CO₂ density. Turbulent Kinetic Energy (TKE) derived from ECOR measurements available in ARM EPCAPE Doppler Lidar profile statistics (DLPROFWSTATS: Newsom et al., 2025) is utilized here to understand the boundary

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layer turbulence. Lastly, the analysis is complemented with high-resolution vertical profiles of temperature, humidity, wind speed, and wind direction collected from radiosondes launched at Scripps Pier (Keeler, 2025). During April through September 2023, radiosondes were launched at 6-hour intervals (local times approximately 6 AM, 12 AM, 6 PM, and 12 PM).

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2.2. SatCORPS GOES-18 satellite cloud products

Satellite retrievals are derived from the GOES-18's Advanced Baseline Imager (ABI) using a family of algorithms referred to as the Satellite Cloud and Radiation Property Retrieval System (SatCORPS). These algorithms are adapted from those developed by the Clouds and Earth's Radiant Energy System (CERES) to ingest radiances from geostationary sensors (Minnis et al., 2008, 2011, and 2023). For this study, the native resolution pixel retrievals at ~ 2 km are produced half hourly and gridded to 0.20°x0.20° grid over the EPCAPE domain, defined here as the region covering the box of 28°N-43°N and 112.5°W-130°W. These gridded data are averaged according to their cloud height into low (height < 2 km), middle (2 km < height < 6 km), and high (height > 6 km) clouds. The cloud products include cloud fraction (CF), cloud optical depth (τ), droplet effective radius (r_e), LWP, temperature, and height. Given the large uncertainties and limitations of optical retrievals during nighttime (optical depth and droplet effective radius) we only retain daytime observations with solar zenith angle (SZA) less than 70°. To minimize retrieval artifacts from thin or broken clouds, we apply additional screening criteria in our analysis: CF > 10%, τ > 2 (Grosvenor et al., 2018). Also, we filter-out grid boxes with cloud top temperature (CTT) lower than 273.15 K and specifically select for this analysis averaged retrievals corresponding to the low height category (< 2 km) with LWP range of 5 – 250 g m⁻² to limit the analysis to stratus and stratocumulus clouds and minimize retrieval uncertainties. On average these filters reduce the data availability by approximately 60 %, however, provides a cleaner and more physically consistent sample for evaluating regime-dependent aerosol–cloud relationships. The SatCORPS algorithm computes LWP from the retrieved cloud optical thickness (τ) and droplet effective radius (r_e) using the relation (Nakajima and King, 1990; Nakajima et al. 1991):

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$$LWP = (4/3) \cdot \rho_w \cdot \tau \cdot r_e / Q \quad (1)$$

where ρ_w is the density of liquid water and Q is the cloud extinction efficiency, approximately 2.0. The algorithm follows the bispectral approach and simultaneously retrieves τ and r_e using the 0.64 μ m and 3.9 μ m reflectances under the assumption of a 1-D, plane-parallel, homogeneous cloud

layer. Because passive satellite sensors are most sensitive to the upper few optical depths of the cloud, the retrieved r_e corresponds to values near cloud top rather than the vertically averaged droplet radius, and the LWP computed following Eq. (1) would be an overestimate in marine stratiform clouds where typically r_e increases from cloud base to cloud top. To account for this bias, an adiabatic correction following Wood and Hartmann (2006) is applied to the LWP computation. The adiabatic LWP is computed using Eq. (2) given below, and accounting for the adiabaticity reduces the LWP derived from Eq (1) by a factor of (5/6) or 17%.

$$LWP_{adb} = (5/9) \cdot \tau \cdot r_e \quad (2)$$

The cloud droplet number concentration (N_d) is estimated following the approximation for subtropical clouds in Painemal and Zuidema (2011) based on the adiabatic approximation. This approach assumes that liquid water content increases linearly with height and incorporates an adiabatic factor of 1.0.

$$N_d = 1.4067 \times 10^{-6} [\text{cm}^{-1/2}] \cdot \tau^{1/2} / r_e^{5/2} \quad (2)$$

Since numerous studies have reported a systematic positive bias in r_e derived from geostationary and sun-synchronous imagers of about 20% relative to in-situ data (e.g. Minnis et al., 2021; Painemal et al., 2023; Painemal et al., 2025), we apply a 0.8 correction factor to the r_e values before computing N_d , to minimize error propagations in Eq. (2).

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2.4. Self-Organizing Maps for synoptic regime classification

Self-Organizing Maps (SOMs; Kohonen, 1982; Kohonen, 1990; Bishop, 1995; Vesanto and Alhoniemi, 2000; Kohonen, 2001; Haykin, 2009) is an unsupervised machine learning technique designed to cluster and visualize high-dimensional data by projecting it onto a two-dimensional grid while preserving the topological relationships inherent in the data. The SOM algorithm groups similar data patterns into neighboring neurons on the grid, with each neuron i represented by a weight vector w_i . This weight vector is iteratively adjusted during training to reflect the distribution of the input data, ensuring that patterns with similar features are positioned close to each other on the grid. Recent studies emphasize the effectiveness of SOMs in synoptic climatology and environmental analysis (Hewitson and Crane, 2002; Sheridan and Lee, 2011; Jiang et al., 2013; Pearce et al., 2014; Juliano and Lebo, 2020; Painemal et al., 2023). The training process of SOMs involves several steps as described in Haykin (1999, 2009):

350 (1) Initialization: The weighting vectors of the neurons are initialized randomly for better
351 convergence. Each neuron in the map is represented by a weighting vector with the same
352 dimensionality as the input data.

353 (2) Determine the winning neuron i : For each input vector x , the algorithm calculates the Euclidean
354 distance between the input vector and each neuron's weight vector. The neuron with the smallest
355 distance to the input is selected as the winner, $\arg\min\|x-w_i\|$, where w_i represents the weight
356 vector of the i^{th} neuron.

357 (3) Adapting weights: The winner and its neighboring neurons are updated to move closer to the
358 input vector. The weight update for a neuron i at time t is given by:

359
$$w_i(t+1)=w_i(t)+\eta(t)h(i)(x-w_i(t));$$

360 where $\eta(t)$ is the learning rate which typically decreases over time and $h(i)$ is the Gaussian
361 neighborhood function, which determines how much a neuron is influenced based on its distance
362 from the winner.

363 (4) Decay of Learning Rate and Neighborhood: Both the learning rate $\eta(t)$ and the neighborhood
364 radius $\sigma(t)$ decrease over time to allow fine-tuning in later training stages: $\eta(t)=\eta_0 e^{-kt}$,
365 $\sigma(t)=\sigma_0 e^{-kt}$, where η_0 and σ_0 are the initial learning rate and neighborhood radius, and k is a time
366 constant controlling the decay rate.

367 (5) Iteration: This process is repeated over multiple epochs, iterating through the dataset either
368 sequentially or in batches. Early epochs focus on global organization with larger neighborhoods
369 and higher learning rates, while later epochs fine-tune the local structure, resulting in a
370 topologically ordered map where similar input patterns are mapped to nearby neurons, allowing
371 for the visualization and clustering of complex datasets.

372 We utilized MiniSOM (Vettigli, 2018), a Python based implementation of SOM, which leverages
373 the NumPy framework for computational efficiency, making it particularly suitable for analyzing
374 moderate-sized datasets with minimal dependencies.

375 3. Results

376 [To interpret the characteristics of aerosols, clouds, and meteorology over Southern](#)
377 [California coast during EPCAPE spring and summer \(April-September\) months, we first identified](#)

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the dominant synoptic patterns (9 regimes) using a SOM classification applied to SLP and 975 hPa winds. For these 9 regimes, we evaluate the dynamic and thermodynamic variables (vertical velocity at 500 hPa, relative humidity, BL stability and coupling state, turbulence, etc.) to characterize the MBL and governing large-scale circulation over the NEP and the Scripps Pier pattern using ERA5 reanalysis meteorology and ARM in-situ radiosonde measurements. In the section following, we evaluate the spatial pattern in cloud properties (low-cloud fraction, cloud droplet number concentration, liquid water path, and cloud top height) from SatCORPS GOES-18 satellite retrievals and ARM ECAPE ground based observations of cloud properties including KAZR CTH, Ceilometer CBH, MWR LWP, etc. for the Scripps Pier and discuss how the key meteorological features drive these regime specific cloud properties. We assess particle number concentration from ARM in-situ merged SMPSAPS measurements to understand how synoptic regimes modulate aerosol variability, and their correspondence to CCN, and N_d . Additionally, we explore the role of boundary layer turbulence in observed N_d and accumulation mode N_a . Finally, to understand the aerosol transport pathways, we analyze the ACSM aerosol species measurements and ARM PBL backtrajectories for the 9 synoptic regimes.

3.1. Regional-scale classification

The first step in the synoptic clustering is to select the meteorological fields that will be used for the pattern classification. To this end, we consider a variable that represents the large-scale features over the region of study and a second parameter that captures local features along the coast. The clear choice that satisfies these conditions over the coastal NEP are, respectively, sea level pressure (SLP, e.g., Juliano and Lebo, 2020) and boundary-layer wind fields at 975 hPa (e.g., Abel and Hall, 2010). We also experimented with adding the 500 hPa geopotential and 850 hPa winds fields to SOM, which resulted in negligible changes in the clustering (not shown). Next, 11 years (2012-2022) of daily April through September SLP and winds are normalized by subtracting the 30-day moving average at each 0.25° grid point and divided by the 30-day running standard deviation. This normalization ensures that the algorithm primarily discerns meaningful meteorological patterns rather than seasonal changes and extreme modes of variability. Alternative anomaly normalizations, such as spatial averaging methods used in previous studies (e.g., Juliano and Lebo, 2020), were tested but were found to disproportionately weigh land-ocean differences in SLP variability. Secondly, to determine the spatial domain extent best suited for capturing

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415 meteorological variability relevant to the NE California coast, we tested three domains of varying
 416 sizes: a large domain (10°N–50°N, 160°W–100°W), a medium-size domain (20°N–50°N, 140°W–
 417 110°W), and a small domain (30°N–40°N, 125°W–115°W). We found that the clustering for the
 418 large domain was dominated by large-scale changes in SLP far offshore, showing modest
 419 differences in meteorological conditions for the coastal region near Scripps Pier. In contrast, the
 420 small domain captured many more details that tended to yield spatially noisy patterns that lacked
 421 consistent features. The medium-sized domain (30° × 30°) provided the most representative
 422 patterns for the Southern California region, effectively capturing the dominant synoptic-scale
 423 features. Finally, we tested several objective methods to determine the optimal number of SOM
 424 nodes. First, we used the silhouette score to evaluate the uniqueness of patterns across different
 425 node selections. This metric informs about how close each point in one cluster is to the points in
 426 the neighboring cluster, with score ranging between -1 and 1. A higher score (> 0.5) suggests the
 427 clusters are well-separated, whereas a negative score suggests wrong cluster assignment. In our
 428 case, the scores ranged from 0.065 for six clusters to 0.021 for nine clusters, degrading further
 429 with higher node counts, which rendered this method unsuitable. Second, we applied a two-step
 430 clustering approach: initially generated an SOM classification with 20 clusters (4 × 5 nodes) and
 431 then regrouped with K-means to reduce the number of patterns. However, this approach produced
 432 slightly noisier and less coherent patterns. Ultimately, the optimal number of nodes/clusters was
 433 chosen visually by testing several configurations (4 × 5, 4 × 4, 3 × 4, 3 × 3, etc.) to ensure clear
 434 classification of regional synoptic features. A 3 × 3 SOM (nine nodes) provided distinct, coherent
 435 synoptic regimes, striking a balance between capturing variability and maintaining interpretability.
 436 Moreover, this 3x3 SOM configuration effectively captures the evolution of the SLP discerned by
 437 the 4x5 SOM, as corroborated by comparing the normalized sea level pressure fields in Fig.1 and
 438 Fig S1.

439 The 9 patterns (regimes) determined by the SOM classification is shown in Fig. 1. These
 440 patterns capture the dominant synoptic features over the NEP and coastal Southern California and
 441 are arranged to reflect a progression in anticyclone/cyclone movement. It is interesting to observe
 442 a coherent transition of the anticyclone-cyclone system that resembles the evolution of weather
 443 disturbances. Pattern 1 displays pronounced high-pressure anomaly centered northwest of the
 444 Scripps Pier with anticyclonic offshore wind anomalies, and occur 14.46 % of the time (the highest
 445 frequency among all regimes). Patterns 2-8 feature the development, eastward advancement, and

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455 southeastward dissipation of a cyclonic system. More specifically, pattern 2 features an
 456 anticyclone strengthening with its center positioned about 10 degrees west of Scripps Pier, and
 457 with intensified offshore anticyclonic anomalous flow, whereas a cyclonic system develops at the
 458 northwest corner. Pattern 3 is characterized by an anomalous anticyclone closer to the Pier, as the
 459 anomalous cyclonic pattern strengthens. Pattern 4 depicts a diminished anomalous anticyclonic
 460 signature now centered even closer to the Pier with modest winds, with the cyclonic center shifting
 461 further south relative to pattern 3. Pattern 5 displays a predominant cyclonic feature centered
 462 directly west of Southern California, producing broad anomalous onshore winds across the region.
 463 Pattern 6 captures a moderate anomalous low-pressure system advancing southeastward covering
 464 much of the domain, accompanied by enhanced anomalous onshore flow. The anomalous low-
 465 pressure pattern further advances along the direction in pattern 7, generating strong anomalous
 466 onshore flow. Pattern 8 shows a modest anomalous low-pressure feature over Southern California
 467 while anomalous anticyclone displaced further south in pattern 7. Pattern 9 presents minimal
 468 changes in SLP and winds and, thus, represents climatological features.

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 Pattern 1 ...

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 Pattern 4 features an anticyclone strengthening with its center slightly north of Scripps Pier, and with intensified offshore flow. Pattern 5

Deleted: Pattern 6 illustrates a moderate low-pressure system covering much of the domain, accompanied by enhanced onshore flow. Pattern 7 is the strongest high-pressure regime, with pronounced (normalized) offshore winds, and occurring 14.34% of the time (the highest frequency among all nodes). Pattern 8 is a transitional regime that shows a northward-displaced anticyclone and development of a modest low-pressure feature over Southern California. Lastly, pattern 9 depicts an additional northward displacement of the anticyclone, while the cyclone is centered near the Pier, generating strong (normalized) onshore winds.

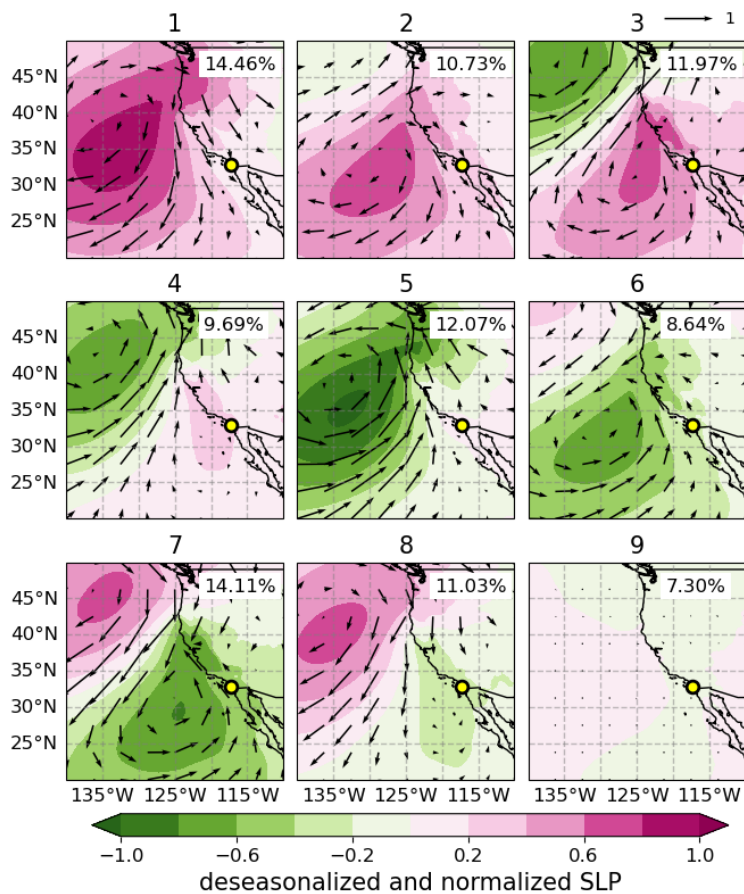
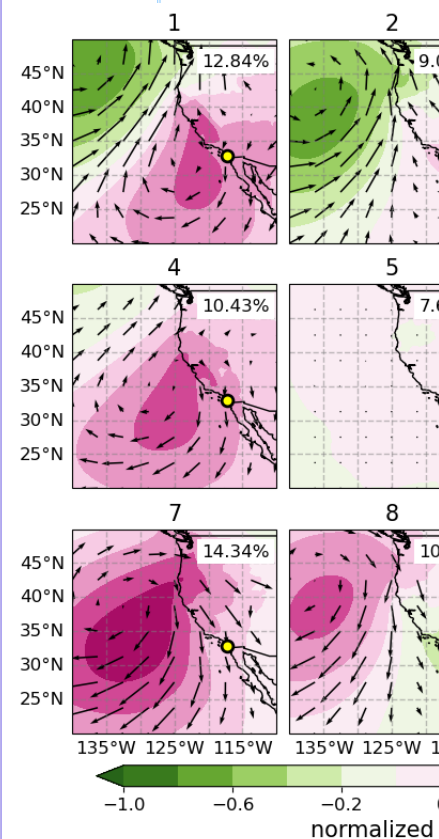


Figure 1: 11-year daily April-September mean composite maps of deseasonalized and normalized SLP and 975 hPa wind fields for the 9 regimes determined from SOM. Clusters are labelled from 1 to 9, and their frequency of occurrence is listed in percentage on the upper-right corner of each map. The yellow circle represents the location of the EPCAPE main site Scripps Pier.

3.2 General features of the synoptic regimes

We use SLP and wind fields in the boundary layer (975 hPa, ~ 300 m a.s.l.) and the free troposphere (750 hPa, ~ 2.5 km a.s.l.) for describing the circulation and transport pathways during

Deleted: It is interesting to observe a coherent transition of the anticyclone-cyclone system that resembles the evolution of weather disturbances, reflected in this clockwise order of clusters: 4, 1, 2, 3, 6, 9, 8, and 7. This SOM-based pattern classification serves as a foundational framework for identifying the dominant synoptic regimes during April to October, 2023 EPCAPE campaign period. By linking large-scale meteorological patterns to observed cloud and aerosol variability at the coast, this classification provides a valuable basis for understanding the meteorological processes that control the marine boundary layer evolution across the Southern California.



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523 April-September 2023 of EPCAPE campaign. Table S1 summarizes the monthly occurrence
 524 frequency of the 9 regimes for the period of study. In addition, low-cloud control variables
 525 examined here include vertical velocity in pressure coordinates at 500 hPa (ω_{500}), 750 hPa relative
 526 humidity (RH_{750}), and lower tropospheric stability (LTS). LTS is defined as the difference in
 527 potential temperature (θ) between 750 hPa and the surface (similar to Klein and Hartmann, 1993).
 528 The meteorological fields for each regime are depicted as mean composites in Fig. 2, and as
 529 anomalies relative to the monthly running mean in Fig. 3. While the discussion is mainly guided
 530 by Fig. 2, Fig. 3 provides quantitative information of magnitude changes of the deseasonalized
 531 fields. The SLP patterns in Fig. 2 features a dominant anticyclone with varying values of
 532 magnitude and extent anticipated by Fig. 1. In contrast, regime 1 depicts the strongest development
 533 of the anticyclone, with boundary layer winds exceeding 10 m/s near the Scripps Pier. Similarly,
 534 the high-pressure system is well developed in regimes 7 and 8, but with their core displaced farther
 535 northwest than in regime 1, and with wind speeds greater than 10 m/s. Regime 2 shows a
 536 moderately developed anticyclone but with relatively modest deseasonalized values (Fig. 3a), with
 537 its center aligned with the latitude of Scripps Pier. Regimes 1, 2, 7, and 8 feature wide areas of
 538 subsidence ($\omega_{500} > 0$) and consistent free tropospheric drying ($RH_{750} < 30\%$) over the ocean. For
 539 these regimes with intense mean and deseasonalized anticyclone, we observe a strengthening of
 540 the coastal winds parallel to the coast south of 40°N. Notably, these coastal winds tends to be
 541 stronger in the boundary layer (Fig. 2a, arrows) than in the lower free troposphere (Fig. 2b, arrows),
 542 which is a common feature of the coastal low-level jet around Cape Mendocino (40.4°N, Parish,
 543 2000). Regimes 3, 4, and 5 are unique in that they feature a weak cyclonic circulation north of
 544 40°N, with westerly winds north of 35°N, and concomitant with 500 hPa ascents (Fig 2a, $\omega_{500} <$
 545 0). Regime 9 features the climatological mean pattern, as discussed in Section 3.1.

546 In terms of 750 hPa winds, consistent with the strengthening of the anticyclonic and
 547 cyclonic circulation, regimes 3–5 exhibit a dominant zonal component, suggesting transport of
 548 marine air masses inland. For 1, 2, and 8 (anticyclones), winds run parallel to the coast, potentially
 549 contributing with a mixture of continental and marine air masses to Scripps Pier. For regimes 6–
 550 7, the wind direction shows dominant meridional component. There is an increase in LTS for all
 551 the regimes with values > 20 K for the broad coastal area south of 40°, except that regimes 4 and 5,
 552 show slightly lower LTS. It is, nevertheless, surprising that deseasonalized anomalies in Fig. 3b
 553 show modest variability for the same coastal area, especially near Scripps Pier, with inter-regimes

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Deleted: Regime 3 captures the weakest anticyclone and confined to the south of the EPCAPE site, a weak cyclonic region over the northern area, and relatively weak winds (< 5 m/s) in the boundary layer. In contrast, Regime 7

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differences smaller than 3 K, and with unclear connections with the atmospheric circulation depicted in Fig. 3a. This implies that the patterns of the mean LTS in Fig. 2b primarily reflect seasonal changes rather than synoptic-scale processes. As we will see in the following sections, the modest variability in LTS cannot explain changes in the cloud fields, confirming the poor correlation between LTS and cloud cover at synoptic scales reported by a number of studies (e.g. Klein et al., 1997).

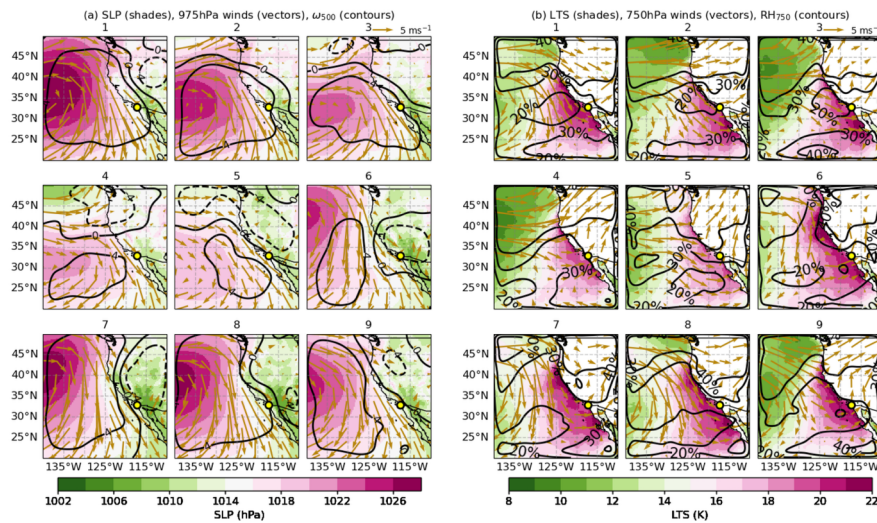
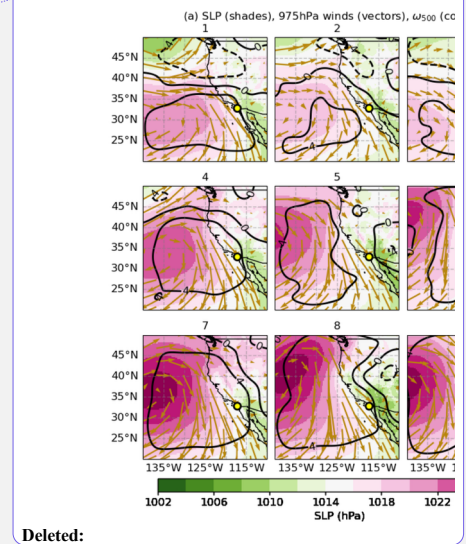


Figure 2. Composite maps of mean meteorological fields for the nine synoptic regimes identified for April–September 2023. (a) Sea level pressure (SLP; color shading), 975 hPa winds (vectors), and pressure vertical velocity at 500 hPa ($\times 10^{-2}$ Pa/s; black contours). (b) Lower tropospheric stability (LTS; shading), 750 hPa winds (vectors), and relative humidity at 750 hPa (RH_{750} ; black contours).



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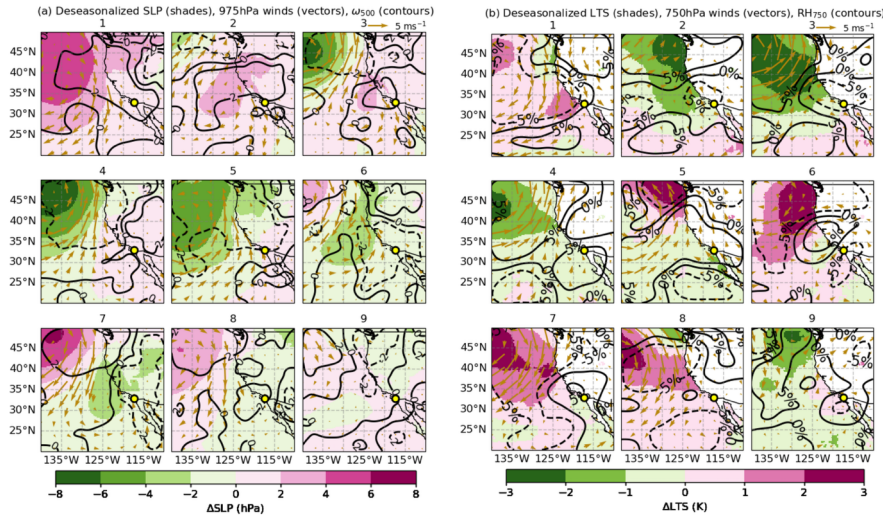
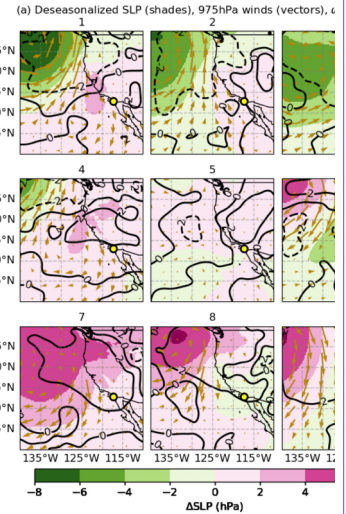


Figure 3. Deseasonalized meteorological fields (using the 30-day running mean) for the nine synoptic regimes identified for April–September 2023. (a) SLP (color shading), 975 hPa winds (vectors), and pressure vertical velocity at 500 hPa ($\times 10^{-2}$ Pa/s; black contours). (b) LTS (shading), 750 hPa winds (vectors), and relative humidity at 750 hPa (RH_{750} ; black contours).

3.3 Atmospheric structure derived from Radiosonde observations at Scripps Pier across nine synoptic regimes

After providing a regional description of the atmospheric variability over the coastal NEP, we center our attention on the thermodynamical properties of the lower troposphere derived from radiosonde observations collected during EPCAPE at Scripps Pier. Figures 4 and 5 provide, respectively, median and deseasonalized atmospheric profiles for each regime. The boundary layer for all regimes is statically stable, with mean LTS values ranging between 15 – 20 K (Fig. 4a). Regime specific features are more easily observed in the θ anomaly (deseasonalized) profiles in Fig. 5a. Regimes experiencing an anomalous anticyclonic (e.g., regimes 3, 4, 5) or cyclonic circulation (e.g., regimes 7, 8) around the Pier depict negative θ anomalies (about -1 K) within the boundary layer, while the other regimes generally show positive θ anomalies. In terms of relative humidity, most regimes maintain high RH ($> 80\%$) in the boundary layer with the expected sharp



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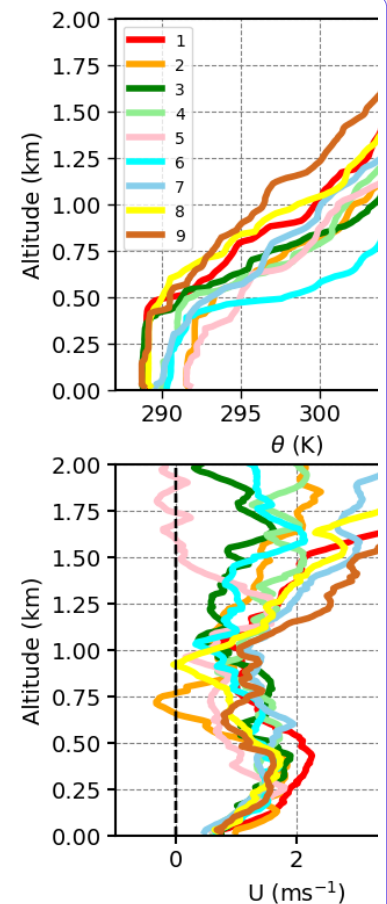
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decrease in the free troposphere (Fig. 4b). Median RH profiles suggest shallow MBL tops (< 1 km) in most regimes, while regimes 7 and 8 feature slightly deeper boundary layers extending beyond 1 km. These regimes are associated with anomalous cyclonic dominant synoptic conditions that promote upward moisture transport, particularly regimes 7 and 8, which maintains elevated RH throughout the lowest 2 km, consistent with moist northwesterly flow and enhanced ascent (Zhou et al., 2015). In addition, stronger boundary-layer turbulence from intensified winds and upper level wind reversal enhancing entrainment under relatively weaker static stability, likely contribute to the boundary-layer deepening observed in regimes 7 and 8. Consistently, these regimes also exhibit positive RH anomalies. Regimes 1 and 2 are typically associated with anomalous high-pressure and associated subsidence in coastal regions and exhibit weak negative RH anomalies.

Wind profiles in Fig 4c generally feature a westerly component with magnitude of less than $\sim 2 \text{ m s}^{-1}$ in the boundary layer. Meridional wind (V) profiles are more revealing of the position and strength of the anticyclone: Most regimes are dominated by a modest but persistent northerly flow (negative V), consistent with cold air advection and coastal subsidence typical of summertime marine stratus regimes (Parish et al., 2000). On the other hand, regimes 7 and, to a lesser extent, 8 display southerly flow (positive V), indicative of warm, moist advection into the coastal boundary layer, likely enhancing turbulence and transport of aerosol from southern shore to the Pier (Painemal et al., 2013a).

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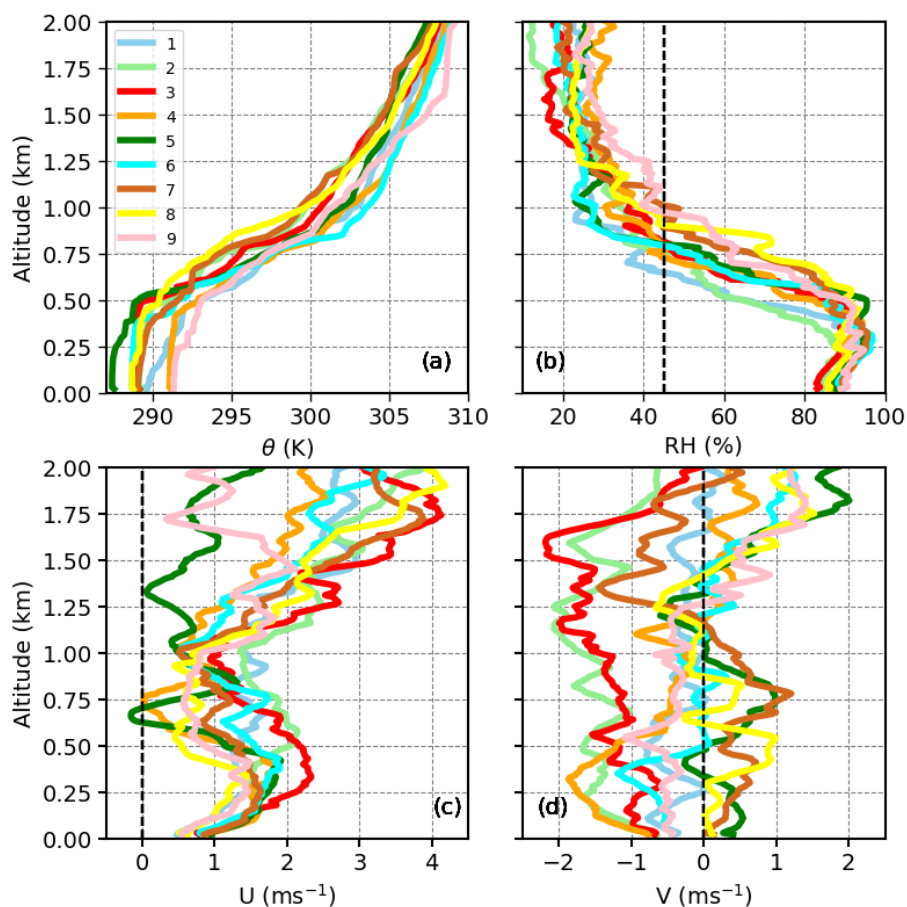


Figure 4. Regime-composite median vertical profiles of thermodynamic variables for the lowest 2 km from radiosonde observations for April to September 2023, for the nine synoptic regimes. (a) potential temperature (θ), (b) relative humidity (RH), (c) zonal wind (U), and (d) meridional wind (V). Vertical dashed line in (b) indicate 45 % RH threshold depicting BLH. The width of the 95 % confidence intervals (CIs) of these profiles suggests that most regimes are significantly different from each other, except for regime 6 where the width of CIs of potential temperature profiles were large.

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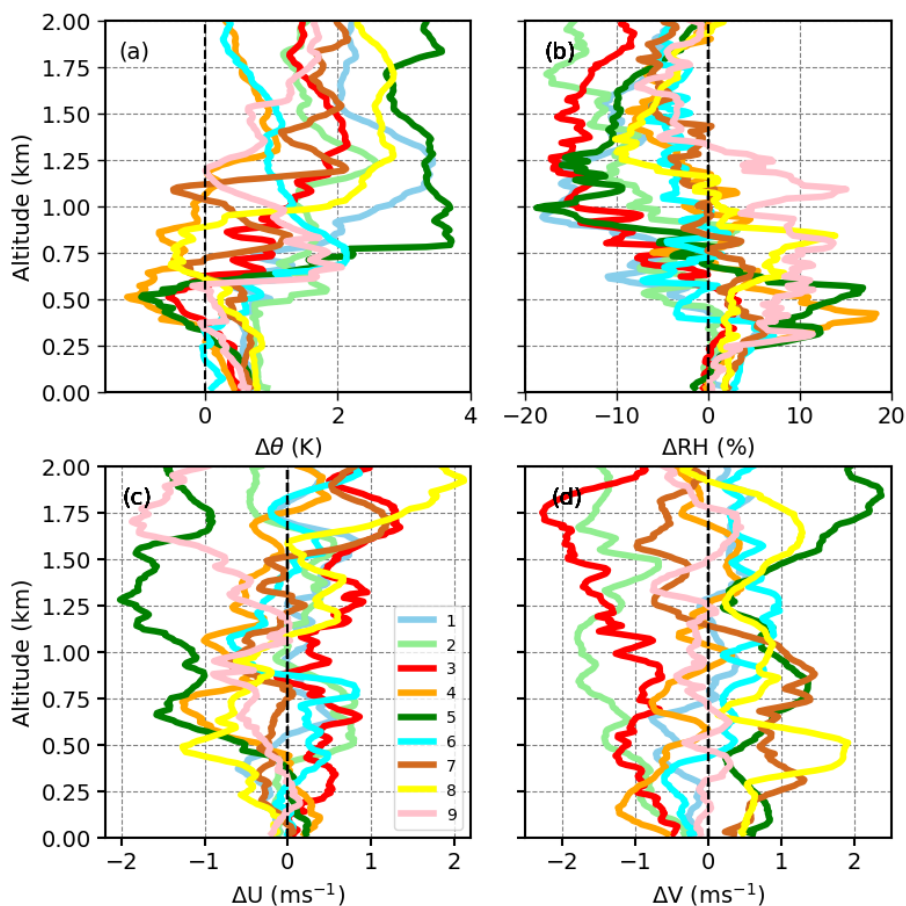
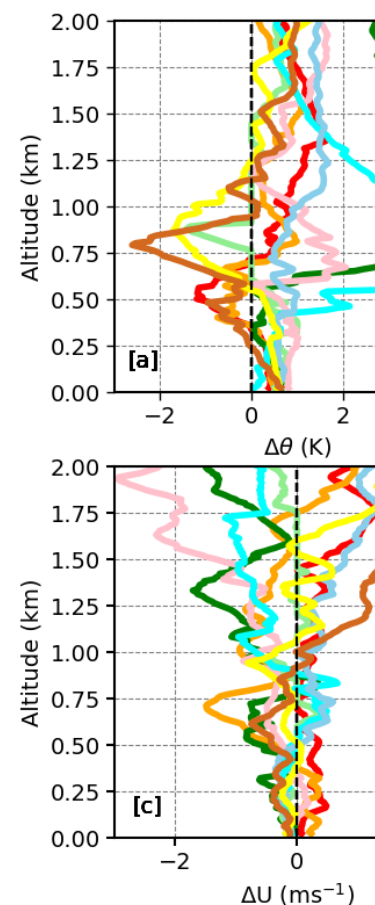
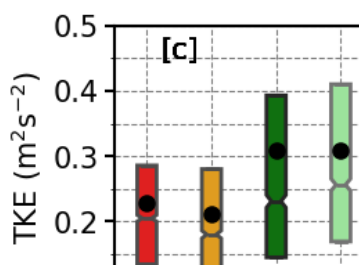
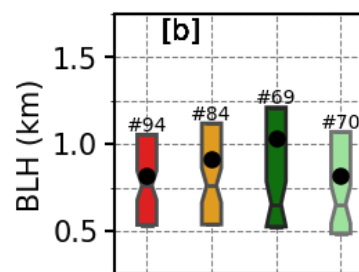
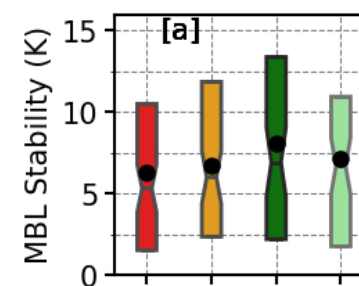


Figure 5. Regime-based median profiles of the deseasonalized thermodynamic variables for the lowest 2 km for April to September 2023, computed as deviations from the 30-day running mean. (a) Potential temperature anomaly ($\Delta\theta$), (b) relative humidity anomaly (ΔRH), (c) zonal wind anomaly (ΔU), and (d) meridional wind anomaly (ΔV). Dashed vertical lines represent the zero-anomaly reference.



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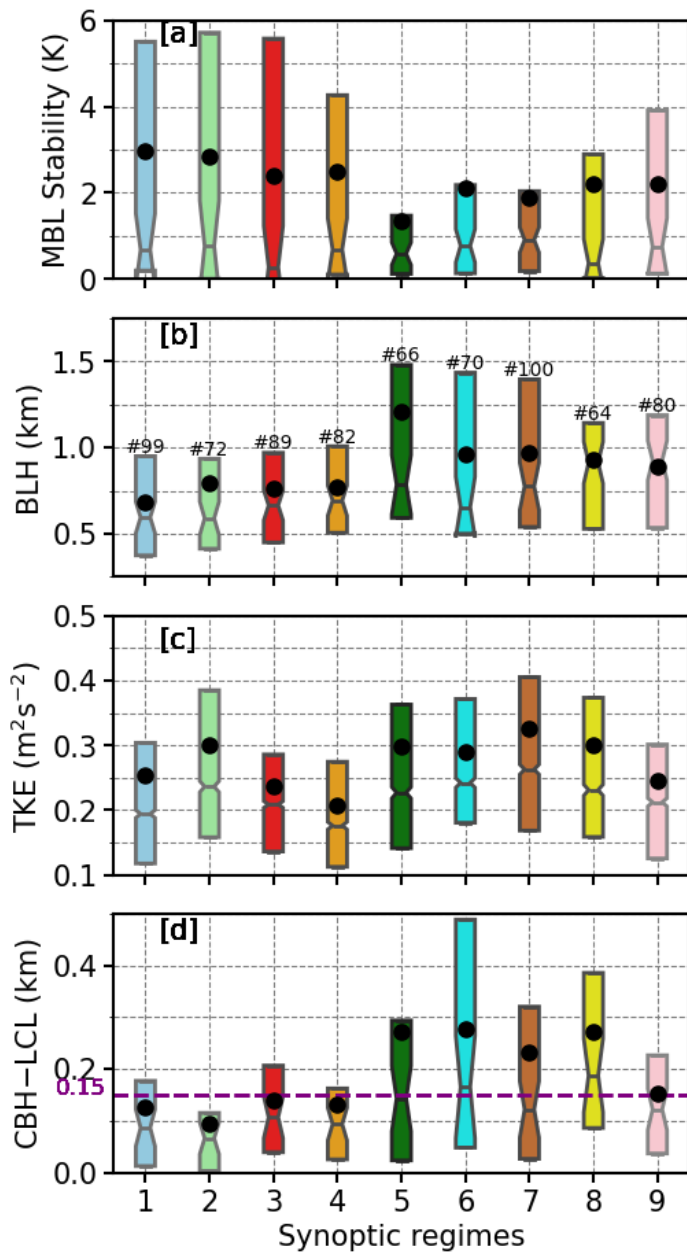


Figure 6: Boxplot of (a) MBL stability metric, (b) boundary layer height (BLH), (c) turbulent kinetic energy (TKE), and (d) CBH – LCL difference, for the nine synoptic regimes for April to September 2023 at Scripps Pier. Boxes show interquartile range with medians marked by horizontal lines, and black circles denote the mean. *Notches represent the 95% confidence interval of the median, according to the test described in Krzywinski and Altman, (2014).* The magenta dashed line in (d) marks the 150 m threshold used in Jones et al. (2011) to identify decoupled boundary layers. *The number of samples for each regime is shown on the figure panel (b).*

Specific properties that characterize the boundary layer are presented in Fig. 6. Boundary-layer stability is quantified from radiosonde observations using a MBL stability metric, defined as the potential temperature difference between 700 m and the surface. Regime-mean values range from 5 to 10 K, with larger values indicating a more stable MBL and smaller values reflecting enhanced turbulence. *Although the medians are below 1 K, regimes 1-4 exhibit larger mean values (~2 K to 3 K) and wider upper-quartile range (> 6 K), representing the stable boundary layer.* Conversely, regimes 5-8 exhibit weakest stability, with mean values (≤ 2 K), consistent with a less stratified boundary layer and enhanced turbulence mixing. The boundary layer height (BLH) is simply estimated as the altitude for which RH drops below 45 % (Bretherton et al. 2010). BLH exhibits moderate variability across regimes (Fig. 6b). *Consistently, regimes 1-4 exhibit shallowest boundary layers with mean BLH ~750 m, consistent with stronger subsidence that inhibits vertical development of the MBL.* In contrast, regimes 5-8 are characterized by substantially deeper boundary layer. Deeper MBL is typically conducive to enhanced vertical cloud extent and increased LWP, a trend consistent with the regime-specific cloud structures to be discussed in Sections 3.4 and 3.5.

Figure 6c shows the distribution of TKE across the synoptic regimes, highlighting substantial regime-dependent modulation of boundary-layer turbulence. *TKE is highest in regimes 5-8 with mean values of approximately 0.3–0.35 m² s⁻², indicating the favoring of strong boundary layer mixing.* In contrast, regimes 1-4 (with the exception of regime 2) exhibit lower mean TKE of about 0.20–0.25 m² s⁻², representing a weakly turbulent boundary layer. *Regime 9 shows intermediate behavior, with turbulence levels ranging between those of the shallow, stable regimes and the deeper, less stable regimes.* Lastly, regime 7 depicts moderate mean TKE, which is also regime with deeper and a weakly stratified BL.

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783 The difference between cloud base height (CBH) and the lifting condensation level (LCL)
 784 provides insight into the degree of cloud-boundary layer coupling (Fig. 6d). A CBH–LCL
 785 separation exceeding approximately 150 m (highlighted by the dashed line) typically signifies
 786 decoupled conditions, wherein the cloud layers are no longer directly connected to the surface
 787 moisture supply and below-cloud turbulence (Wood and Bretherton, 2004; Jones et al., 2011).
 788 Regimes 5–8 frequently exhibit upper quartiles with CBH–LCL values that exceed the 150-m
 789 threshold, indicating frequent decoupling. Conversely, regimes 1–4 maintain tightly clustered
 790 CBH–LCL distributions near or below 150 m, indicative of well-coupled marine boundary layers.
 791 In such regimes, cloud bases closely follow the lifting condensation level, enhancing aerosol–
 792 cloud interactions and generally supporting higher N_d as discussed in the section 3.6, assuming
 793 sufficient aerosol availability (Wood, 2012).

795 3.4 Cloud characteristics for synoptic regimes

796 To characterize the link between synoptic-scale meteorology and low-level clouds along
 797 the Southern California coast during the EPCAPE, we create regime composites of SatCORPS
 798 GOES-18 cloud properties. Figure 7 presents the spatial mean distributions of key low-level cloud
 799 properties: low-level cloud fraction (LCF), N_d , LWP, and CTH. Figure 8 shows the corresponding
 800 spatial anomalies of these variables, calculated relative to the 30-day running mean climatology.
 801 Figs. 7a and 8a show that low-level clouds are less frequent when the subtropical anticyclone
 802 center is closer to the coastal Southern California or if it is weaker (regimes 1–5). In these regimes,
 803 the fractional low-cloud amount is below 50 % along the shoreline and increased to 70 – 80 %
 804 over the southern offshore domain. About 10 - 20 % of mid+high cloud incidence (Fig. S2) in
 805 these regimes along the coastline indicates that the corresponding low-cloud reduction is partially
 806 attributed to obscuration of higher clouds in the satellite sensor field of view. Notably, regime 5 is
 807 partially linked to synoptic storm systems in midlatitudes, indicating that deeper convection and
 808 frontal systems may play a dominant role in shaping the clouds in this regime. In contrast, regimes
 809 characterized by an offshore high pressure and a developing low pressure over land (regimes 6–8)
 810 display greater low cloud amount exceeding 70 % along the southern California shoreline and
 811 wider offshore. Indeed, the positive deseasonalized anomalies in LCF were above 10 % in these
 812 regimes and this increase in low-cloud coverage is consistent with wide regions with subsidence
 813 and a reinforcement of the northerly winds (Fig. 2a), two factors that favor the strengthening of

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831 the thermal inversion (Myers and Norris, 2013; Wood, 2012). Regime 9, the regime closest to
832 climatological neutrality, displays average LCF values of $\sim 70\%$, but shows negative anomalies
833 (~ 5 to 10%) around the EPCAPE site.

834 Figures 7b and 8b show the spatial mean and anomaly fields of SatCORPS GOES-18
835 N_d across the nine synoptic regimes. All regimes exhibit a strong coastal gradient in N_d with local
836 maxima ($>200\text{ cm}^{-3}$) occurring nearshore and a systematically westward decrease. This well-
837 known pattern is consistent with an expected continental aerosol outflow, dilution and precipitation
838 scavenging offshore. Interestingly, under well-developed high-pressure conditions with stronger
839 boundary layer winds (e.g., regimes 1- 8 with the exception of regime 6), N_d enhancement is
840 limited to a narrow coastal band and decreases abruptly to $\sim 100\text{ cm}^{-3}$ offshore. This suggests that
841 intense anticyclonic circulations hinder the transport of continental aerosol over the open ocean,
842 confining CCN sources to coastal regions. Notably, regime 6 features the largest extent of positive
843 N_d anomalies and mean values greater than 175 cm^{-3} , associated with a northwest displacement of
844 the anticyclone and winds that run parallel to the coast north of 35°N . This unique synoptic
845 configuration was also identified in Painemal et al. (2015) as the circulation that drives the highest
846 N_d during MAGIC over the NEP.

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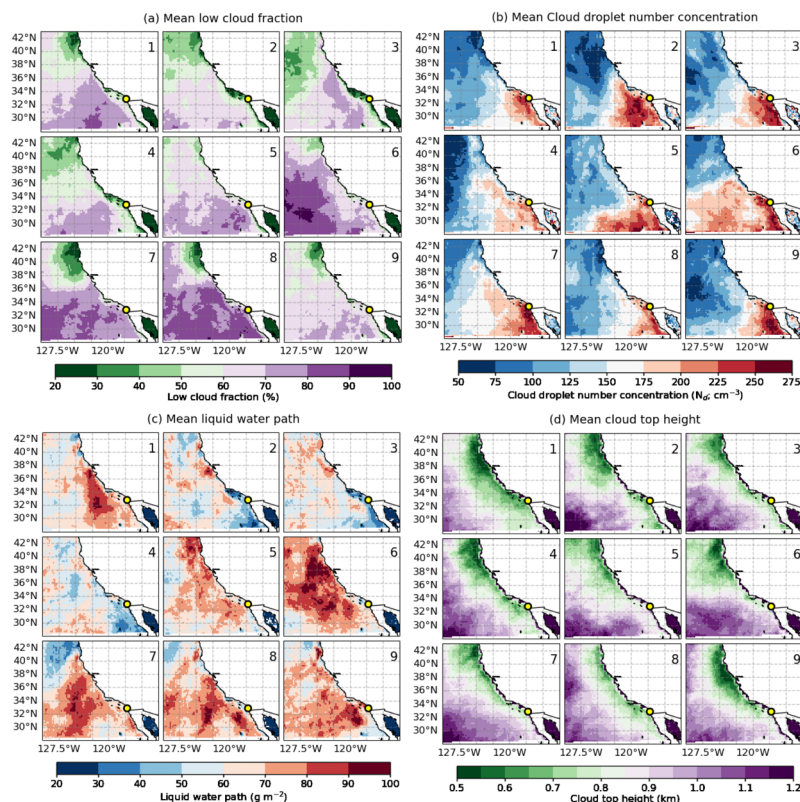
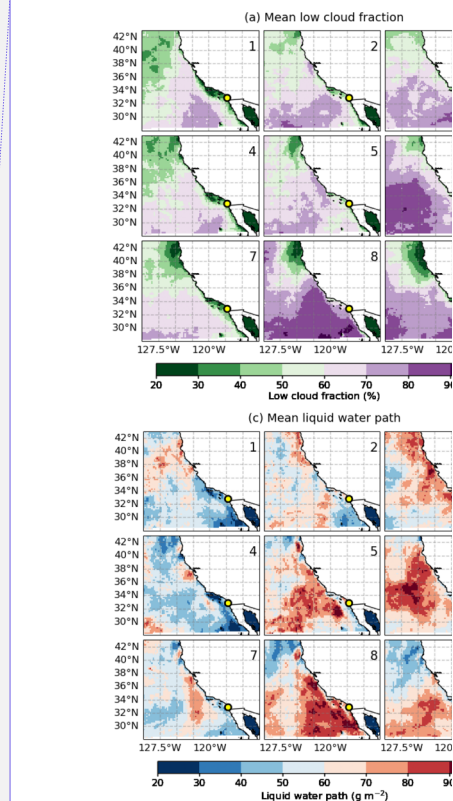


Figure 7: SatCORPS GOES-18 cloud properties composited across nine synoptic regimes for April to September 2023. (a) low-cloud fraction, (b) cloud droplet number concentration, (c) liquid water path, (d) cloud top height, for the daytime warm boundary layer clouds with low cloud fraction > 10 %, cloud optical depth > 2, and LWP range 5 – 250 g m⁻². The magenta circle indicates the Scripps Pier site.

The LWP variation in 9 synoptic regimes are featured in Fig. 7c and 8c. Broadly, the regimes of anomalous high-pressure areas around the coastal Southern California (e.g., regimes 2, 3, 4) with developing cyclone in the northwest relate well with the regimes of lower LWP below 60 g m⁻² along the coast, and anomalies reaching as much as 20 g m⁻² less than the mean



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878 climatology. These regimes are often characterized by shallower marine boundary layers with
 879 CTH below 800 m. Regimes 6-9 exhibit enhanced LWP frequently exceeding 75 g m^{-2} across
 880 large spatial extents. These regimes also show strong positive LWP anomalies, in some cases
 881 surpassing 20 g m^{-2} compared to climatological means. High values of LWP in these regimes
 882 appear to coincide with regimes of anomalous cyclone to the coast and a boundary layer deepening
 883 (Fig. 8d). Regionally, satellite CTH (Fig. 7d) shows shallower clouds along the coast (a region
 884 with cooler sea surface), with cloud top deepening farther offshore over warmer waters. Most
 885 synoptic regimes exhibit mean CTH values within 800 m along coastal California, except regimes
 886 5-7, which reach $\sim 1 \text{ km}$. Deseasonalized CTH patterns highlight distinct variations: most
 887 anomalous anticyclone dominant regimes (1-4) display systematically lower cloud tops, while the
 888 other regimes except regime 8 show higher cloud tops, particularly over the Southern California.

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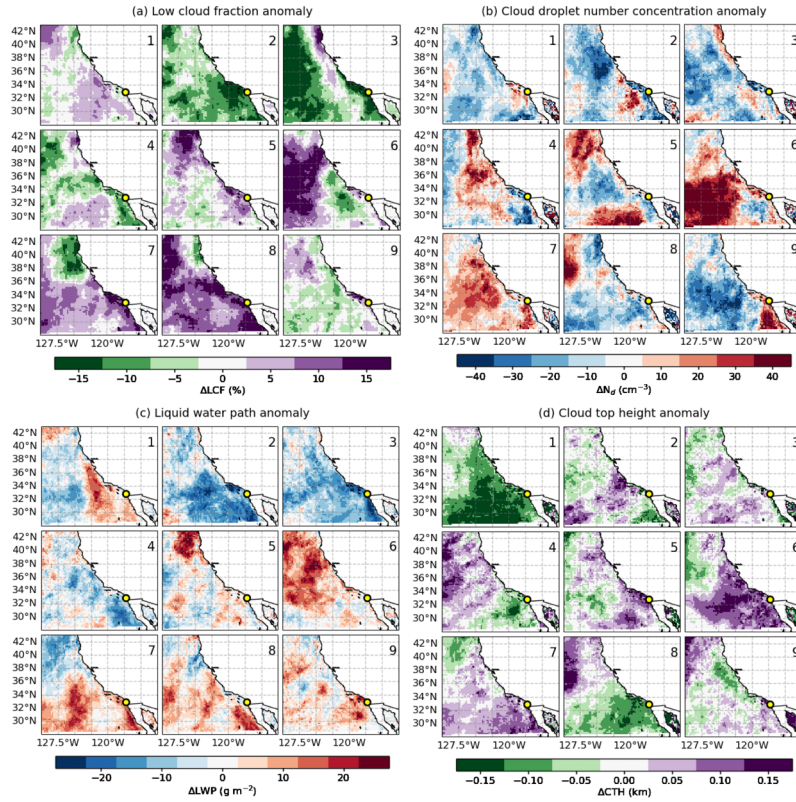
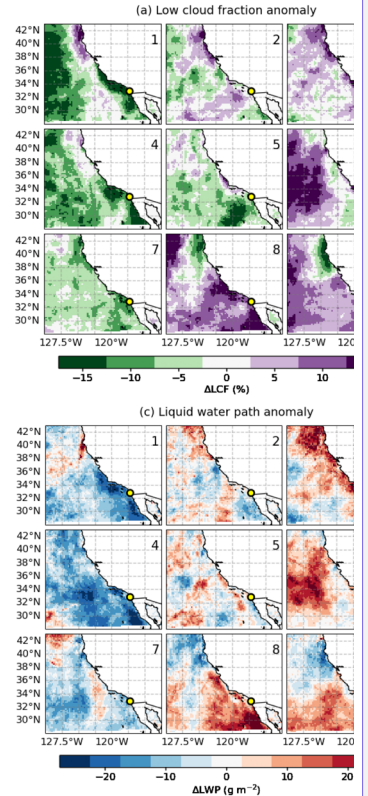


Figure 8: SatCORPS GOES-18 composite anomalies across nine synoptic regimes for April to September 2023. (a) low-cloud fraction, (b) cloud droplet number concentration, (c) liquid water path, (d) cloud top height, for the daytime warm boundary layer clouds with low cloud fraction > 10 %, cloud optical depth > 2, and LWP range 5 – 250 g m⁻². The magenta circle indicates the Scripps Pier site. Anomalies are computed relative to the 30-day running mean climatology.

3.5 Cloud characteristics from observations at Scripps Pier

Regime-specific comparison of SatCORPS satellite retrievals and EPCAPE ground-based observations of key cloud properties are shown in Fig. 9. The SatCORPS satellite data here correspond to the 0.2° grid box around Scripps Pier. Both GOES-18 and KAZR-derived CTHs



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927 exhibit similar variability across regimes however satellite derived CTHs shows consistently
 928 higher range up to an overestimate of ~250 m. A key difference is the smaller lower quartile
 929 magnitude for the KAZR, likely attributed to the ability of the radar to detect small shallow
 930 cumulus clouds that are undetected at the satellite pixel resolution. Both the ground based and
 931 remotely derived CTH show the shallowest median cloud tops (<1000 m) in regimes 1-4, where
 932 the anticyclone is centered closer to Scripps Pier, as indicated by positive SLP anomalies over the
 933 pier and adjacent land areas (Fig. 7d and 8d). In contrast, deeper cloud tops are observed in regimes
 934 with an anticyclone accompanied by a weak coastal low (regimes 5-8, Fig. 2a), reflected in
 935 negative anomalous SLP around Scripps Pier (Fig. 3a). To note, highest surface precipitation
 936 events were noticed in regimes 6 and 7 (0.45 % and 0.95 % occurrence frequency) although which
 937 is < 0.1 % occurrence frequency and the datasets are removed from the analysis. The ceilometer
 938 derived CBH in Fig. 9b shows that regime 6 often develops cloud bases closer to the surface
 939 (median ~ 250 m), under the most stable boundary layer conditions (Fig. 6a). The mean ceilometer
 940 derived CBH in Fig 9b is within 450 m in regimes with an anticyclone centered close to Scripps
 941 Pier (regimes 1-4). Regimes 5-8, on the other hand, show the highest mean cloud base (> 600 m)
 942 in accordance with increased TKE, deeper, and decoupled BL. Figure 9c shows LWP variation
 943 across the regimes, from both the ground-based MWR and GOES-18 SatCORPS retrievals, both
 944 exhibit broadly consistent regime-to-regime variability except that the MWR LWP are slightly
 945 higher. At the Scripps Pier site, regime 2, characterized by moderate synoptic forcing, shows the
 946 lowest mean LWP. Regimes 5-8 consistently exhibit reduced LWP, whereas the climatologically
 947 closer depicting regime 9 displays largest LWP.

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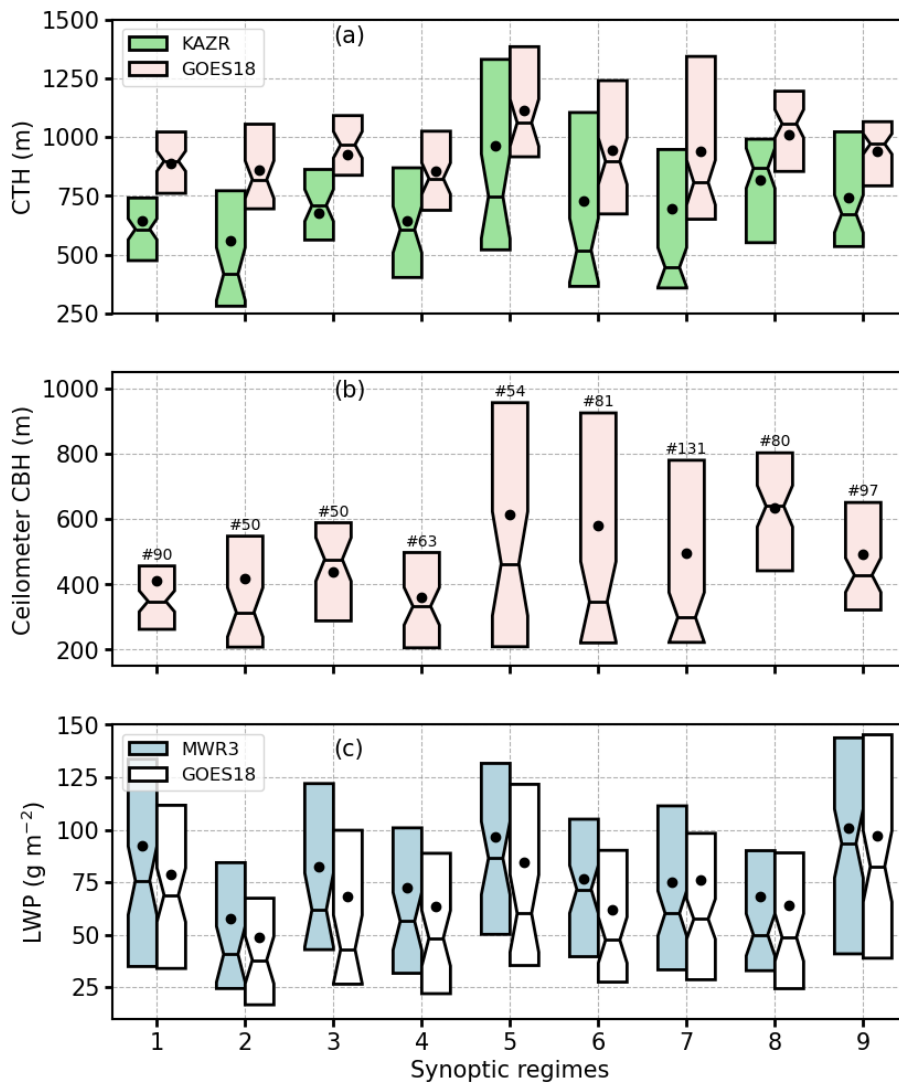
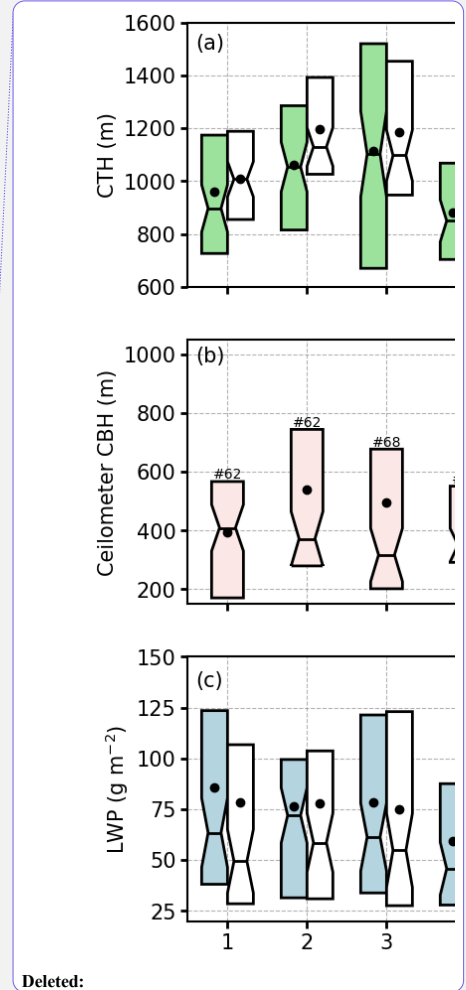


Figure 9: Comparisons of SatCORPS GOES-18 satellite vs. EPCAPE ground-based observations of (a) cloud top height, (b) cloud base height, and (c) liquid water path for the daytime, non-precipitating warm boundary layer clouds with hourly cloud frequency $\geq 20\%$, low cloud fraction $> 10\%$, cloud optical depth > 2 , and LWP range $5 - 250 \text{ g m}^{-2}$. Notches represent the 95%



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confidence interval of the median. The number of samples for each regime is shown on the panel(b).

3.6 Aerosol and cloud droplet concentration at Scripps Pier

To assess how synoptic regimes modulate aerosol variability and transport at Scripps Pier, we analyze number concentrations of smaller particles ($N_a \leq 0.1 \mu\text{m}$, $N_{a \leq 0.1}$) and larger accumulation-mode particles ($0.1 < N_a < 1 \mu\text{m}$, $N_{a > 0.1}$), derived from merged SMPS and APS measurements (Fig. 10a). Smaller particles are typically associated with fresh local emissions and pollution, whereas larger particles reflect aging-driven growth or contributions from marine and continental sources such as sea spray or dust. Both size modes exhibit substantial variability across synoptic regimes. As inferred from Fig. 10a, upper quartile concentrations of $N_{a \leq 0.1}$ exceed 600 cm^{-3} for all the regimes, but with the lowest medians for regimes 6 and 9. While $N_{a > 0.1}$ generally follow a similar regime evolution with the median values $> 300 \text{ cm}^{-3}$, regimes 3, 4, and 9 exhibit a narrow range of these particles. Overall, $N_{a \leq 0.1}$ are significantly higher than $N_{a > 0.1}$ in most regimes.

In terms of CCN at 0.2% of supersaturation ($\text{CCN}_{0.2\%}$, Fig. 10b, blue), regime changes are somewhat similar to $N_{a > 0.1}$, with concentrations comparable to those for $N_{a \leq 0.1}$. CCN at 0.1 % supersaturation ($\text{CCN}_{0.1\%}$) is, as expected, smaller than $\text{CCN}_{0.2\%}$ but with qualitatively similar regime changes. The accumulation mode particle concentration $N_{a \leq 0.1}$ is higher than CCN concentrations at 0.1% SS but lower than CCN concentrations at 0.2% SS. This finding is consistent with Dedrick et al. (2026) that found SS below 0.2 % at Scripps Pier. Changes in CCN with supersaturation can be further analyzed in the context of clouds by examining variation in N_d derived from GOES-18 and from the remote sensors at the pier (Fig. 10c). N_d values are similar to the concentrations for $\text{CCN}_{0.1\%}$, suggesting small magnitudes of supersaturations present in this region, limiting the number of particles activated despite relatively large aerosol concentrations (Fig. 10a). Both satellite and the ground-based remote sensors show similar changes in N_d with regimes, but with larger interquartile ranges for the ground-based observations. The discrepancies between ground-based and GOES-18 N_d cannot be easily explained as we do not count on independent in-situ observations to validate these computations. Therefore, the data interpretation will be based on features common to both satellite and ground-based N_d . Regimes 2 as well as 6-8 consistently exhibit higher N_d with the mean N_d ranging $\sim 250\text{--}400 \text{ cm}^{-3}$, whereas regimes 1, 3,

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4, and 9 show lower mean N_d ($\sim 200 - 250 \text{ cm}^{-3}$). This variability in N_d aligns with TKE pattern in regimes (Fig. 6c); as regimes with stronger turbulence tend to exhibit higher N_d , even when particle number concentrations and CCN concentrations are comparable to, or lower than, those in the weekly turbulent regimes.

While aerosol loading is controlled by synoptic and local variability, N_d responses are likely influenced by BL turbulence and cloud dynamics. For assessing the impact of turbulence in aerosol and cloud droplet concentration, we bin N_d as function of accumulation mode N_a ($N_{a>0.1}$) and TKE bins (Fig. 11). As TKE increases from 0.1 to $0.5 \text{ m}^2 \text{ s}^{-2}$, $N_{a>0.1}$ increase from 320 to 520 cm^{-3} , suggesting that enhanced turbulence is associated with higher concentration of accumulation mode aerosols. In addition, we observe an increase of the ground-based N_d with TKE, with changes that exceed 200 cm^{-3} , reinforcing the role of turbulence in strengthening aerosol activation into CCN. The averaged N_d as a function of TKE and N_a indicates that an increase in N_a combined with strong TKE leads to a higher N_d . It appears that the relationship between TKE and N_d are tighter, only when there is a sufficiently higher concentration of accumulation mode aerosol particles ($N_{a>0.1} > 400 \text{ cm}^{-3}$).

Backtrajectories in Fig. 12 are dominated by a flow that runs parallel to the coast (Han et al., 2025; Maneenoi et al., 2025). A departure from this pattern is observed for regimes 1-3, which feature a significant number ($>30\%$) of trajectories that originate from or intersect land areas. Given the modest changes in the backtrajectory pattern per regime, it is not possible to establish a relationship between long-range transport, backtrajectories, and aerosol variability. This suggests that for this coastal site, local aerosol sources and transport (e.g., land-sea breeze), are, at least, as important as the synoptic meteorology for explaining aerosol variability. In terms of aerosol composition, non-refractive organics is the dominant species at Scripps Pier, followed by sulfate and ammonium (Fig. 13). A synoptic-scale maximum in all species (organics, sulphate, Ammonium and Nitrate) is identified for regime 4. Regimes 3 and 5 exhibit a minimum in organics. With greater percentage of land intersecting trajectories, regime 2 depict higher concentration of organics, however, the species concentrations are non-correlative nature to the land intersecting trajectories likely due to the seasonally dominant marine sources of these species.

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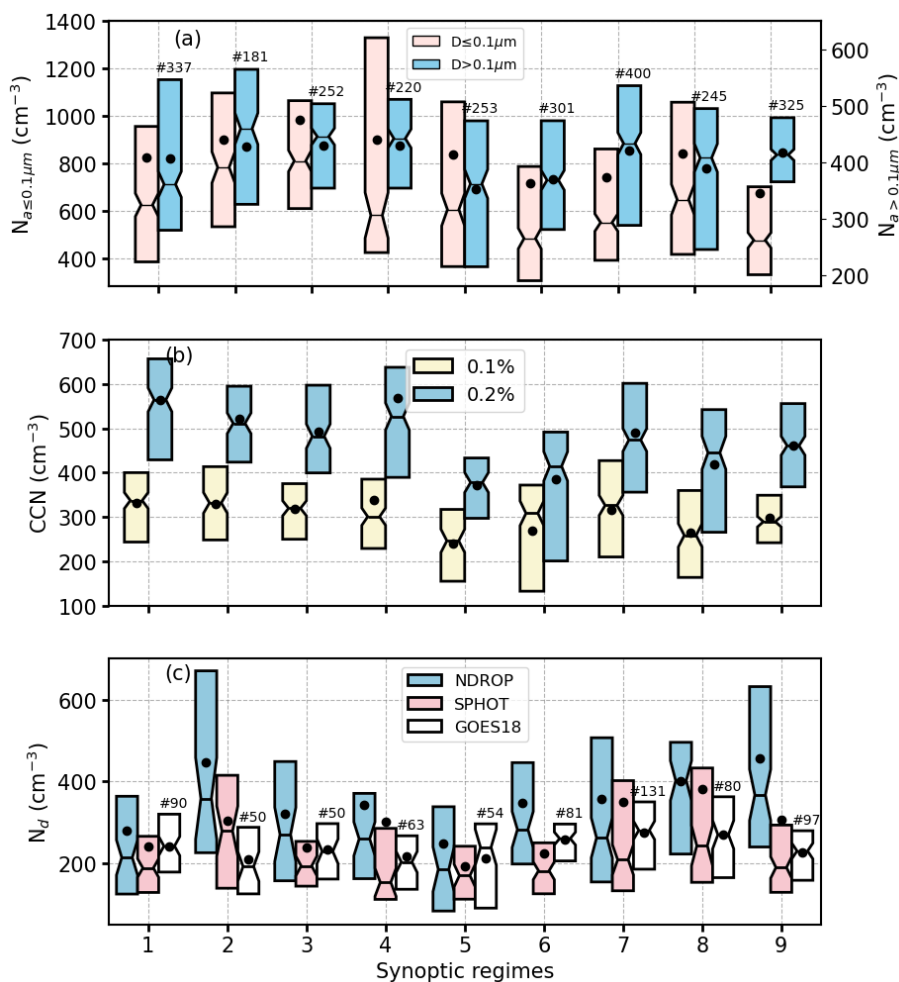
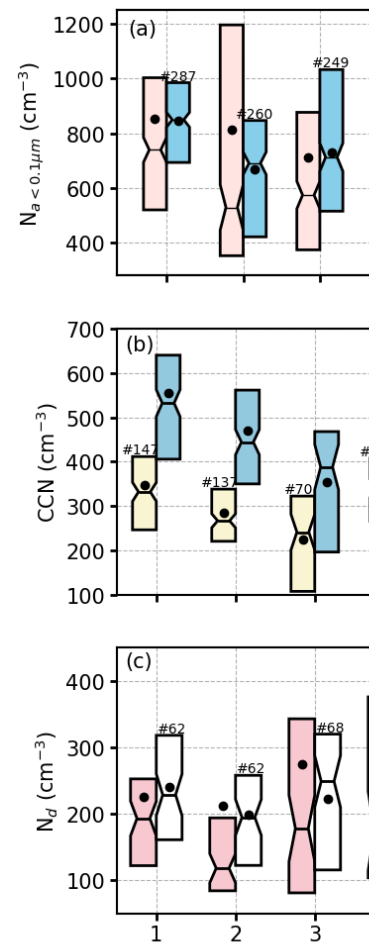


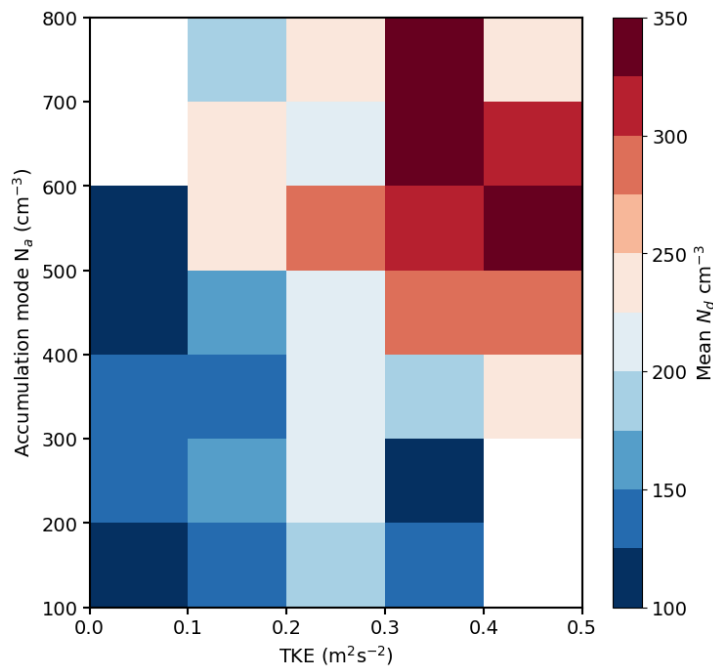
Figure 10: Boxplot of (a) aerosol number concentrations N_a (cm^{-3}), (b) cloud condensation nuclei (cm^{-3}), and (c) cloud droplet number concentration (cm^{-3}) for nine synoptic regimes at Scripps Pier for April to September 2023 for the non-precipitating daytime conditions. Notches represent the 95% confidence interval of the median. The number of samples for each regime is shown on the figure.



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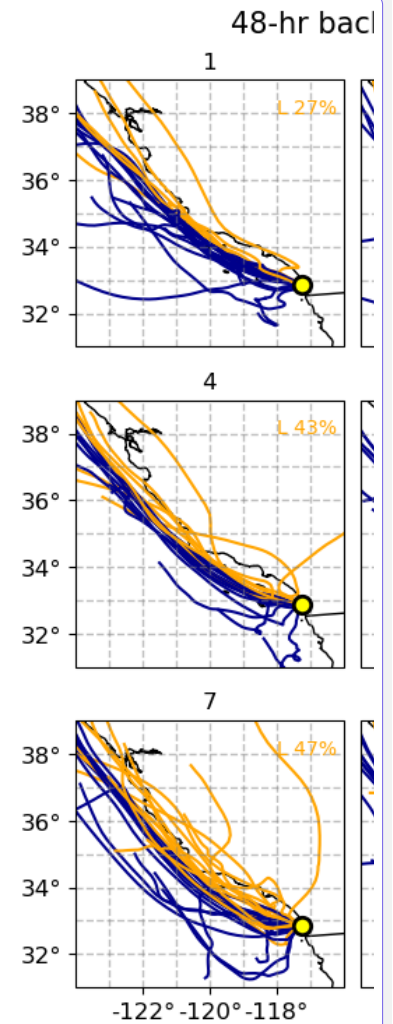
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Figure 11: Relationship between turbulence kinetic energy, and, aerosol and cloud droplet number concentration depicted in a two-dimensional binning of N_d as a function of TKE and N_d for particle size range 0.1-1 μm .



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Figure 11

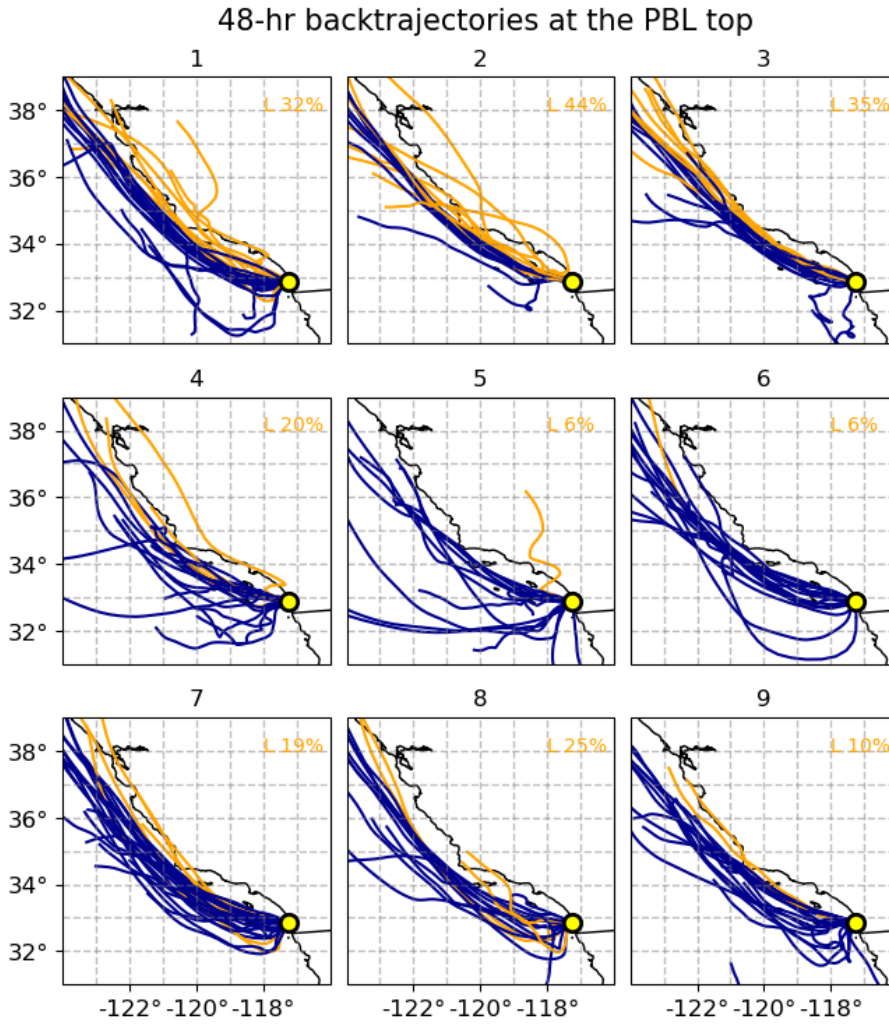


Figure 12: ARMTRAJ-PBL airmass backtrajectories initiated at Scripps Pier (yellow circle) at PBL top for the nine synoptic regimes labelled from 1 to 9. Trajectories from or crossed over land are shown in orange color, and the corresponding percentage of trajectories for each regime is shown on the figure.

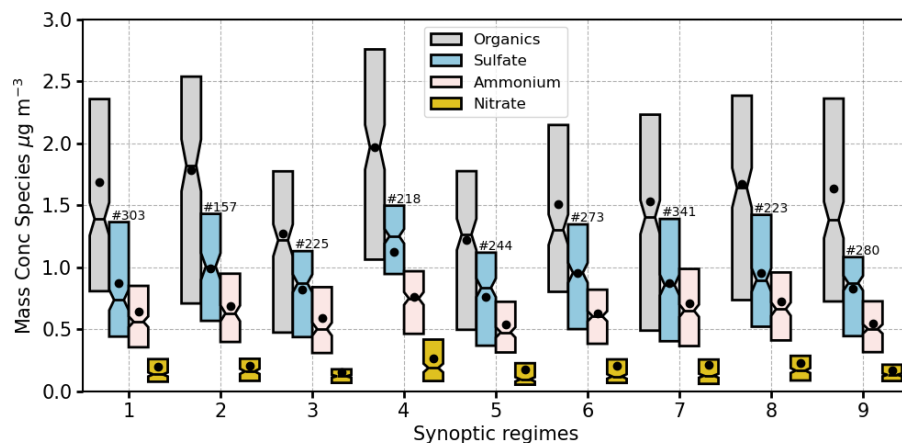
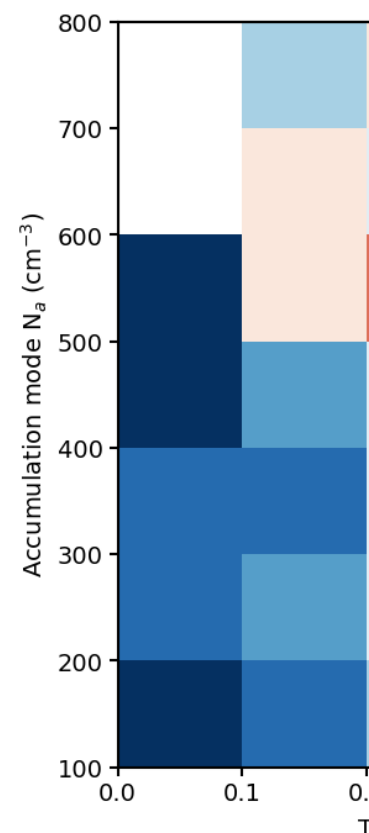


Figure 13: Mass concentration of aerosol composition at Scripps Pier for April to September 2023 non-precipitating daytime conditions for Organics (gray), sulfate (blue), ammonium (pink), and Nitrate (gold). Notches (sometimes negligible) represent the 95% confidence interval of the median. The number of samples for each regime is shown on the figure.

4. Summary and discussions

We classified the atmospheric circulation over the northeast Pacific coastal region using Self-Organizing Maps, with the goal of understanding how synoptic variability modulates changes in aerosol and cloud characteristics. Detailed MBL and local cloud and aerosol observations were provided by the ARM for the ground-based site at Scripps Pier in Southern California and GOES-18 satellite cloud products from SatCORPS during the ARM DOE Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) campaign. We identify nine synoptic regimes, representing dominant meteorological patterns influencing coastal Southern California during April through September 2023. The regimes can be interpreted in terms of the anticyclone/cyclone evolution as follows: regime 1 captures the broadest spatial development of the high pressure, with ubiquitous subsidence. Regime 2 features a relatively well-developed anticyclone at the center of the domain, with a cyclonic development at the northwestern edge of the NEP. The cyclone migrates southward, confining the anticyclone south of 35°N in regimes 3 and 4. This cyclone reaches its maximum southward extent for regime 5, featuring upward motions



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1154 that are typical of midlatitude storms, conditions often associated with heavy precipitation episodes
 1155 (Neiburger et al., 1961; Gershunov et al., 2019). As the low pressure moves eastward over land in
 1156 regime 6, a new migrating anticyclone moves to the northwest, with strengthening and eastward
 1157 displacement in regimes 7 and 8. Regime 9 represents conditions that minimal depart from the
 1158 climatological mean.

1159 MBL structure exhibits pronounced regime-dependent variability, reflecting contrasts in
 1160 stability, humidity, and circulation. Regimes 1-4, with an anomalous anticyclone closer to Scripps
 1161 Pier, are characterized by a shallower boundary layer, weaker turbulence, and coupled MBL. In
 1162 contrast, regimes 5-8, with an anomalous cyclone closer to Scripps Pier and a well-developed
 1163 anticyclone core (particularly for regimes 6-8) north of Scripps Pier, feature a deeper boundary
 1164 layer, weaker MBL static stability, with regime 7 possessing the highest mean TKE. Generally
 1165 speaking, stable boundary layers are associated with the presence of shallow boundary layer,
 1166 (regimes 1-4), while the reduced stability in regimes 5-8, support deeper, more turbulent layers,
 1167 which are conditions typically associated with transition toward shallow cumulus convection
 1168 (Teixeira et al., 2011; Zhou et al., 2015; Bretherton and Blossey, 2017). Zonal winds are modest
 1169 westerlies ($<4 \text{ m s}^{-1}$), whereas meridional winds are predominantly northerlies in all regimes but
 1170 shifts to southerlies in regimes 7 and 8, favoring advection of warm moist air from the south and
 1171 resulting in increased clouds and precipitation. Regime 9 which most closely resembles the
 1172 climatological mean pattern, exhibit MBL characteristics intermediate between those of the stable
 1173 regimes (1-4) and the more turbulent, less stable regimes 5-8.

1174 The regional analysis of SatCORPS GOES-18 regime composites of LCF, N_d , LWP, and
 1175 CTH reveal the influence of synoptic-scale meteorology on low-level clouds along the Southern
 1176 California coast. Across all regimes, cloud cover remains high off the California coast, generally
 1177 exceeding 70 % off California coast. Synoptic regimes characterized by an anticyclone centered
 1178 near 30–35°N and positioned closer to coastal Southern California (regimes 1-4) exhibit slightly
 1179 reduced low-cloud amount (LCF $<50\%$) and negative anomalies (-5 to -15%) along the shoreline.
 1180 In these regimes, the spatial pattern of LWP closely mirrors the reduction in LCF, and CTHs
 1181 remain shallower. Conversely, a northwest displacement of the anticyclone and a weak low-
 1182 pressure pattern inland (regimes 7-8) appear to support extensive stratocumulus (LCF $>75\%$) and
 1183 positive LCF anomalies ($\sim 15\%$) under weaker subsidence along the coast. Regimes 7 and 8 also
 1184 feature a boundary layer deepening (CTH $>1 \text{ km}$) and a consistent increase in LWP. N_d exhibits

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1226 strong coastal gradients for all regimes, exceeding 200 cm^{-3} nearshore and decreasing offshore,
 1227 consistent with continental aerosol outflow and more active precipitation scavenging farther
 1228 offshore (e.g. Wood et al., 2012). Wind strengthening and a flow that runs parallel to the coastline
 1229 for all the synoptic regimes appear to confine aerosol advection to a narrow coastal band, resulting
 1230 in a drastic decrease in N_d of 100 cm^{-3} just 5° degrees west from Baja California (30°N , 115°W),
 1231 except that the regimes 6 and 7 show wider area of greater N_d and positive N_d anomalies
 1232 ($>20 \text{ cm}^{-3}$).

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1233 Comparisons between SatCORPS satellite derived and ECAPE ground-based radar
 1234 observations at Scripps Pier show that the satellite CTH are higher ($\sim 250 \text{ m}$) than the ground based
 1235 radar measurements. The radar can detect small shallow clouds typically well below the inversion,
 1236 which are too small to be resolved at the satellite pixel resolution, which causes satellites to report
 1237 slightly higher cloud tops. Additionally, GOES-18 cloud-top height retrievals can be challenging
 1238 along the shoreline boundaries due to issues with surface temperature. Satellite and the ground-
 1239 based microwave LWP agrees within $5\text{--}20 \text{ g m}^{-2}$ with ground-based LWP being always higher.

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1240 N_d derived from ground-based cloud-mode sun photometer derived cloud optical depth and
 1241 microwave radiometer derived LWP, NDROP N_d (N_d derived from MFRSR derived cloud optical
 1242 depth and microwave radiometer derived LWP), and satellite retrievals show considerable
 1243 variation in range but similar pattern in variation for the synoptic regimes, though the NDROP N_d
 1244 are systematically higher (Fig. 3a, Sorooshian et al., 2019). This N_d comparison also highlights the
 1245 challenges of indirectly deriving N_d with remote sensing observations (e.g., Grosvenor et al.,
 1246 2018). While N_d estimated from GOES-18 has the advantage of being derived with retrievals from
 1247 a radiometrically consistent algorithm, the coarse pixel resolution (2 km) prevents the detection of
 1248 small clouds. While ground-based retrievals are in principle more accurate, the need of combining
 1249 data from 2 different instruments (microwave and visible radiometers) could result in significant
 1250 noise in the estimated N_d , especially when biases in LWP or cloud optical depth are not properly
 1251 characterized. Even though retrievals of cloud droplet effective radius are available from the sun-
 1252 photometer and the multifilter rotating shadowband radiometer, the derivation of r_e from ground-
 1253 based passive radiometers is more prone to uncertainties than cloud optical depth (e.g. Chiu et al,
 1254 2012). Given how critical N_d is for understanding aerosol effects on clouds, future field
 1255 deployments would benefit from dedicated efforts of intercomparing and evaluating N_d products,
 1256 especially when in-situ cloud microphysical observations are available.

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1272 Analysis of particle number concentrations at Scripps Pier reveals that the regime
 1273 classification does not result in evident aerosol changes, possibly because the site is near multiple
 1274 local pollution sources, while winds modestly change at the site during the period of study. Indeed,
 1275 backtrajectories reveal predominantly coastal-parallel flow, with regime 1-3 featuring land
 1276 influence, but minimal trajectory variability, suggesting that local sources and mesoscale processes
 1277 are important for understanding aerosol variability (e.g., land-sea breeze).

1278 CCN concentration at 0.2 % supersaturation mirrors the changes in accumulation mode
 1279 particle concentration, whereas CCN at 0.1 % more closely matches the N_d values. These findings
 1280 aligns with the low values of supersaturation over the coastal region (Dedrick et al., 2026), and
 1281 how this environmental constraint prevents more aerosols from being activated into droplets
 1282 despite high aerosol concentrations. For instance, the highest TKE value for regimes 7-8 are
 1283 concomitant with high mean N_d and the N_d highest upper quartile. Conversely, the lower N_d in
 1284 regimes 1-4, despite having slightly higher concentrations of CCN and accumulation mode
 1285 aerosols, appears to be partially explained by the low turbulence for these regimes. In a broader
 1286 sense, the N_d variability shown in Fig. 11, reflects the combined influence of accumulation mode
 1287 aerosol concentration and boundary layer turbulence, with the highest N_d occurring under
 1288 conditions of both elevated accumulation mode concentrations and enhanced TKE, which are two
 1289 primary factors governing droplet formation. The analysis also suggests that due to weak values
 1290 of supersaturations, a relatively small fraction of large mode aerosols (accumulation mode) is
 1291 activated for concentrations smaller than 600 cm^{-3} , especially when the turbulence is modest. It
 1292 follows that detailed information of updraft velocity and supersaturations are essential for
 1293 understanding observational regressions between N_a - N_d , metric commonly referred to as the
 1294 aerosol-cloud interactions (ACI) metric (Bellouin et al., 2019). Because specific meteorological
 1295 regimes feature unique characteristics in terms of inversion strength, boundary layer deepening,
 1296 and turbulence, the classification proposed here offers an alternative approach to the problem of
 1297 disentangling the meteorological control over N_d variability, which is critical for understanding
 1298 how aerosols impact clouds in the context of the aerosol indirect effect.

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Supplemental material

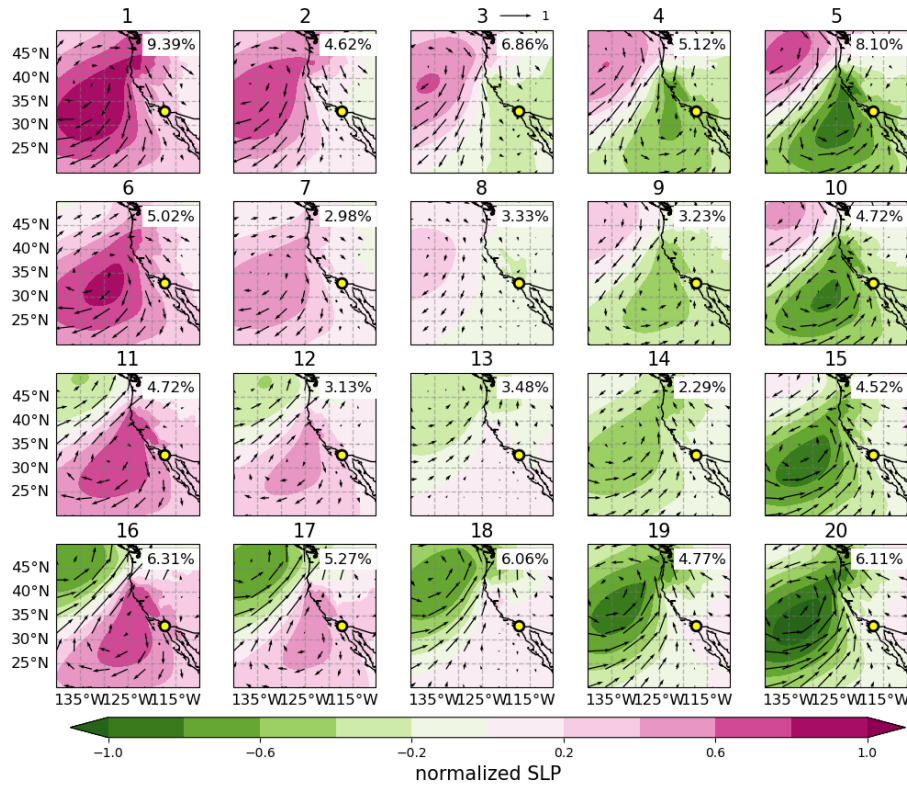


Figure S1: 4x5 SOM composite of the normalized field

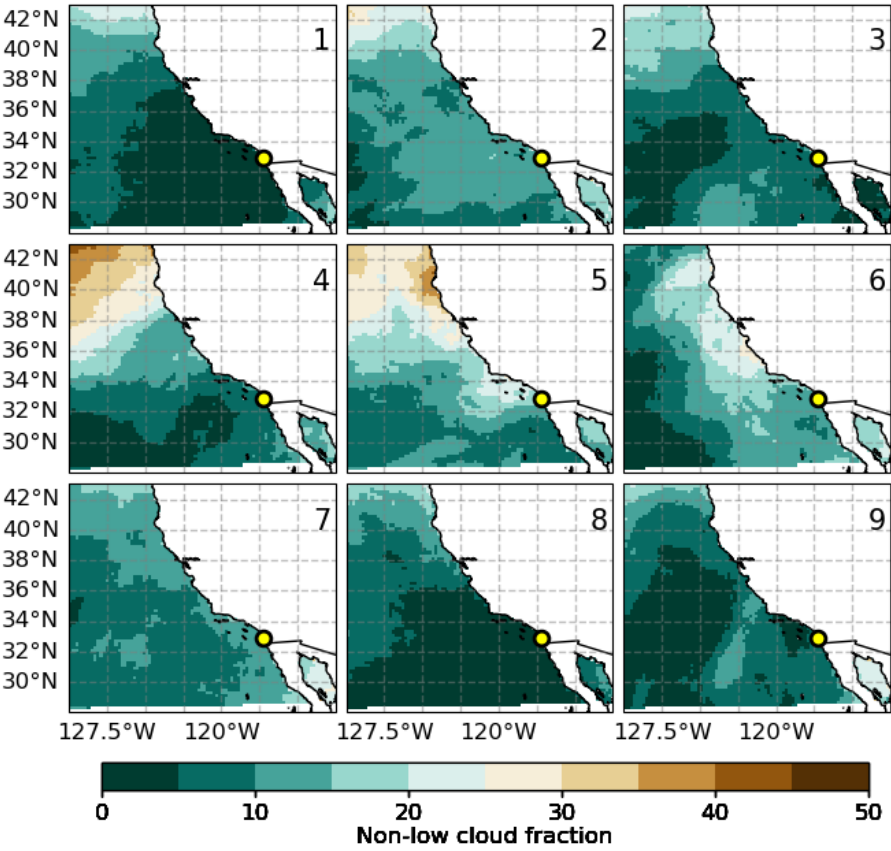
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The Python implementation for generating Self-Organizing Maps was obtained from the MiniSom library, available at <https://github.com/JustGlowing/minisom>. The ARM EPCAPE measurements are available through https://adc.arm.gov/discovery/results/site_code::epc/start_date::2023-02-15/end_date::2024-02-14.

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[Figure S2: Non-low cloud fraction derived from SatCORPS GOES-18 cloud fraction for the nine synoptic classifications.](#)

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Table S1: The number of days in each node reflecting the contribution from individual months.

<u>Regimes/ Months</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
<u>Apr</u>	<u>5</u>	<u>4</u>	<u>2</u>	<u>4</u>	<u>4</u>	<u>1</u>	<u>5</u>	<u>3</u>	<u>2</u>
<u>May</u>	<u>5</u>	<u>2</u>	<u>4</u>	<u>2</u>	<u>5</u>	<u>5</u>	<u>2</u>	<u>3</u>	<u>3</u>
<u>Jun</u>	<u>3</u>	<u>4</u>	<u>7</u>	<u>1</u>	<u>2</u>	<u>2</u>	<u>5</u>	<u>4</u>	<u>2</u>
<u>Jul</u>	<u>2</u>	<u>4</u>	<u>0</u>	<u>4</u>	<u>3</u>	<u>4</u>	<u>7</u>	<u>2</u>	<u>5</u>
<u>Aug</u>	<u>6</u>	<u>1</u>	<u>7</u>	<u>3</u>	<u>1</u>	<u>5</u>	<u>3</u>	<u>2</u>	<u>3</u>
<u>Sep</u>	<u>4</u>	<u>3</u>	<u>3</u>	<u>6</u>	<u>2</u>	<u>1</u>	<u>4</u>	<u>2</u>	<u>5</u>
<u>Total</u>	<u>25/185</u>	<u>18/185</u>	<u>25/185</u>	<u>20/185</u>	<u>17/185</u>	<u>18/185</u>	<u>26/185</u>	<u>16/185</u>	<u>20/185</u>

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1390 **ARM ECAPE data access:**

1391 Atmospheric Radiation Measurement (ARM) user facility. 2023. Active Remote Sensing of
1392 CLOUDS (ARSCL) product using Ka-band ARM Zenith Radars (ARSCLKAZRBNDIKOLLIAS),
1393 2023-02-15 to 2024-02-14, ARM Mobile Facility (EPC) La Jolla, CA; AMF1 (main site for
1394 ECAPE on Scripps Pier) (M1). Compiled by K. Johnson, S. Giangrande and T. Toto. ARM Data
1395 Center. Data set accessed on 2025-05-18.

1396
1397 Atmospheric Radiation Measurement (ARM) user facility. 2023. Cloud optical depth retrieved
1398 from multi-channel sunphotometer (SPHOTCOD2CHIU), 2023-02-15 to 2024-02-
1399 13, ARM Mobile Facility (EPC) La Jolla, CA; AMF1 (main site for ECAPE on Scripps Pier)
1400 (M1). Compiled by T. Fairless, S. Giangrande, C. and L. Ma. ARM Data Center. Data set
1401 accessed 2025-05-09.

1402
1403 Atmospheric Radiation Measurement (ARM) user facility. 2023. Balloon-Borne Sounding System
1404 (SONDEWNP), 2023-02-15 to 2024-02-14, ARM Mobile Facility (EPC) La Jolla, CA; AMF1
1405 (main site for ECAPE on Scripps Pier) (M1). Compiled by E. Keeler, K. Burk and J. Kyröuac.
1406 ARM Data Center. Data set accessed 2025-04-01.

1407
1408 Atmospheric Radiation Measurement (ARM) user facility. 2023. MWR Retrievals
1409 with MWRRET Version 2 (MWRRET2TURN), 2023-02-15 to 2024-02-14, ARM Mobile Facility
1410 (EPC) La Jolla, CA; AMF1 (main site for ECAPE on Scripps Pier) (M1). Compiled by K.
1411 Gaustad and D. Zhang. ARM Data Center. Data set accessed 2025-07-01.

1412
1413 Atmospheric Radiation Measurement (ARM) user facility. 2023. Air mass trajectories to support
1414 studies using ARM data (ARMTRAJPBL). 2023-03-01 to 2024-02-13, ARM Mobile Facility

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SC and DP designed the study. SC performed the analysis and drafted the manuscript with contributions from all the co-authors. CP and LR provided the ground-based aerosol and corrected CCN measurements. All co-authors participated in discussions and manuscript review.

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1426 (EPC) La Jolla, CA; AMF1 (main site for EPCAPE on Scripps Pier) (M1). ARM Data Center.
1427 Data set accessed 2024-08-08.
1428
1429 Atmospheric Radiation Measurement (ARM) user facility. 2023. Ceilometer (CEIL10M), 2023-
1430 02-15 to 2024-02-14, ARM Mobile Facility (EPC) La Jolla, CA; Supplemental Facility 2 (Mt
1431 Soledad lab) (S2). Compiled by D. Zhang, V. Morris and B. Ermold. ARM Data Center. Data set
1432 accessed 2025-02-04.
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456

References

- Abel, M. R. and Hall, A.: Local and synoptic mechanisms causing Southern California's Santa Ana winds, *Clim. Dyn.*, 34, 847–857, <https://doi.org/10.1007/s00382-009-0650-4>, 2010.
- Beddows, D. C. S., Dall'osto, M., and Harrison, R. M.: An enhanced procedure for the merging of atmospheric particle size distribution data measured using electrical mobility and time-of-flight analysers, *Aerosol Sci. Technol.*, 44, 11, <https://doi.org/10.1080/02786826.2010.502159>, 2010.
- Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., et al.: Bounding global aerosol radiative forcing of climate change, *Rev. Geophys.*, 58, <https://doi.org/10.1029/2019RG000660>, 2020.
- Berta, V. Z., Han, S., Atsushi, O., Dedrick, J. L., Maneenoi, N., and Russell, L. M.: Aerosol quantification products at Mt. Soledad and Scripps Pier during EPCAPE 2023–24, in: *Aerosol Microphysics and Chemical Measurements at Mt. Soledad and Scripps Pier during the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) from February 2023 to February 2024*, UC San Diego Library Digital Collections, <https://doi.org/10.6075/J0WM1DSC>, 2025.
- Bishop, C. M.: Neural Networks for Pattern Recognition, Oxford University Press, New York, 1995.
- [Boers, R., and Mitchell, R. M.: Absorption feedback in stratocumulus clouds influence on cloud top albedo, *Tellus* \(1994\), 46A, 229- 241](#)
- Bretherton, C. S. and Blossey, P. N.: Understanding mesoscale aggregation of shallow cumulus convection using large-eddy simulation, *J. Adv. Model. Earth Syst.*, 9, 2798–2821, 2017.
- Bretherton, C. S., Wood, R., George, R. C., Leon, D., Allen, G., and Zheng, X.: Southeast Pacific stratocumulus clouds, precipitation and boundary layer structure sampled along 20°S during

1487 VOCALS-Rex, *Atmos. Chem. Phys.*, 10, 10639–10654, [https://doi.org/10.5194/acp-10-10639-](https://doi.org/10.5194/acp-10-10639-2010)
 1488 2010, 2010.
 1489
 1490 Chen, Y. C., Christensen, M., Stephens, G., et al.: Satellite-based estimate of global aerosol–cloud
 1491 radiative forcing by marine warm clouds, *Nat. Geosci.*, 7, 643–
 1492 646, <https://doi.org/10.1038/ngeo2214>, 2014.
 1493
 1494 Chiu, J. C., Marshak, A., Huang, C.-H., Várnai, T., Hogan, R., Giles, D. M., Holben, B. N.,
 1495 O'Connor, E., Knyazikhin, Y., and Wiscombe, W. J.: Cloud droplet size and liquid water path
 1496 retrievals from zenith radiance measurements: examples from the Atmospheric Radiation
 1497 Measurement Program and the Aerosol Robotic Network, *Atmos. Chem. Phys.*, 12, 10313–
 1498 10329, <https://doi.org/10.5194/acp-12-10313-2012>, 2012.
 1499
 1500 Chiu, J. C., Huang, C., Marshak, A., Slutsker, I., Giles, D. M., Holben, B. N., Knyazikhin, Y., and
 1501 Wiscombe, W. J.: Cloud optical depth retrievals from the Aerosol Robotic Network (AERONET)
 1502 cloud mode observations, *J. Geophys. Res.*, 115, D14202, <https://doi.org/10.1029/2009JD013121>,
 1503 2010.
 1504
 1505 Christensen, M. W., Jones, W. K., and Stier, P.: Aerosols enhance cloud lifetime and brightness
 1506 along the stratus-to-cumulus transition, *Proc. Natl. Acad. Sci. U.S.A.*, 117, 17591–
 1507 17598, <https://doi.org/10.1073/pnas.1921231117>, 2020.
 1508
 1509 Clement, A. C., Burgman, R., and Norris, J. R.: Observational and model evidence for positive
 1510 low-level cloud feedback, *Science*, 325, 460–464, <https://doi.org/10.1126/science.1171255>, 2009.
 1511
 1512 Clemesha, R. E. S., Gershunov, A., Iacobellis, S. F., and Cayan, D. R.: Daily variability of
 1513 California coastal low cloudiness: A balancing act between stability and subsidence, *Geophys. Res.*
 1514 *Lett.*, 44, 3330–3338, <https://doi.org/10.1002/2017GL073075>, 2017.
 1515

1516 Cook, D. R. and Sullivan, R. C.: Eddy Correlation Flux Measurement System (ECOR) Instrument
 1517 Handbook, U.S. Department of Energy, Atmospheric Radiation Measurement user facility,
 1518 Richland, Washington, DOE/SC ARM-TR-052, 2025.
 1519
 1520 Covert, D. S., Kapustin, V. N., Bates, T. S., and Quinn, P. K.: Physical properties of marine
 1521 boundary layer aerosol particles of the mid-Pacific in relation to sources and meteorological
 1522 transport, *J. Geophys. Res.*, 101, D3, 6919–6930, <https://doi.org/10.1029/95JD03068>, 1996.
 1523
 1524 Dedrick, J. L., Osawa, A., Russell, L. M., Miller, M., Robinson, L., Chang, R., Williams, A. S.,
 1525 Berta, V. Z., Elavarasi, R., Petters, M. D., Wheeler, M., Han, S., Pelayo, C., Maneenoi, N., Lubin,
 1526 D., Uin, J., Enekwizu, O., Zawadowicz, M., and Mayol-Bracero, O.: Quantitative estimates of
 1527 cloud supersaturation and particle scavenging by urban coastal stratocumulus during EPCAPE,
 1528 submitted to *J. Atmos. Sci.*, 2026.
 1529
 1530 Feng, Y., Lindenmaier, I., Theisen, A., Wang, D., Collis, S., Tian, J., Silber, I., Gupta, S., Zhang,
 1531 D., Mather, J., Comstock, J., Jackson, R., O'Brien, J., and Raut, B.: ARM FY2025 Radar Plan, ed.
 1532 by Robert Stafford, ARM user facility, DOE/SC-ARM-TR-308, <https://doi.org/10.2172/2482518>,
 1533 2024.
 1534
 1535 Gaustad, K. L. and Turner, D. D.: MWRRET Value-Added Product: The Retrieval of Liquid
 1536 Water Path and Precipitable Water Vapor from Microwave Radiometer (MWR) Data Sets, ARM-
 1537 TR-081.1, U.S. Department of Energy, 2009.
 1538
 1539 Gershunov, A., Shulgina, T., Clemesha, R. E., Guirguis, K., Pierce, D. W., Dettinger, M. D., and
 1540 Cayan, D. R.: Precipitation regime change in Western North America: The role of atmospheric
 1541 rivers, *Sci. Rep.*, 9, 9944, <https://doi.org/10.1038/s41598-019-46169-w>, 2019.
 1542
 1543 Grosvenor, D. P., Sourdeval, O., Zuidema, P., Ackerman, A., Alexandrov, M. D., Bennartz, R., et
 1544 al.: Remote sensing of droplet number concentration in warm clouds: A review of the current state
 1545 of knowledge and perspectives, *Rev. Geophys.*, 56, 409–
 1546 453, <https://doi.org/10.1029/2017RG000593>, 2018.

1547
1548 Gryspeerdt, E., Quaas, J., and Bellouin, N.: Constraining the aerosol influence on cloud fraction, *J.*
1549 *Geophys. Res. Atmos.*, 121, 3566–3583, <https://doi.org/10.1002/2015JD023744>, 2016.

1550
1551 Han, S., Williams, A. S., Russell, L. M., Berta, V. Z., Dedrick, J. L., Pelayo, C., Maneenoi, N.,
1552 Osawa, A., Silber, I., Zhang, D., Zawadowicz, M. A., and Sedlacek III, A. J.: Nearby Sites Show
1553 Similar Upwind Sources and Differing Semivolatile Concentrations in Coastal Aerosol
1554 Particles, *ACS ES&T Air*, 2, 2824–2837, <https://doi.org/10.1021/acsestair.5c00191>, 2025.

1555
1556 Hartmann, D., Ockert-Bell, M. E., and Michelsen, M. L.: The effect of cloud type on Earth’s
1557 energy balance: Global analysis, *J. Climate*, 5, 1281–1304, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0442(1992)005<1281:TEOCTO>2.0.CO;2)
1558 [0442\(1992\)005<1281:TEOCTO>2.0.CO;2](https://doi.org/10.1175/1520-0442(1992)005<1281:TEOCTO>2.0.CO;2), 1992.

1559
1560 Haykin, S.: Neural Networks and Learning Machines, 3rd Edn., Pearson Education, Inc.,
1561 McMaster University, Hamilton, available at: [http://dai.fmph.uniba.sk/courses/NN/haykin.neural-](http://dai.fmph.uniba.sk/courses/NN/haykin.neural-networks.3ed.2009.pdf)
1562 [networks.3ed.2009.pdf](http://dai.fmph.uniba.sk/courses/NN/haykin.neural-networks.3ed.2009.pdf), 2009.

1563
1564 Haykin, S.: Neural Networks: A Comprehensive Foundation, 2nd Edn., Prentice Hall, 1999.

1565
1566 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al.: The
1567 ERA5 global reanalysis, *Q. J. R. Meteorol. Soc.*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>,
1568 2020.

1569
1570 Hewitson, B. and Crane, R.: Self-organizing maps: applications to synoptic climatology, *Clim.*
1571 *Res.*, 22, 13–26, <https://doi.org/10.3354/cr022013>, 2002.

1572
1573 Husar, R. B. and Patterson, D. E.: Regional scale air pollution: Sources and effects, *Ann. N. Y.*
1574 *Acad. Sci.*, 338, 399–417, <https://doi.org/10.1111/j.1749-6632.1980.tb17136.x>, 1980.

1575
1576 Husar, R., Patterson, D., Blumenthal, D., White, W., and Smith, T.: Three-dimensional distribution
1577 of air pollutants in the Los Angeles Basin, *J. Appl. Meteorol. Climatol.*, 16, 1089–
1096, <https://doi.org/10.1175/1520-0450-16.10.1089>, 1977.

1578
1579 Iacobellis, S. F. and Cayan, D. R.: The variability of California summertime marine stratus:
1580 Impacts on surface air temperatures, *J. Geophys. Res. Atmos.*, 118, 9105–
1581 9122, <https://doi.org/10.1002/jgrd.50652>, 2013.
1582
1583 Jiang, N., Kim, N., Dirks, K., and Luo, K.: Classification of synoptic weather types using the self-
1584 organising map and its application to climate and air quality data visualisation, *Weather and*
1585 *Climate*, 33, 52–75, 2013.
1586
1587 Jones, C. R., Bretherton, C. S., and Leon, D.: Coupled vs. decoupled boundary layers in VOCALS-
1588 REX, *Atmos. Chem. Phys.*, 11, 7143–7153, <https://doi.org/10.5194/acp-11-7143-2011>, 2011.
1589
1590 Juliano, T. W. and Lebo, Z. J.: Linking large-scale circulation patterns to low-cloud
1591 properties, *Atmos. Chem. Phys.*, 20, 7125–7138, <https://doi.org/10.5194/acp-20-7125-2020>, 2020.
1592
1593 Keeler, E.: Balloon-Borne Sounding System (SONDE) Instrument Handbook, ed. by Robert
1594 Stafford, U.S. Department of Energy, DOE/SC-ARM/TR-029, <https://doi.org/10.2172/1020712>,
1595 2025.
1596
1597 Klein, S. A. and Hartmann, D. L.: The seasonal cycle of low stratiform clouds, *J. Climate*, 6, 1587–
1598 1606, 1993.
1599
1600 Klein, S. A., Hartmann, D. L., and Norris, J. R.: On the relationships among low-cloud structure,
1601 sea surface temperature, and atmospheric circulation in the summertime northeast Pacific, *J.*
1602 *Climate*, 10, 2550–2563, 1997.
1603
1604 Kohonen, T.: The self-organizing map, *Proc. IEEE*, 78, 1464–1480, 1990.
1605
1606 Kohonen, T.: Self-Organizing Maps, 3rd Edn., Springer-Verlag, Berlin, Heidelberg, New York,
1607 501 pp., <https://doi.org/10.1007/978-3-642-56927-2>, 2001.
1608

1609 Kohonen, T.: Self-organized formation of topologically correct feature maps, *Biol. Cybern.*, 43,
 1610 59–69, <https://doi.org/10.1007/BF00337288>, 1982.
 1611
 1612 Krzywinski, M. and Altman, N.: Points of significance: Comparing samples – part I, *Nat.*
 1613 *Methods*, 11, 215–216, <https://doi.org/10.1038/nmeth.2858>, 2014.
 1614
 1615 Lebassi-Habtezion, B., González, J., and Bornstein, R.: Modeled large-scale warming impacts on
 1616 summer California coastal-cooling trends, *J. Geophys. Res.*, 116,
 1617 D20114, <https://doi.org/10.1029/2011JD015759>, 2011.
 1618
 1619 Lewis, E. R.: Marine ARM GPCI Investigation of Clouds (MAGIC) Field Campaign Report, U.S.
 1620 Department of Energy, <https://doi.org/10.2172/1343577>, 2016.
 1621 Lu, R. and Turco, R. P.: Air pollutant transport in a coastal environment – II. Three-dimensional
 1622 simulations over Los Angeles basin, *Atmos. Environ.*, 29, 1499–
 1623 1518, [https://doi.org/10.1016/1352-2310\(95\)00015-Q](https://doi.org/10.1016/1352-2310(95)00015-Q), 1995.
 1624
 1625 Lu, R. and Turco, R. P.: Air pollutant transport in a coastal environment. Part I: Two-dimensional
 1626 simulations of sea-breeze and mountain effects, *J. Atmos. Sci.*, 51, 2285–
 1627 2308, [https://doi.org/10.1175/1520-0469\(1994\)051<2285:APTIAC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<2285:APTIAC>2.0.CO;2), 1994.
 1628
 1629 Maneenoi, N., Russell, L., Han, S., Dedrick, J. L., Williams, A., Berta, V. Z., Pelayo, C., et
 1630 al.: Photochemical and cloud and aerosol aqueous contributions to regionally-emitted shipping and
 1631 biogenic non-sea-salt sulfate aerosol in coastal California, *ACS ES&T Air*, 2, 648–
 1632 664, <https://doi.org/10.1021/acsestair.4c00352>, 2025.
 1633
 1634 [McComiskey, A., G. Feingold, A. S. Frisch, D. D. Turner, M. A. Miller, J. C. Chiu, Q. Min, and](#)
 1635 [J. A. Ogren \(2009\), An assessment of aerosol-cloud interactions in marine stratus clouds based on](#)
 1636 [surface remote sensing, J. Geophys. Res., 114, D09203, doi:10.1029/2008JD011006.](#)
 1637
 1638 Minnis, P., Sun-Mack, S., Chen, Y., Chang, F.-L., Yost, C. R., Smith, W. L. Jr., Heck, P. W.,
 1639 Arduini, R. F., Bedka, S. T., Yi, Y., Hong, G., Jin, Z., Painemal, D., Palikonda, R., Scarino, B.,

1640 Spangenberg, D. A., Smith, R. A., Trepte, Q. Z., Yang, P., and Xie, Y.: CERES MODIS cloud
 1641 product retrievals for Edition 4, Part I: Algorithm changes, *IEEE Trans. Geosci. Remote Sens.*, 51,
 1642 2744–2780, <https://doi.org/10.1109/TGRS.2020.3008866>, 2021.
 1643
 1644 Minnis, P., Trepte, Q. Z., Sun-Mack, S., Chen, Y., Doelling, D. R., Young, D. F., Spangenberg,
 1645 D. A., Miller, W. F., Wielicki, B. A., Brown, R. R., and Gibson, S. C.: Cloud detection in nonpolar
 1646 regions for CERES using TRMM VIRS and Terra and Aqua MODIS data, *IEEE Trans. Geosci.
 1647 Remote Sens.*, 46, 3857–3884, 2008.
 1648
 1649 Minnis, P., Sun-Mack, S., Young, D. F., Heck, P. W., Garber, D. P., Chen, Y., Spangenberg, D.
 1650 A., Arduini, R. F., Trepte, Q. Z., Smith, W. L., and Ayers, J. K.: CERES edition-2 cloud property
 1651 retrievals using TRMM VIRS and Terra and Aqua MODIS data – Part I: Algorithms, *IEEE Trans.
 1652 Geosci. Remote Sens.*, 49, 4374–4400, 2011.
 1653
 1654 Minnis, P., Sun-Mack, S., Smith, W. L. Jr., Trepte, Q. Z., Hong, G., Chen, Y., Yost, C. R., Chang,
 1655 F.-L., Smith, R. A., Heck, P. W., and Yang, P.: VIIRS Edition 1 Cloud Properties for CERES, Part
 1656 1: Algorithm Adjustments and Results, *Remote Sens.*, 15,
 1657 578, <https://doi.org/10.3390/rs15030578>, 2023.
 1658
 1659 Morris, V. R.: Ceilometer Instrument Handbook, DOE/SC-ARM-TR-020, U.S. Department of
 1660 Energy, <https://doi.org/10.2172/1036530>, April 2016.
 1661
 1662 Myers, T. A. and Norris, J. R.: Observational evidence that enhanced subsidence reduces
 1663 subtropical marine boundary layer cloudiness, *J. Climate*, 26, 7507–
 1664 7524, <https://doi.org/10.1175/JCLI-D-12-00736.1>, 2013.
 1665
 1666 Neiburger, M., Johnson, D. S., and Chien, C.-W.: Studies of the Structure of the Atmosphere over
 1667 the Eastern Pacific Ocean in the Summer, University of California Press, 94 pp., 1961.
 1668
 1669 [Nakajima, T., M. D. King, J. D. Spinhirne, and L. F. Radke \(1991\), Determination of the optical](#)
 1670 [thickness and effective particle radius of clouds from reflected solar radiation measurements. Part](#)

1671 [II: Marine stratocumulus observations, *J. Atmos. Sci.*, 48, 728–751, doi:10.1175/1520-0469](#)
 1672 [\(1991\)0482.0.CO;2.](#)
 1673
 1674 Newsom, R. K., Sivaraman, C., Shippert, T. R., and Riihimaki, L. D.: Doppler Lidar Vertical
 1675 Velocity Statistics Value-Added Product, DOE/SC-ARM-TR-149, U.S. Department of Energy,
 1676 Atmospheric Radiation Measurement user facility, Richland, Washington, 2025.
 1677
 1678 Norris, J. R. and Iacobellis, S. F.: North Pacific cloud feedbacks inferred from synoptic-scale
 1679 dynamic and thermodynamic relationships, *J. Climate*, 18, 4862–
 1680 4878, <https://doi.org/10.1175/JCLI3558.1>, 2005.
 1681
 1682 Painemal, D.: Global estimates of changes in shortwave low-cloud albedo and fluxes due to
 1683 variations in cloud droplet number concentration derived from CERES-MODIS satellite
 1684 sensors, *Geophys. Res. Lett.*, 45, 9288–9296, <https://doi.org/10.1029/2018GL078880>, 2018.
 1685
 1686 Painemal, D., Chiu, J.-Y. C., Minnis, P., Yost, C., Zhou, X., Cadetdu, M., Eloranta, E., Lewis, E.
 1687 R., Ferrare, R., and Kollias, P.: Aerosol and cloud microphysics covariability in the northeast
 1688 Pacific boundary layer estimated with ship-based and satellite remote sensing observations, *J.*
 1689 *Geophys. Res. Atmos.*, 122, 2403–2418, <https://doi.org/10.1002/2016JD025771>, 2017.
 1690 Painemal, D., Minnis, P., and Nordeen, M.: Aerosol variability, synoptic-scale processes, and their
 1691 link to the cloud microphysics over the northeast Pacific during MAGIC, *J. Geophys. Res.*
 1692 *Atmos.*, 120, 5122–5139, <https://doi.org/10.1002/2015JD023175>, 2015.
 1693
 1694 Painemal, D., Smith, W. L. Jr., Gupta, S., Moore, R., Cairns, B., McFarquhar, G. M., and O’Brien,
 1695 J.: Can we rely on satellite visible/infrared microphysical retrievals of boundary layer clouds in
 1696 partially cloudy scenes? Implications for climate research, *Geophys. Res. Lett.*, 52,
 1697 e2024GL113825, <https://doi.org/10.1029/2024GL113825>, 2025.
 1698
 1699 Painemal, D. and Zuidema, P.: Assessment of MODIS cloud effective radius and optical thickness
 1700 retrievals over the Southeast Pacific with VOCALS-REx in situ measurements, *J. Geophys.*
 1701 *Res.*, 116, D24206, <https://doi.org/10.1029/2011JD016155>, 2011.

1702

1703 Painemal, D. and Zuidema, P.: The first aerosol indirect effect quantified through airborne remote
 1704 sensing during VOCALS-REx, *Atmos. Chem. Phys.*, 13, 917–931, [https://doi.org/10.5194/acp-13-](https://doi.org/10.5194/acp-13-917-2013)
 1705 917-2013, 2013a.

1706

1707 Painemal, D., Minnis, P., Sun-Mack, S., and Wood, R.: The impact of horizontal heterogeneities,
 1708 cloud fraction, and liquid water path retrievals on MODIS droplet effective radius retrievals, *J.*
 1709 *Geophys. Res. Atmos.*, 118, 6564–6575, <https://doi.org/10.1002/jgrd.50374>, 2013b.

1710

1711 Painemal, D., Chellappan, S., Smith, W. L. Jr., Spangenberg, D., Park, J. M., Ackerman, A., Chen,
 1712 J., Crosbie, E., Ferrare, R., Hair, J., Kirschler, S., Li, X.-Y., McComiskey, A., Moore, R. H.,
 1713 Sanchez, K., Sorooshian, A., Tornow, F., Voigt, C., Wang, H., Winstead, E., Zeng, X., Ziemba,
 1714 L., and Zuidema, P.: Wintertime synoptic patterns of midlatitude boundary layer clouds over the
 1715 western North Atlantic: Climatology and insights from in-situ ACTIVATE observations, *J.*
 1716 *Geophys. Res. Atmos.*, 128, e2022JD037725, <https://doi.org/10.1029/2022JD037725>, 2023.

1717

1718 Parish, T. R.: Forcing of the summertime low-level jet along the California coast, *J. Appl.*
 1719 *Meteorol. Climatol.*, 39, 2421–2433, 2000.

1720

1721 Pearce, J. L., Waller, L. A., Chang, H. H., et al.: Using self-organizing maps to develop ambient
 1722 air quality classifications: a time series example, *Environ. Health*, 13,
 1723 56, <https://doi.org/10.1186/1476-069X-13-56>, 2014.

1724

1725 Raphael, M. N.: The Santa Ana winds of California, *Earth Interact.*, 7, 1–
 1726 13, [https://doi.org/10.1175/1087-3562\(2003\)007<0001:TSAWOC>2.0.CO;2](https://doi.org/10.1175/1087-3562(2003)007<0001:TSAWOC>2.0.CO;2), 2003.

1727

1728 Russell, L. M., Miller, M., Lubin, D., Ackerman, A., Silber, I., Fridlind, A., Eloranta, E., Witte,
 1729 M., Muelmenstaedt, J., Lebsock, M., Burrows, S., Painemal, D., Aiken, A., Chang, R., Wang, D.,
 1730 Liggio, J., Petters, M., Wheeler, M., et al.: EPCAPE Field Campaign, Final Campaign Report,
 1731 DOE/SC-ARM-25-010, U.S. Department of Energy, April 2025.

1732

1733 Sheridan, S. C. and Lee, C. C.: The self-organizing map in synoptic climatological research, *Prog.*
 1734 *Phys. Geogr.*, 35, 109–119, 2011.
 1735
 1736 Shilling, J. and Levin, M.: ACSM, corrected for composition-dependent collection efficiency
 1737 (ACSMCDCE), ARM Data Center, <https://doi.org/10.5439/1641833>, 2024.
 1738
 1739 Shilling, J. E. and Levin, M. S.: Scanning Mobility Particle Sizer (SMPS)-Aerodynamic Particle
 1740 Sizer (APS) Merged Size Distribution (mergedsmpsaps) Value-Added Product Report, DOE/SC-
 1741 ARM-TR-294, U.S. Department of Energy, Atmospheric Radiation Measurement user facility,
 1742 Richland, Washington, 2023.
 1743
 1744 Silber, I., Comstock, J. M., Kiebert, M. R., and Russell, L. M.: ARMTRAJ: a set of multipurpose
 1745 trajectory datasets augmenting the Atmospheric Radiation Measurement (ARM) user facility
 1746 measurements, *Earth Syst. Sci. Data*, 17, 29–42, <https://doi.org/10.5194/essd-17-29-2025>, 2025.
 1747
 1748 Sorooshian, A., and Coauthors: Aerosol–Cloud–Meteorology Interaction Airborne Field
 1749 Investigations: Using Lessons Learned from the U.S. West Coast in the Design of ACTIVATE off
 1750 the U.S. East Coast, *Bull. Am. Meteorol. Soc.*, 100, 1511–1528, [https://doi.org/10.1175/BAMS-D-](https://doi.org/10.1175/BAMS-D-18-0100.1)
 1751 18-0100.1, 2019.
 1752
 1753 Sullivan, R. C., Billesbach, D. P., Biraud, S., Chan, S., Hart, R., Keeler, E., Kyrouac, J., Pal, S.,
 1754 Pekour, M., Sullivan, S. L., Theisen, A., Tuftedal, M., and Cook, D. R.: Over three decades, and
 1755 counting, of near-surface turbulent flux measurements from the Atmospheric Radiation
 1756 Measurement (ARM) user facility, *Earth Syst. Sci. Data*, 17, 5007–
 1757 5038, <https://doi.org/10.5194/essd-17-5007-2025>, 2025.
 1758
 1759 Teixeira, J., et al.: Tropical and sub-tropical cloud transitions in weather and climate prediction
 1760 models: The GCSS/WGNE Pacific Cross-section Intercomparison (GPCI), *J. Clim.*, 24, 5223–
 1761 5256, <https://doi.org/10.1175/2011JCLI3672.1>, 2011.
 1762

1763 Turner, D. D., Clough, S. A., Liljegren, J. C., Clothiaux, E. E., Cady-Pereira, K. E., and Gaustad,
 1764 K. L.: Retrieving liquid water path and precipitable water vapor from the Atmospheric Radiation
 1765 Measurement (ARM) microwave radiometers, *IEEE Trans. Geosci. Remote Sens.*, 45, 3680–
 1766 3690, <https://doi.org/10.1109/TGRS.2007.903703>, 2007.
 1767
 1768 Vesanto, J. and Alhoniemi, E.: Clustering of the self-organizing map, *IEEE Trans. Neural*
 1769 *Netw.*, 11, 586–600, <https://doi.org/10.1109/72.846731>, 2000.
 1770
 1771 Vettigli, G.: MiniSom: Minimalistic and Numpy-Based Implementation of the Self Organizing
 1772 Map, available at: <https://github.com/JustGlowing/minisom/>, 2018.
 1773
 1774 Weaver, C. P. and Ramanathan, V.: Relationships between large-scale vertical velocity, static
 1775 stability, and cloud radiative forcing over Northern Hemisphere extratropical oceans, *J.*
 1776 *Climate*, 10, 2871–2887, [https://doi.org/10.1175/1520-0442\(1997\)010<2871:RBLSVV>2.0.CO;2](https://doi.org/10.1175/1520-0442(1997)010<2871:RBLSVV>2.0.CO;2), 1997.
 1777
 1778
 1779 Widener, K., Bharadwaj, N., and Johnson, K.: Ka-Band ARM Zenith Radar Handbook, DOE/SC-
 1780 ARM/TR-106, <https://doi.org/10.2172/1035855>, 2012.
 1781
 1782 Wood, R.: Stratocumulus clouds, *Mon. Weather Rev.*, 140, 2373–
 1783 2423, <https://doi.org/10.1175/mwr-d-11-00121.1>, 2012.
 1784
 1785 Wood, R. and Bretherton, C. S.: Boundary layer depth, entrainment, and decoupling in the cloud-
 1786 capped subtropical and tropical marine boundary layer, *J. Climate*, 17, 3576–
 1787 3588, [https://doi.org/10.1175/1520-0442\(2004\)017<3576:BLDEAD>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<3576:BLDEAD>2.0.CO;2), 2004.
 1788
 1789 Wood, R., Leon, D., Lebsock, M., Snider, J., and Clarke, A. D.: Precipitation driving of droplet
 1790 concentration variability in marine low clouds, *J. Geophys. Res.*, 117,
 1791 D19210, <https://doi.org/10.1029/2012JD018305>, 2012.
 1792

1793 Zhang, J., Zhou, X., Goren, T., and Feingold, G.: Albedo susceptibility of northeastern Pacific
1794 stratocumulus: the role of covarying meteorological conditions, *Atmos. Chem. Phys.*, 22, 861–
1795 880, <https://doi.org/10.5194/acp-22-861-2022>, 2022.

1796

1797 Zheng, Y., Rosenfeld, D., and Li, Z.: Sub-cloud turbulence explains cloud-base updrafts for
1798 shallow cumulus ensembles: First observational evidence, *Geophys. Res. Lett.*, 48,
1799 e2020GL091881, <https://doi.org/10.1029/2020GL091881>, 2021.

1800

1801 Zhou, C., Zelinka, M. D., Dessler, A. E., and Klein, S. A.: The relationship between interannual
1802 and long-term cloud feedbacks, *Geophys. Res. Lett.*, 42, 10463–
1803 10469, <https://doi.org/10.1002/2015GL066698>, 2015.

1804

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