DOE/SC-ARM-25-010

EPCAPE Field Campaign Final Campaign Report

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DISCLAIMER

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Acronyms and Abbreviations

ACI – Aerosol Cloud Interactions

ACSM – aerosol chemical speciation mass spectrometer

AERI – atmospheric emitted radiance interferometer

AETH – aethelometer

AMF1 – first ARM Mobile Facility

AOSMET – automated weather station

APS – aerodynamic particle sizer

ARM – Atmospheric Radiation Measurements

AWARE – ARM West Antarctic Radiation Experiment

BNL – Brookhaven National Laboratory

CCN – Cloud Condensation Nuclei

CCN – cloud condensation nuclei counter

CEIL – ceilometer

CO – carbon monoxide, nitrous oxide, and water monitor

CPCF – condensation particle counter, fine

CPCU – condensation particle counter, ultrafine

CSPHOT – CIMEL sun photometer

DL – doppler lidar

E3SM – Energy Exascale Earth System Model

ECOR – eddy correlation flux

ENA – Eastern North Atlantic

EPCAPE – Eastern Pacific Cloud Aerosol Precipitation Experiment

GNDRAD – ground radiometer

HSRL – high spectral resolution lidar

HTDMA – humidified tandem differential mobility analyzer

KAZR – Ka-band zenith cloud radar

LA/LB – Los Angeles/Long Beach

LANL – Los Alamos National Laboratory

LASIC – Layered Atlantic Smoke Interactions with Clouds

LD – Laser Disdrometer

MAGIC – Marine ARM GPCI Investigations of Clouds

MASRAD – Marine Stratus Radiation Aerosol and Drizzle

MFR – multifilter radiometer

MFRSR – multifilter rotating shadowband radiometer

MPL – micropulse lidar

MWR – 2-channel microwave radiometer

MWR – microwave radiometer

MWR3C – 3-channel microwave radiometer

NASA – National Aeronautics and Space Administration

NEPH– nephelometer

NOAA – National Oceanic and Atmospheric Administration

O3 – ozone monitor

ORG – Optical Rain Gauge

PNNL – Pacific Northwest National Laboratory

PSAP – particle soot absorption photometer

PWD – present weather detector

RRM – Regionally-Refined Model

RWP – radar wind profiler

SACR* (Ka) – scanning arm cloud radar

SCM – Single Column Model

SEBS – surface energy balance

SKYRAD – sky radiometer

SMPS – scanning mobility particle sizer

SO2 – sulfur dioxide monitor

SONDE – balloon-borne sounding system, launched 2-4 times per day

SP2 – single-particle soot photometer

TBRG – tipping bucket precipitation gauge

TKE – Turbulent Kinetic Energy

TSI – total sky imager

UHSAS – ultra-high sensitivity aerosol spectrometer

VDIS – 2D Video Disdrometer

WBPluvio – weighing bucket precipitation gauge

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1.0 Summary

The focus of the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) was to characterize the extent, radiative properties, aerosol interactions, and precipitation characteristics of stratocumulus clouds in the Eastern Pacific across all four seasons at a coastal location. DOE ARM AMF1 with AOS was successfully deployed from February 14, 2023, through February 14, 2024, in La Jolla, California, at Scripps Pier and Mt. Soledad.

EPCAPE provided an unprecedented characterization of the annual cycle of both clouds and aerosol properties. An important enhancement to this study was the collection of simultaneous in-cloud aerosol and droplet measurements at Mt. Soledad to investigate the differences in these cloud properties during regional polluted and clean marine conditions. EPCAPE observations included support from three collaborating agencies—the National Science Foundation and Environment and Climate Change Canada for measurements at Mt. Soledad and the Office of Naval Research for the SCILLA aircraft campaign in June 2023. Together, the two-site suite of instruments provided a comprehensive characterization of the cloud properties in a year with extensive cloud coverage. The comparison of aerosol properties across the sites constrained the role of local sources and quantified the effects of land-sea breezes. The Soledad site complemented the Pier site by providing a higher-altitude perspective of cloud layers and in situ cloud sampling for more than 800 hours. The measurements successfully characterized aerosol and cloud properties nearly continuously at both sites, collecting an unprecedented dataset for understanding aerosol and cloud climatologies, cloud radiative fluxes, and aerosol-cloud interactions (ACI). Instruments allocated by DOE ARM performed well, with only short periods of routine and unplanned maintenance.

The relevance of this campaign to the ARM mission is its strategic location in an accessible and economically significant region of the world that lacks long-term observations of its frequent, persistent, and climatically important coastal stratocumulus cloud cover. The clouds lie in one of the largest regions of upwelling-driven stratocumulus layers that are likely most impacted by aerosol indirect effects. Still, earth system models do not accurately simulate the processes that control their radiative effects. The coastal orography incites significant additional uncertainties related to cloud turbulence, air motion spectrum, and drop size distributions.

Half of the world's population is concentrated along coastlines, making coastal areas major pollution sources. These sources are important for causing ACI, which, in turn, affects the coastal populations by changing cloud properties. Global climate models do a poor job of representing cloudiness along coastlines, including the western coast of the U.S. The aerosol in the region ranges from a clean marine background to frequent intrusions from large and regionally homogeneous, well-characterized, surface-based pollution sources (the Los Angeles-Long Beach urban port megacity), providing a large dynamic range of aerosol conditions for investigation.

2.0 Results

The EPCAPE measurements meet the EPCAPE scientific objectives by using the comprehensive ARM aerosol and cloud measurement suite to provide an unprecedented characterization of the extent, thickness, and precipitation of stratocumulus clouds in a wide range of aerosol conditions in the northeastern Pacific across all four seasons at a coastal location. In addition, the guest instrumentation augmented the ARM aerosol suite by providing advanced instrumentation that can be operated long-term (12 months) because of easy access by UCSD PIs and collaborators. Below-cloud instrumentation, including cloud, precipitation, radiation, and aerosol instruments, were situated on the Scripps Pier (Fig. 1). These instruments are listed in Table 1. The scanning Doppler lidar and radar (SACR) were located at the Mt. Soledad site (Fig. 2), located less than 2 km inland (250 m above sea level), to allow for sampling downwind of the pier below, in, and above clouds depending on conditions. All the measurements collected by ARM instrumentation are posted to the ARM archive (https://www.arm.gov/research/campaigns/amf2023epcape).

Table 1. ARM Instruments Deployed at EPCAPE (all are part of AMF1 except for *)

Lidars
MPL: micropulse lidar
DL: doppler lidar
CEIL: ceilometer
Radars
KAZR: Ka-band zenith cloud radar
RWP: radar wind profiler
SACR* (Ka and W bands): scanning arm cloud radar
Precipitation
VDIS: 2D video disdrometer
LD: laser disdrometer
ORG: optical rain gauge
PWD: present weather detector
TBRG: tipping bucket precipitation gauge
WBPluvio: weighing bucket precipitation gauge
Radiometers
MWR3C: 3-channel microwave radiometer
MWR: 2-channel microwave radiometer
SKYRAD: sky radiometer
GNDRAD: ground radiometer
MWR: microwave radiometer
AERI: atmospheric emitted radiance interferometer
MFRSR: multifilter rotating shadowband radiometer
CSPHOT: CIMEL sun photometer
MFR: multifilter radiometer
Atmospheric and Boundary State
SEBS: surface energy balance
ECOR: eddy correlation flux
SONDE: balloon-borne sounding system (4/d for intensives, otherwise 2/d)
TSI: total sky imager
AOSMET: automated weather station
Aerosol and Trace Gas Systems
SMPS: scanning mobility particle sizer

CCN: cloud condensation nuclei counter
UHSAS: ultra-high sensitivity aerosol spectrometer
APS*: aerodynamic particle sizer
SP2*: single-particle soot photometer
HTDMA: humidified tandem differential mobility analyzer
ACSM: aerosol chemical speciation mass spectrometer
NEPH (dry, wet): nephelometers at dry and ambient relative humidity
CPCF: condensation particle counter, fine
CPCU: condensation particle counter, ultrafine
AETH: aethelometer
PSAP: particle soot absorption photometer
O3: ozone monitor
SO2: sulfur dioxide monitor
CO: carbon monoxide, nitrous oxide, and water monitor

ARM engineers, technicians, and instrument mentors set up the instrumentation at the start of the campaign, which was run continuously until the end of the campaign. ARM technicians and instrument mentors provided daily checks on instrumentation according to the standard protocols. Some modifications were needed to provide sufficient power at the pier and Soledad sites. Measurements were collected 24 hours per day and seven days per week to capture full daily cycles of cloud formation and dissipation. Online instrumentation was run using standard DOE protocols, typically multiple measurements per hour, for consistency with ARM data sets worldwide. The radar operations were continuous throughout the campaign, with minor interruptions due to power and weather issues.

Satellite observations were collected to generalize the AMF1 measurements to the broader region offshore of and in coastal southern California and northern Baja. GOES-17 retrievals (SatCORPS) provided by the NASA Langley Cloud Group are relevant for characterizing the cloud diurnal cycle at a regional scale, analyzing synoptic-scale variability, and conducting Lagrangian studies. In addition, the National Weather Service NEXRAD radar (KNKX) at San Diego provided an important baseline to complement ARM radar measurement capacity.

There were two Intensive Operation Periods (IOPs): EPCAPE-Chem, focused on characterizing low clouds and their chemistry at Mt Soledad, extending from April through June, and EPCAPE-Radiation, characterizing higher clouds and their radiative properties extending from July through September. Most of the guest instruments, including those provided by Russell, Petters, Liggio, Wentzell, and Wheeler covered the majority of both IOPs or the entire campaign. Additional instrumentation from Smith and Witte targeted the first IOP, and Paulson, Farmer, and Galewsky focused on the second IOP and targeted periods later in the campaign. A critical aspect of both EPCAPE IOPs is the characterization of the diurnal cycle of coastal clouds. For this reason, we launched four sondes per day during the highest stratocumulus cloud frequency (April – September) and two sondes per day during the remainder of the year (Feb- Mar; Oct- Jan). Two sondes per day were necessary to characterize the annual cycle, and four sondes per day were needed to provide the day/night and night/day transitions relevant to the cloudier months. The uncertainties of the prevalent but poorly understood diurnal cycle of stratocumulus clouds are well known [*Duynkerke and Hignett*, 1993; *Hignett*, 1991] and are amply illustrated by the ARM MASRAD data set.

Some highlights of the EPCAPE observations include:

- Persistent and characteristic cloudiness for multiple-day events, allowing spin-up time for simulations as well as investigation of diurnal cycles.
- Unexpected events, including the first tropical storm to hit Southern California since 1939 (https://www.arm.gov/news/blog/post/91659) and extreme atmospheric rivers (https://www.latimes.com/environment/story/2024-04-25/atmospheric-rivers-could-pound-california-with-more-extreme-rain, https://www.latimes.com/environment/story/2024-04-25/atmospheric-rivers-could-pound-california-with-more-extreme-rain).
- The extent of Guest-PI observations of in-cloud size distributions and composition (Russell, Petters, Paulson, Smith, Liggio, Wheeler, Wentzell, Chang, Galewsky) includes sampling more than 800 hours of in-cloud events.
- EPCAPE measurements illustrate a variety of low-cloud conditions over the 12-month campaign, with a substantial range of liquid water content, inversion strengths, and drizzle and a nearly perfect record of instrument uptime to date.
- The consistency of northwesterly trajectories for spring and summer provides consistent large-scale forcings, effectively allowing more focus on the range of microphysics by constraining the macrophysics.
- The typical light precipitation conditions renders EPCAPE an important example of the type of drizzling conditions that are pervasive in the many marine stratocumulus decks that cover the oceans.
- The range of aerosol concentrations from similar upwind source mixtures provides a large and unique dynamic range of aerosols that likely have very similar compositions. Because the sources are so consistent, ACI processes are more likely to be statistically significant because the sources are so consistent.

The EPCAPE observations provide a wealth of measurements for addressing the following topics:

- *Seasonal Cycles.* Marine stratocumulus is a persistent feature of the Southern California coastline and is often present during EPCAPE (Fig. 3), with a variety of classic studies examining properties and trends for more than 30 years using intensive aircraft campaigns [*Lenschow et al.*, 1988; *Stevens et al.*, 2003] as well as ocean and weather observations [*Koracin et al.*, 2004]. The detailed characterization of the full annual cycle of clouds and their properties provided by EPCAPE fulfills this need for global climate models, providing accurate measurements of cloud vertical extent and radiative properties, in addition to characterizing the range and frequency of regional precipitation that occurs. Seasonal cycles also contribute to long-range transport patterns, which affect the sources and, hence, the composition of aerosol particles (Fig. 4).
- *Diurnal Cycles.* The daily changes in cloud thickness and precipitation are linked to the interaction of longwave cooling and shortwave heating, driven by competing effects of ocean upwelling, coastal orography, and solar forcing [*Ackerman et al.*, 2004; *Ackerman et al.*, 1993; *Bretherton et al.*, 2007]. Vertical profiles at sunrise have been shown to be of critical importance to prediction of inland solar power predictions [*Wu et al.*, 2020; *Wu et al.*, 2019; *Zapata et al.*, 2020; *Zapata et al.*, 2019]. Drizzle evaporation can lead to decoupling as the marine boundary layer (MBL) deepens and cloud-top radiative cooling is no longer able to maintain a well-mixed MBL.

- *Predicting Inland Cloud Cover.* Predicting cloud cover and its evolution in coastal regions, especially those that border the semi-permanent stratocumulus belts, such as in Southern California, is essential for the design and operation of solar photovoltaic arrays. Models of all types struggle to form and maintain the thin marine boundary layer clouds often present in coastal regions; recent work has shown very little predictive power from existing observational networks [*Wu et al.*, 2019]. In a recent modeling and observational study of marine boundary layer clouds over the eastern North Atlantic, Kazemirad and Miller [2020] demonstrated the capabilities of using high-resolution numerical models and ARM observational data sets to simulate and evaluate marine boundary layer cloud metamorphosis. This approach enables the identification of individual processes that shape the cloud structure and optical properties. It also provides an avenue for synergistic model tuning, but the ENA clouds are strongly synoptically forced, and the topographical effects are modest. A similar approach may be used to improve real-time forecasts in coastal regions, for example, by utilizing the comprehensive suite of relevant observations available from AMF1 at EPCAPE.
- *Quantifying Cloud Radiative Properties.* Thick overcast conditions result in radiation received at the surface that is entirely diffuse. Thus, in cloudy regions, photovoltaic arrays are oriented at an optimal angle that attempts to maximize the harvest of radiation in the direct beam when clear but allows significant diffuse radiation to be harvested as cloud cover increases [*Kafka and Miller*, 2019]. The optimal tilt angle for fixed photovoltaic arrays is generally determined from inputs of latitude and seasonal cloud cover, while land use considerations may necessitate dual-angle approaches [*Kafka and Miller*, 2020]. In addition to the efficiency of solar photovoltaic arrays, the power utilization characteristics of a particular region are also important.
- *Aerosol Effects on Cloud Brightening and Surface Temperature.* Cloud fraction and LWP are the strongest controls on cloud optical thickness [*Brenguier et al.*, 2003; *Nakajima and King*, 1992], yielding the most dramatic localized changes in cloud radiative effects when aerosols can affect these cloud properties [*Goren and Rosenfeld*, 2014]. However, aerosol effects on LWP and cloud fraction are countervailing [*Ackerman et al.*, 2004; *Albrecht*, 1989] and conditional [*Mulmenstadt and Feingold*, 2018], resulting in small effects on the temporal mean [*Gryspeerdt et al.*, 2019; *Toll et al.*, 2019]. The Twomey effect is not as strong in any particular cloud scene, but it is a positive-definite contribution to cloud optical thickness and is the larger contributor to the global mean radiative forcing [*Bellouin et al.*, 2020] and the surface energy budget.

Aerosol Effects on Cloud Lifetime and Water Budget. Aerosols injected into the cloud layer can strongly influence cloud particle and droplet size distributions. The perturbed droplet size distribution leads to rapid adjustments of other cloud properties [Boucher et al., 2014; Sherwood et al., 2015], most notably LWP and cloud fraction. On the one hand, droplet size controls drizzle formation [Albrecht, 1989]. Drizzle removes water from the cloud, some falling to the surface. However, much evaporates before reaching the surface, cooling and moistening the sub-cloud layer and modifying the sub-cloud buoyancy profile. On the other hand, in clouds with droplets too small to initiate precipitation even in the unperturbed state, an aerosol perturbation does not lead to drizzle suppression but rather to positive feedback between enhanced evaporation of the smaller drops and turbulent entrainment of dry air into the cloud, leading to a reduction of LWP and cloud fraction [Ackerman et al., 2004; Bretherton et al., 2007].

Figure 1. ARM AMF1 vans installed on Scripps Pier in November 2023.

Figure 2. ARM SACR, guest vans, and SIO and LANL vans were installed at Mt. Soledad in November 2024.

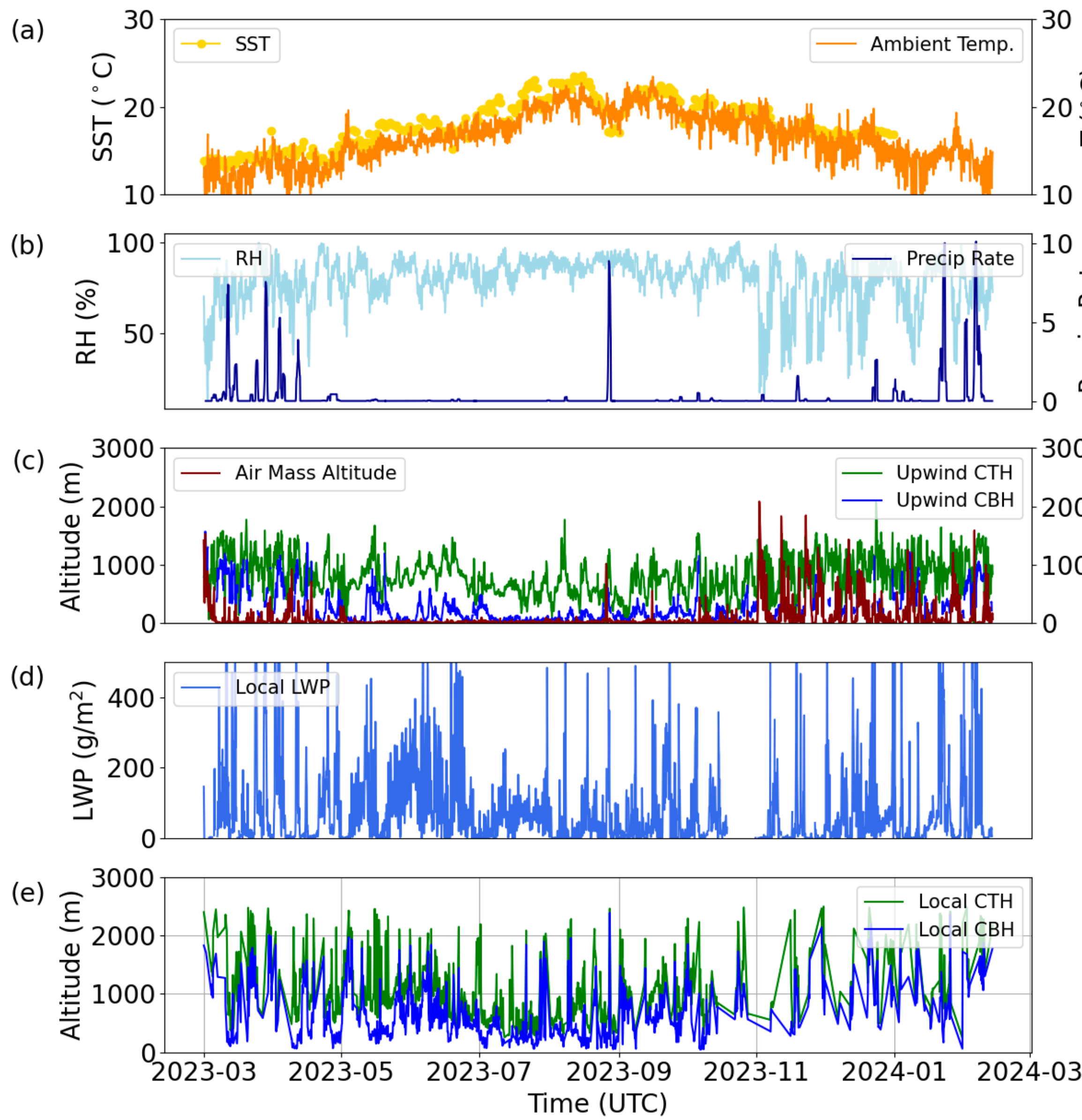

Figure 3. Time series of meteorological conditions during EPCAPE: (a) sea surface temperature (°C, yellow) and ambient air temperature (°C, orange); (b) relative humidity (%, light blue) and precipitation rate (mm/day, navy); (c) 24-hr averaged air mass altitude (maroon), cloud base height (CBH) (blue), cloud top height (CTH) (green) in meters unit; (d) cloud LWP (g/m^2) measured at Scripps Pier (royal blue); (e) local cloud base height (CBH) (blue) and cloud top height (CTH) (green) measured at Scripps Pier in meters unit. (a) and (b) were retrieved and calculated from AOSMET at Scripps Pier, La Jolla, California. (c) was computed by utilizing the minis cloud products using VISST algorithm based on the trajectory and (d) and (e) were retrieved from ARM VAP products and the local measurements at Scripps Pier from Feb 15, 2023 - Feb 14, 2024.

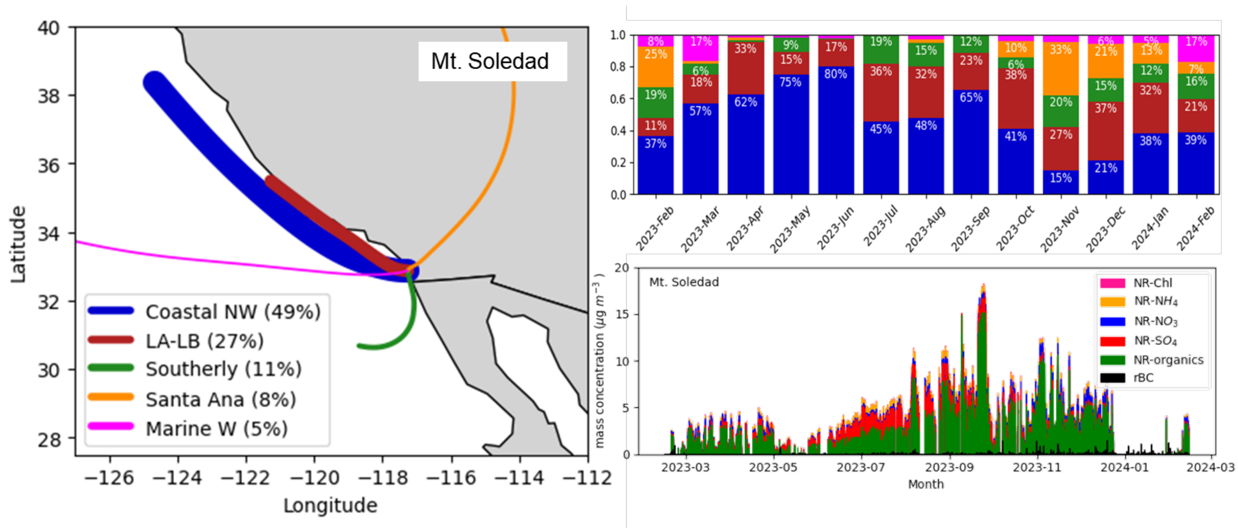

Figure 4. . Clustered ARMTRAJ back trajectories [*Silber et al.*, 2024] at Mt. Soledad (left), monthly contributions of each cluster (top right), and mass concentrations of refractory black carbon (rBC) and AMS non-refractory (NR) mass components at Mt. Soledad (bottom right). The time series indicates elevated NR-sulfate and NR-ammonium concentrations during the summer, coinciding with back trajectories from coastal regions and the LA-LB. In contrast, higher concentrations of NR-organics, NR-nitrate, and rBC associated with Santa Ana winds suggest an influence from inland San Diego.

3.0 Publications and References

<u>Published Datasets:</u>

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4.0 Lessons Learned

ARM support for this campaign was excellent. There was good communication to address and document the minor maintenance issues, and technical staff support was always available.

The only significant loss of measurements from the campaign was the leak caused by the late addition of the CCN in the AOS. This issue likely resulted from the late arrival to the campaign after instrument repairs by the manufacturer, which meant that it was not added and tested by the setup team or the mentors. Personnel or resource limitations meant that this issue was not identified until the end of the project when ARM mentors did an excellent job of diagnosing the problem. The only lesson learned is to allocate additional resources to assessing instrument performance earlier in the project.

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