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Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) Science Plan

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Executive Summary

Coastal cities provide the opportunity to characterize marine clouds and the substantial effects of manmade particles on cloud properties and processes. La Jolla lies to the north of San Diego, California, but it is often about a day directly downwind of the major pollution sources located in the ports of Los Angeles and Long Beach. The large dynamic range of aerosol particle concentrations combined with the multi-hour to multi-day persistence of stratocumulus cloud layers makes the site ideal for investigating the seasonal changes in cloud and aerosol properties as well as the quantitative relationships between cloud and aerosol properties.

The focus of the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) is 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, the Scripps Pier and the Scripps Mt. Soledad sites in La Jolla. An important enhancement to this study will be the collection of simultaneous in-cloud aerosol and droplet measurements to investigate the differences in these cloud properties during regional polluted and clean marine conditions. The combined observations will provide an unprecedented set of constraints for the following questions:

1. Cloud and Aerosol Climatology: What are the seasonal and diurnal cycles of marine stratocumulus cloud and aerosol properties on the northeastern Pacific coast?
2. Cloud Radiative Fluxes: How do cloud properties, including the ratio of direct-to-diffuse radiation, change as coastal clouds are advected inland?
3. Aerosol-Cloud Interactions: Will retrieved cloud properties reflect the regional signatures of aerosol?

Each of these questions reflects a topic of current controversy in the literature that cannot be addressed without the type of comprehensive data set that this project is expected to provide.

The relevance of this campaign to the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility mission is its strategic location in an accessible and economically important 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, but climate models do not accurately simulate the processes that control their radiative effects. Furthermore, the coastal orography incites significant additional uncertainties related to cloud turbulence, air motion spectrum, and drop size distributions. Finally, the aerosol in the region ranges from a clean marine background to frequent intrusions from a large and regionally homogeneous, well-characterized, surface-based pollution source (the Los Angeles-Long Beach urban port megacity), providing a large dynamic range of aerosol conditions for investigation.

Acronyms and Abbreviations

ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACCP	Aerosol, Cloud, Convection and Precipitation
ACE-2	Aerosol Characterization Experiment-2
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ACI	aerosol-cloud interactions
ACSM	aerosol chemical speciation mass spectrometer
AERI	atmospheric emitted radiance interferometer
AEROMMA	Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas
AERONET	Aerosol Robotic Network
AETH	aethelometer
AMF	ARM Mobile Facility
AOS	Aerosol Observing System
AOSMET	automated weather station
APS	aerodynamic particle sizer
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds Value-Added Product
ASR	Atmospheric System Research
AWARE	ARM West Antarctica Radiation Experiment
BNL	Brookhaven National Laboratory
BOAS	Biological and Oceanic Atmospheric Study
CAP-MBL	Clouds, Aerosol, and Precipitation in the Marine Boundary Layer
CCN	cloud condensation nuclei; cloud condensation nuclei particle counter
CEIL	ceilometer
CIRPAS	Center for Interdisciplinary Remotely Piloted Aircraft Studies
CN	condensation nuclei
CO	carbon monoxide, nitrous oxide, and water monitor
CPCF	condensation particle counter, fine
CPCU	condensation particle counter, ultrafine
CSPHOT	CIMEL sun photometer
CVI	counterflow virtual impactor
DL	Doppler lidar
DMS	dimethyl sulfide
DOE	U.S. Department of Energy
DSD	drop size distribution

DYCOMS-II	Dynamics and Chemistry Of Marine Stratocumulus-II
E3SM	Energy Exascale Earth System Model
ECOR	eddy correlation flux measurement system
ENA	Eastern North Atlantic
EPCAPE	Eastern Pacific Cloud Aerosol Precipitation Experiment
E-PEACE	Eastern Pacific Emitted Aerosol Cloud Experiment
FASE	Fog and Stratocumulus Evolution Experiment
FTIR	Fourier-transform infrared spectroscopy
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water Experiment
GNDRAD	ground radiometer
GOES	Geostationary Operational Environmental Satellite
GPCI	GCSS Pacific Cross-Section Intercomparison
HSRHI	hemispherical sky range-height indicator
HTDMA	humidified tandem differential mobility analyzer
INTERPSONDE	Interpolated Sonde Value-Added Product
IOP	intensive operational period
KASACR	Ka-Band Scanning ARM Cloud Radar
KAZR	KA-band ARM Zenith Radar
LA/LB	Los Angeles/Long Beach
LANL	Los Alamos National Laboratory
LASIC	Layered Atlantic Smoke Interactions with Clouds
LDIS	laser disdrometer
LDQUANTS	Laser Disdrometer Quantities Value-Added Product
LES	large-eddy simulation
LWP	liquid water path
MACAWS	Marine Aerosol Cloud and Wildfire Study
MAGIC	Marine ARM GPCI Investigation of Clouds
MASE	Marine Stratus Experiment
MASRAD	Marine Stratus Radiation Aerosol and Drizzle
MBL	marine boundary layer
MFR	multifilter radiometer
MFRSR	multifilter rotating shadowband radiometer
MFRSRCLDOD	Cloud Optical Properties from MFRSR Using Min Algorithm Value-Added Product
MICROBASEEN	Microbase Ensemble Data Products
MICROBASEKAPLUS	Improved MICROBASE Product with Uncertainties Value-Added Product
MPL	micropulse lidar

MWR	microwave radiometer
MWR3C	3-channel microwave radiometer
MWRRET	Microwave Radiometer Retrievals Value-Added Product
NAAMES	North Atlantic Aerosols and Marine Ecosystems Study
NASA	National Aeronautics and Space Administration
NEPH	nephelometer
NICE	Nucleation in California Experiment
NIR	near-infrared
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NSF	National Science Foundation
NWP	numerical weather prediction
O3	ozone monitor
OACOMP	Organic Aerosol Component Value-Added Product
ORG	optical rain gauge
PCASP	passive cavity aerosol spectrometer probe
PI	principal investigator
PMF	positive matrix factorization
PNNL	Pacific Northwest National Laboratory
PPI	plan position indicator
PSAP	particle soot absorption photometer
PWD	present weather detector
PWV	precipitable water vapor
RHI	range-height indicator
RRM	reginal refined model
R/V	research vessel
RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SatCORPS	Satellite ClOud and Radiation Property retrieval System
SCM	single-column model
SEBS	surface energy balance system
SKYRAD	sky radiometer
SMPS	scanning mobility particle sizer
SO2	sulfur dioxide monitor
SOLEDAD	Stratocumulus Observations of Los Angeles Emissions-Derived Aerosol Droplets
SONDE	balloon-borne sounding system
SP2	single-particle soot photometer

TBRG	tipping bucket rain gauge
TCAP	Two-Column Aerosol Project
TKE	total kinetic energy
TSI	total sky imager
UCSD	University of California, San Diego
UHSAS	ultra-high-sensitivity aerosol spectrometer
VAP	value-added product
VARANAL	Constrained Variational Analysis Value-Added Product
VDIS	2D video disdrometer
VDISQUANTS	Video Disdrometer Quantities Value-Added Product
VIPR	Vapor In-Cloud Profiling Radar
VPT	vertically pointing profile
WAIS	West Antarctic Ice Sheet
WB	weighing bucket rain gauge
XRF	X-ray fluorescence

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1.0 Background

Coastal cities provide the opportunity to characterize marine clouds and the substantial effects of manmade particles on cloud properties and processes. La Jolla lies to the north of San Diego, California, but given the frequent northwesterlies, it is often about a day directly downwind of the major and nearly continuous pollution sources (S Liu et al. 2011) located in the ports of Los Angeles and Long Beach (LA/LB, Figure 1). Since much of the distance between LA/LB and La Jolla is over ocean, sampling at La Jolla provides snapshots of aerosol-cloud interactions (ACI) between marine stratocumulus and manmade aerosol particles (Sanchez et al. 2016). The large dynamic range of concentrations of aerosol particles combined with the multi-hour to multi-day persistence of stratocumulus cloud layers makes the site ideal for investigating quantitative relationships between cloud properties and aerosols.

Figure 1. Map of Southern California coast showing locations of La Jolla and the ports of Los Angeles and Long Beach (LA/LB). The direction of typical prevailing winds is also illustrated, showing the frequent transport path of pollutants to La Jolla. The transit time of the port emissions to La Jolla is typically 12 to 36 hr (Hawkins and Russell,2010, S Liu et al. 2011).

Modeling studies have shown substantial uncertainties and sensitivities to natural marine cloud condensation nuclei (CCN) sources (Burrows et al. 2018, McCoy et al. 2015, SL Wang et al. 2018), meaning that to reduce uncertainties in indirect effects we must be able to better quantify the marine CCN budget at background and urban-influenced conditions (Lohmann and Feichter 2005, Twomey 1977). While models provide important constraints on these uncertainties, actually quantifying their magnitude requires substantial observations in multiple open-ocean and coastal regions in order to characterize the variety of cloud properties and the variety of aerosol sources (Sanchez et al. 2018, 2017a, 2016).

The northeastern Pacific Ocean is home to one of the most persistent stratocumulus cloud layers in the world, with consistent surface cooling provided by ocean upwelling and with the influence of climatological subsidence on boundary-layer structure. The characteristics of these clouds are unique in many ways. For example, the northeastern Pacific features a broad area with high cloud droplet number concentration (Bennartz and Rausch 2017), suggesting active aerosol-cloud interactions. In addition, satellite evidence indicates that the northeastern Pacific stratocumulus cloud decks in the subtropical region are most susceptible to changes in their outgoing shortwave radiation due to changes in cloud microphysics (Painemal 2018). Previous studies conducted in Northern California suggested that the shallowness of the MBL coupled with extremely strong overhead inversions near the coastline produce near adiabatic cloud liquid water contents, which are efficient at implementing the first aerosol indirect effect (Kim et al. 2012). While multilayer clouds can occur in this region (Muelmenstaedt et al. unpublished results), the decoupling processes and residual layers associated with North Atlantic and Southern Ocean features have not been frequently observed (Durkee et al. 2000, Stevens et al. 2003). Drizzle formation is an important process that can deform these layers by producing pockets of clear air surrounded by clouds known as open cells (Petters et al. 2006, Stevens et al. 2005, Wood 2007), but there is little information about drizzle fluxes in these regions given the small amount of precipitation involved. These features and knowledge gaps motivate the need to characterize the seasonal changes in marine stratocumulus properties over the northeastern Pacific.

The northeastern Pacific Ocean borders a region with perhaps more measurements of aerosol than any other region on the planet (California) but there is little analysis of coastal influences of marine sources because the focus of the existing pollution monitoring sites has been on local air quality, which typically targets urban centers. In addition, long-term measurements needed for a climatological characterization of cloud and drizzle properties are scarce over the region. One aspect that makes La Jolla such a unique observing site for aerosol particles is its location downwind of a large and relatively continuous pollution source (S Liu et al. 2011). The distance between the LA/LB sources and La Jolla provides an effective averaging time, allowing both mixing and reactions of pollutants (Figure 1). The resulting mixture is more representative of the aerosol that is found a few hours downwind of global megacities, which today covers much of the planet. The reason this feature is important for ACI is that the dependence of cloud properties on aerosol in such conditions may be different from those of the more canonical ship tracks is the presence of continuous sources that may effectively “saturate” clouds providing a different environment than the relatively narrow and confined plumes of ship tracks. While plumes may be continuously diluted by entrainment of adjoining clean air, polluted air masses may extend widely so that large areas do not have clean air accessible at the scale of boundary-layer eddies.

The site for the EPCAPE campaign will be the Scripps Pier, with a few instruments (including the Scanning ARM Cloud Radar [SACR]) at Mt. Soledad. The project will measure from February 2023 through January 2024. There is room for six first ARM Mobile Facility (AMF1) vans on the north side of the Scripps Pier, which is a secure location with programmable key card access. The Aerosol Observing System (AOS) van is expected to be located at the end of the pier between the existing instrument sheds. Power will be provided to the vans by an agreement between UCSD and ARM. Permission from Scripps has been obtained, pending agreement on location logistics, power upgrades, and Coastal Commission approval. The requested AMF1 instruments that are to be located at the Soledad site are the SACR, laser disdrometer (LDIS), and 2-channel microwave radiometer (MWR). Standard operating procedures are requested for radar (vertically pointing profile [VPT], hemispherical sky range-height indicator [HSRHI], and plan position indicator [PPI] in the case of SACR, if available) and other instrumentation.

The project includes investigators from both universities and national laboratories (Table 1). Four investigators (Burrows, Muelmenstaedt, Wang, Aiken) represent three different DOE laboratories (Pacific Northwest National Laboratory [PNNL], Los Alamos National Laboratory [LANL], Brookhaven National

Laboratory [BNL]) and have current funded work related to the scientific questions raised here. Four investigators (Fridlind, Ackerman, Lebsock, Painemal, Witte) are working at National Aeronautics and Space Administration (NASA) laboratories and also have current projects related to these questions. All expect that their analyses of the proposed observations will enhance their expected future laboratory-based projects.

Table 1. EPCAPE investigators and their roles.

Investigator	Defined EPCAPE Role
Russell	Overall coordination and analysis; providing and analyzing aerosol filters.
Lubin	Analysis and interpretation of AERI and related radiometric measurements.
Eloranta	Coordination and analysis of lidar measurements.
Silber	Analysis and interpretation of radar and lidar data; modeling of cloud formation.
Aiken	Interpretation of ACSM and related aerosol properties.
Wang	Interpretation of precipitation and drizzle properties.
Petters	Analysis and interpretation of CCN and HTDMA measurements.
Muelmenstaedt	Observationally constrained E3SM cloud modeling.
Burrows	Comparisons of E3SM aerosol model simulations to observations.
Miller	Analysis and interpretation of cloud structure and radiative properties.
Chang	Providing and analyzing fog drop spectrometer.
Liggio	Interpretation of gas-phase measurements and providing ground counterflow virtual impactor (CVI).
Wheeler	Interpretation of ground CVI measurements.
Ackerman	Evaluation and improvement of ModelE3 aerosol and stratiform cloud fields.
Fridlind	Observation-based aerosol-aware case studies for LES and ModelE3 SCM.
Witte	Analysis of microphysics-turbulence interactions in observations, LES, E3SM.
Lebsock	Comparison of retrieved cloud properties to satellite and model products.
Painemal	Interpreting satellite products from GOES-17 to support observations.

*Aiken and Wang also serve ARM roles as site operations staff (Aiken) and instrument mentor (Wang), for which they are responsible for instrument operation and uncertainty characterization. As part of this project, their roles are scientific interpretation of the results in the context of the other measurements as part of work that is not funded by ARM.

2.0 Scientific Objectives

The focus of this project is to characterize the extent, radiative properties, aerosol interactions, and precipitation of stratocumulus clouds in the Eastern Pacific across all four seasons at a coastal location, the Scripps Pier and the Mt. Soledad sites in La Jolla, California. An important enhancement to this study will be the collection of simultaneous in-cloud aerosol and droplet measurements to investigate the differences in these cloud properties during regional polluted and clean marine conditions. The combined observations will provide an unprecedented set of constraints for the following questions:

1. Cloud and Aerosol Climatology: What are the seasonal and diurnal cycles of marine stratocumulus cloud and aerosol properties on the northeastern Pacific coast?
2. Cloud Radiative Fluxes: How do cloud properties, including the ratio of direct-to-diffuse radiation, change as coastal clouds are advected inland?
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Each of these questions reflects a topic of current controversy in the literature that cannot be addressed without the type of comprehensive data set proposed here. The discussion below illustrates some of the large variety of scientific questions that are embedded in each of these three topics, allowing a rich scientific landscape for investigations with this data set.

3.0 Measurement Strategies

The campaign plan will be to locate most of the AMF1 instrumentation at the main site at Scripps Pier and a few additional instruments at the Scripps Mt. Soledad site (Figure 2), which will expand the short deployment in 2012 to include the much more comprehensive suite of cloud and aerosol measurements that is possible with AMF1. Below-cloud instrumentation, including cloud, precipitation, radiation, and aerosol instruments, will be situated on the Scripps Pier. These instruments are listed in section "6. ARM Resources Required." Additional instrumentation (scanning radar) will be located at the Mt. Soledad site, located less than 2 km inland (250 m above sea level), which will allow for sampling downwind of the pier below, in, and above clouds depending on conditions. Statistics are not available on how frequently the Soledad location is below, in, and above cloud (other than the seasonally limited prior study), as that will be an important outcome of this 12-month data set.

The general work plan is that ARM engineers, technicians, and instrument mentors will set up the instrumentation at the start of the campaign and that the requested instrumentation will run continuously until the end of the campaign. ARM technicians and instrument mentors will provide daily checks on instrumentation according to the standard protocols. Some modifications may be needed to provide sufficient power at the pier and Soledad sites, depending on the number of vans and power required for each of them. Measurements will be collected 24 hr per day and 7 days per week in order to capture full daily cycles of cloud formation and dissipation. Online instrumentation will be run using standard DOE protocols, typically multiple measurements per hour, for consistency with ARM data sets worldwide. The radar operations should be continuous throughout the campaign, if possible, due to the sparse, episodic, yet very important role of storms in this dry region. Guest instrumentation will use protocols appropriate to the expected conditions.

Figure 2. Overview (top left) of Scripps sites in La Jolla, California, with enlarged details for Mt. Soledad (top right) and pier (bottom).

The planned measurements will meet the proposed scientific objectives by using the comprehensive ARM cloud measurement suite to provide an unprecedented characterization of the extent, thickness, and precipitation of stratocumulus clouds in the northeastern Pacific across all four seasons at a coastal location. In addition, the guest instrumentation will augment the ARM aerosol suite by providing advanced instrumentation that can be operated long-term (12 months) because of easy access by UCSD principal investigators (PIs) and collaborators.

Satellite observations (which may include EarthCare, and the A-Train/C-Train constellation) will be used to generalize the AMF1 measurements to the broader region offshore of and in coastal southern California and northern Baja California. GOES-17 retrievals (SatCORPS) provided by the NASA Langley Cloud Group will be relevant for characterizing the cloud diurnal cycle at a regional scale for analyzing synoptic-scale variability and for Lagrangian studies. In addition, the National Weather Service NEXRAD radar (KNKX) at San Diego will provide an important baseline with which to complement ARM radar measurements capacity. We also plan to get the radiative flux divergence across the cloud layer by adding radiometers from the Lubin group at the mountain site.

3.1 Intensive Operational Periods

There will be two intensive operational 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. A critical aspect of both EPCAPE IOPs is characterization of the diurnal cycle of coastal clouds. For this reason, we require four sondes per day during the highest stratocumulus cloud frequency (April–September) and two sondes per day during the remainder of the year (February−March; October−January). Two sondes per day are necessary to characterize the annual cycle, and four sondes per day are needed to provide the day/night and night/day transitions relevant to the cloudier months.

Two sondes per day are sufficient to characterize boundary-layer structure and mixing, which provides basic seasonal statistics to characterize cloud structure. These sondes will be launched at local noon and midnight to show the differences between daytime and nighttime cloud structure. The two additional sondes, at approximately 6am and 6pm local time, are required to characterize the transitions, which are driven by the changes in surface heating associated with sunrise and sunset. The uncertainties of the prevalent but poorly understood diurnal cycle of stratocumulus clouds is well known (Duynkerke and Hignett 1993, Hignett 1991) and is amply illustrated by the Marine Stratus Radiation Aerosol and Drizzle (MASRAD) data set.

Vertical profiles at sunrise have been shown to be of critical importance to prediction of inland solar power predictions (E Wu et al. 2020a, 2019, Zapata et al. 2020, 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. Synoptic events could cause MBL depth to fluctuate enough to cause decoupling that is not driven by the diurnal cycle. In fact, there could be instances in which the cloud type is more in transition mode, such as shallow cumuli rising into stratocumulus. Thus, the need to document the general decoupling state, which is intimately linked to the cloud structure, is a powerful justification for additional soundings.

4.0 Project Management and Execution

The resources that will be needed from ARM for this campaign are AMF1, including standard meteorological instrumentation, a broadband and spectral radiometer suite, and remote-sensing measurements including lidars and radars, plus the AOS system for aerosol observations. AMF1 is well suited for this deployment. Specific AMF1 instrumentation included as part of this proposal are listed in Table 2.

Table 2. ARM instruments requested (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
KASACR: Ka-band Scanning ARM Cloud Radar
Precipitation
VDIS: 2D video disdrometer
LDIS: laser disdrometer
ORG: optical rain gauge
PWD: present weather detector
TBRG: tipping bucket precipitation gauge
WB: 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 IOPs, 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 instrument that is not currently available as part of AMF1 but it is requested to be added if it becomes available because it would enhance the scientific objectives of this project.

4.1 Instruments

Lidars. DL will measure drizzle and air motion velocities that can be combined with the radar Doppler velocity measurements in order to separate drizzle fall velocities from air motion. DL is critical for total kinetic energy (TKE) and vertical profiling, providing important constraints for sub-cloud turbulence. DL is also important for thermodynamic decoupling even if not fully decoupled. MPL provides cloud base height, some aerosol profile information, and information about cloud profile close to cloud base. Aerosol information retrieved by the MPL is based on backscatter ratio assumptions; CEIL provides cloud base height with a first range gate at 11 m. Either CEIL or MPL is required for all MWR, AERI, and Active Remote Sensing of Clouds Value-Added Product (ARSCL VAP) retrievals. High-spectral-resolution lidar (HSRL) systems would reduce the assumptions required for retrievals and will be requested by Eloranta from other funding sources (Eloranta 2005).

Radars. The KAZR provides the full vertical structure of clouds from a few hundred meters above ground level up to the tropopause at vertical and temporal resolutions of 30 m and 2 s, respectively (Riihimaki et al. 2017). The operation at the Ka-band enables the detection of both intense and light precipitation for Q1 and Q3 (Silber et al. 2019) as well as relatively small hydrometeors (such as larger cloud droplets [Verlinde et al. 2013]), while the KAZR Doppler capabilities allow the examination of cloud microphysical composition and processes (Q1, Q3), as well as dissipation rate estimates for Q2 (Chen et al. 2018). Finally, the use of radar reflectivity and power-law parameterizations and the synergistic use of the KAZR and lidar measurements enable the retrieval of precipitation rate for Q1 and Q3. These features and instrument characteristics provide an essential component for the characterization of clouds from both macro- and microphysical perspectives, which is crucial for the objectives of the proposed studies. The radar wind profiler (RWP) is a Doppler radar that measures the horizontal wind profile and turbulence intensity every 6 min up to an altitude of ~5 km in all weather conditions. Its vertical beam can be used to study precipitation and vertical velocity of large hydrometeors in cloud.

KASACR will be deployed at Mt. Soledad to allow better characterization of horizontal cloud and precipitation structure, with a potentially extensive data set and with a significantly higher sensitivity than precipitation radars (NEXRAD). KASACR will be used to quantify the cloud and sub-cloud drizzle evolution from the pier to Mt. Soledad (in VPT mode) and would provide valuable information about the spatial structure of cloud fields (for Q1, Q2, Q3; in PPI and HSRHI scan strategies [Kollias et al. 2014]). The EPCAPE deployment of the KASACR at the Mt. Soledad site enhances our ability to answer Q1 (climatology of cloud properties) and Q2 (land surface influence on clouds). The deployment at Mt. Soledad would enable an almost 360° coverage of the cloud and precipitation fields surrounding the central site. The KASACR provides significantly higher sensitivity relative to the WSR-88D (NEXRAD) network, allowing the detection of some tenuous cloud layers as well as the evaluation and spatial characterization of light precipitation (drizzle) common to the Eastern Pacific (Comstock et al. 2004), both upwind and downwind from the central AMF1 site at the pier. As the marine boundary layer moves inland, mechanical mixing generated by the abrupt increase in surface roughness begins to influence and eventually dominate the in-cloud mixing generated by cloud-top cooling and enhanced entrainment (Ching et al. 2010). A key scientific focus is the evolution of the cloud dynamic and microphysical structure as marine stratocumulus clouds transition to continental stratocumulus and cumulus clouds, which should be observable with the KASACR from Mt. Soledad.

We need to understand these transitions because many ARM sites (AMF and fixed) are in coastal regions, although the scientific objective was to measure marine clouds, namely MASRAD, Two-Column Aerosol Project (TCAP), Layered Atlantic Smoke Interactions with Clouds (LASIC), North Slope of Alaska (NSA), and Eastern North Atlantic (ENA). Knowledge of potential modifications at coastlines could assist in the interpretation of data from these and other deployments. Periodic sectorial range-height indicator (RHI) scans when pointing at a narrow range of azimuths centered over the pier would enable acquiring information about the three-dimensional mesoscale structure of some cloud systems predominantly upwind from the central site. Hemispheric PPI scans at minimum elevation angle (0.5° moving from south-west-north, for which Mt. Soledad serves as the highest topographic feature over a range of several tens of kilometers) would allow the characterization of cloud cell structure and the retrieval of precipitation rates over distances of a few tens of kilometers from the central site (Lamer et al. 2019). The deployment at the elevated Mt. Soledad site would likely reduce ground clutter impact on the measurements at such a minimal elevation angle. Periodic PPI scans at a few additional elevation angles (above 3°) covering all azimuths (360°) would provide comprehensive snapshots of the cloud field over altitudes of up to a few kilometers common to the region and would potentially inform about the influence of land surfaces on the cloud microphysical structure. Finally, periodic VPT measurements would enable cross-calibration of the KASACR with the AMF1 KAZR located at the Scripps Pier, and add the ability to supplement the central site with a secondary set of advanced cloud-base precipitation rates while using the zenith-pointing lidar measurements that will be performed at the Mt. Soledad site (O'Connor et al. 2005).

Precipitation. VDIS, LDIS, WB, TBRG, and ORG will be used to collect measurements of precipitation properties. Disdrometers will provide details about the drop size distribution and drop fall velocity. Rain gauges will be used to collect measurements of rainfall rate and rainfall accumulation. These precipitation measurements are crucial to monitoring the calibration of the collocated radar, providing observational analyses on aerosol and precipitation related topics, and supporting model evaluation and development. Multiple disdrometers and rain gauges will be used to compare precipitation at the pier and Soledad sites to better characterize the effects of coastal orography on precipitation.

Radiometers. MWR3C will provide the primary independent remote-sensing retrieval of cloud liquid water path (LWP). This newer system operates in three channels, 28.3, 30, and 89 GHz, and with the highest-frequency channel can retrieve LWP for optically thinner clouds than the earlier MWR. This capability with optically thin clouds will be particularly useful in examining the life cycle of coastal marine stratiform clouds and possible ACI. The 2-channel MWR, which operates at 28.3 and 31.4 GHz, has a 27-year track record. Its installation at Mt. Soledad (together with CEIL) will allow the examination of cloud LWP downwind (and inland) from the pier (where the MWR3C will be installed; Q1, Q2, Q3), and will serve as the backup direct and robust retrieval of cloud LWP (Cadeddu et al. 2013). The SKYRAD system comprises the essential set of broadband shortwave and longwave measurements using upward-looking pyranometers and pyrgeometers. Our prior work has shown that these instruments' radiometric calibration has sufficient quality that significant changes in cloud microphysical properties can manifest in statistically significant responses in downwelling surface irradiances measured by SKYRAD (Lubin and Vogelmann 2006). The GNDRAD system is the downward-looking equivalent of SKYRAD, providing continuous monitoring of surface albedo and broadband emissivity (when combined with SKYRAD). Spectral longwave zenith radiance measurements from AERI provide remote-sensing retrievals of cloud droplet effective radius (Lubin and Vogelmann 2006, Rowe et al. 2019, Turner 2007, Turner et al. 2007) and are therefore essential for ACI investigation. The MFRSR measures diffuse and global downwelling hemispheric irradiance in six wavelength bands between 415 and 940 nm, which are used to provide a high-quality cloud optical depth data product. The MFR is the six-channel spectrally resolved equivalent of GNDRAD's shortwave component and provides measurements of surface albedo that are useful for accurate radiative transfer simulations. The CSPHOT, which contains eight 10-nm-wide spectral channels (at 340, 380, 440, 500, 675, 870, 1020, and 1640 nm), is the primary measurement of total column aerosol optical depth. Its zenith radiance scans can also provide a backup source of cloud optical depth and effective droplet radius retrievals. For Q2, surface upwelling measurements in both shortwave and longwave are necessary to study the relative significance of opposing cloud effects: increasing albedo and decreasing longwave emission. In combination with other data products, GNDRAD measurements would aid studies on how cloud properties can influence the balance of opposing cloud effects. TSI observations would provide validation for irradiance-based cloud coverage metrics, which are subject to the accuracy of clear-sky models that can misconstrue instances of high clear-sky irradiance with cloud enhancement effects.

Atmospheric and Boundary State. Surface and vertical observations of meteorological parameters (AOSMET, PWD, SONDE) will provide crucial information on the meteorological conditions during sampling. SONDE measurements provide vertical profiles needed for model initialization and nudging. Four per day are requested during the IOPs, including the first prior to sunrise to better support inland solar forecasts. SEBS and ECOR provide rough retrievals of surface turbulent fluxes. The TSI records fractional sky coverage by cloud cover and is essential for sorting and interpreting all radiation measurements. For example, under overcast skies hemispheric irradiance measurements can be used to retrieve cloud optical properties, while under broken cloud cover zenith radiances should be used. The TSI also offers opportunities for image classification and resource prediction using deep neural networks, a growing topic of research in solar forecasting (Q2).

Aerosol and Trace Gas. Measuring the dry aerosol number size distribution (SMPS, UHSAS) will be critical to characterizing aerosol climatology (Q1) and to understanding the aerosol effect on cloud microphysical and radiative properties (Q3). In addition, the particle hygroscopicity will provide direct observations of the expected ability of those particles to activate (CCN) so that they can be compared to actual cloud properties. Additional measurements to characterize the physical and chemical properties of the aerosol population will provide important insight on the source and potential for the particles to act as cloud droplets (HTDMA, ACSM, NEPH [dry, wet], CPCF, CPCU) and provide insights into the causes of model biases in predicted CCN. Instruments characterizing the age and anthropogenic influence of the air mass are able to discern the relationships between aerosol properties and the emissions sources and in situ atmospheric transformations impacting aerosol in the sampled air mass (AETH, PSAP, O3, SO2, CO).

4.2 VAPS Requested

The following value-added products (VAPs) are requested for this project for the reasons noted:

- VARANAL (Constrained Variational Analysis) – provides output required for model forcing for LES and other simulations.
- ARSCL (Active Remote Sensing of Clouds) – provides output required for cloud radar interpretation and structure.
- MICROBASEEN (Microbase Ensemble Data Products), MICROBASEKAPLUS (Improved MICROBASE Product with Uncertainties) – provides output required for cloud microphysics from ARSCL; log-normal based retrieval. (PIs will also use AERI and other algorithms.)
- MFRSRCLDOD (Cloud Optical Properties from MFRSR Using Min Algorithm) – provides output required for cloud optical depth products from MFRSR.
- MWRRET (Microwave Radiometer Retrievals) – provides output required to retrieve LWP and precipitable water vapor from 2- and 3-channel retrievals (can be compared to AERI retrieval at the low end of $50 g/m^2$), both Illingworth and Turner versions.
- INTERPSONDE (Interpolated Sonde) – provides gridding of the SONDE measurements onto standard grids for modeling by constraining and interpolating from multiple sensors.
- LDQUANTS (Laser Disdrometer Quantities) – provides drop size distributions (DSDs) and associated rainfall rates/accumulation as those raindrops fall to the ground from laser disdrometer.
- VDISQUANTS (Video Disdrometer Quantities) – provides DSDs and associated rainfall rates/accumulation as those raindrops fall to the ground from video disdrometer.
- OACOMP (Organic Aerosol Component) – provides source-related characterization of organic components by positive matrix factorization (PMF) of the ACSM organic components.

We also request the products that are available from Satellite ClOud and Radiation Property retrieval System (SatCORPS).

4.3 Collaborative Measurements

PI Russell will request DOE Atmospheric System Research (ASR) program support to enable science by providing filter sampling at the Scripps Pier to complement the chemical analysis available from the AMF1 ACSM. This sampling will be housed in an AMF1 AOS van at the pier and is being proposed separately through the ARM approval process as an add-on measurement. The samples will be collected weekly by ARM staff, similar to the ARM West Antarctica Radiation Experiment (AWARE) deployment (J Liu et al. 2018a, 2018b), and will provide refractory components including organics and sea salt. A conditional sampling system will be designed by PI Russell to trigger cut-off of the filter pump during local high-condensation-nuclei (CN) events so that filter samples are more representative of regional background conditions rather than local activities.

Co-PIs Russell and Petters have requested National Science Foundation (NSF) support (in collaboration with Suzanne Paulson) to locate the Russell instrumentation van (Figure 3) for simultaneous deployment at Mt. Soledad for in-cloud sampling of detailed aerosol chemical composition, including offline filter analysis for organic functional groups (Fourier-transform infrared spectroscopy; FTIR) and elements (X-ray fluorescence; XRF). The Russell van will also include SP2 and APS measurements, for comparison to AMF1 AOS measurements at the Scripps Pier. The Russell van will include a high-resolution, time-of-flight, event-enabled Aerodyne AMS to provide aerosol composition and concentration aloft for comparison to the AOS ACSM deployed at the pier. Funding will also be requested to deploy the fog droplet monitor from Co-PI Chang (Dalhousie) at this site to characterize the droplet size distribution in cloud. Environment Canada expects to also provide a Brechtel ground-based CVI (Figure 3) for deployment at the Mt. Soledad site to enable in-cloud composition sampling of droplet residuals (Sanchez et al. 2016). Co-PI Liggio will request support to bring a chemical ionization mass spectrometer, which previously demonstrated at Mt. Soledad that cloud water chemistry was likely responsible for enhancements in low-molecular-weight polar organics such as isocyanic (HNCO) and formic acids in cloud droplets, with scavenging efficiencies beyond what can be expected from Henry's Law solubility (Zhao et al. 2014). In situ aerosol measurements of interstitial aerosol and aerosol from evaporated cloud droplets performed inside the cloud would strengthen the evidence required for answering a number of questions raised in Q1 and Q3. These additional data sets would specifically enhance Q3, as it will provide a substantial enhancement to the AMF1 instruments at a very minimal cost given the proximity of the site to Scripps.

Co-PI Lubin will contribute a shortwave spectroradiometer of the type successfully deployed at the West Antarctic Ice Sheet Divide (WAIS Divide) with AWARE (Wilson et al. 2018) and more recently at Siple Dome Field Camp in West Antarctica during December 2019 to January 2020. Measurement of shortwave spectral irradiance between 350 and1700 nm complements the mid-infrared AERI radiance measurements, in that cloud optical properties (optical depth and effective radius) can be retrieved under thicker clouds that emit in the longwave as blackbodies (with no spectral sensitivity to microphysics). The related algorithms make use of the sensitivity in the 1.6-micron window to phase and effective droplet or particle size, combined with optical depth-dependent attenuation at shorter conservative-scattering wavelengths. In Antarctica, Lubin was successful with a straightforward algorithm based on McBride et al. (2011) and was able to discern microphysical contrasts between climatologically typical summer stratiform clouds and clouds in a considerably warmer air mass that caused surface melt (Nicolas et al. 2017, Wilson et al. 2018). More advanced algorithms are available that use irradiance throughout much of the shortwave spectrum to reduce retrieval uncertainties (LeBlanc et al. 2015). The combination of this shortwave instrument with AERI will provide robust spectroscopic retrieval of cloud microphysical properties over a wide range in cloud LWP, suitable for ACI studies. The current instrument is manufactured by StellarNet (Inc.), and comprises a pair of miniature spectrometers (visible-wavelength and near-infrared [NIR]) coupled using fiber optical cables to a radiometric diffusing cosine collector. These components are enclosed in a small weatherproof housing with a small footprint that can easily be accommodated on the roof of the AMF or similar structure. Power requirements are minimal (at Siple Dome this spectroradiometer was solar powered; Figure 3). For this project, it is preferable to co-locate it with the MPL, which can provide independent verification of cloud phase via lidar depolarization.

Figure 3. Russell instrumentation van deployed at Mt. Soledad in 2012 with droplet probes sampling in cloud (top left); Lubin spectroradiometer at Siple Dome Field Camp, Antarctica, in 2020 (top right); Environment Canada Brechtel CVI (bottom left) and Chang fog drop monitor (bottom right) deployed at Halifax, Canada, in 2016.

Co-PI Eloranta plans to propose deployment of his HSRL with NSF support. Co-PI Witte will request flight time for the Naval Postgraduate School (formerly Center for Interdisciplinary Remotely Piloted Aircraft Studies; CIRPAS) Twin Otter aircraft for a 4-6 week IOP during the months of maximum low cloud cover (March-July). Flights will be designed to sample aerosol, microphysics, and meteorological state upwind of the Scripps Pier. The Twin Otter will also be equipped to measure surface fluxes over the ocean that can be used to inform Lagrangian modeling studies of air masses arriving at the ground-based measurement sites.

National Oceanic and Atmospheric Administration (NOAA) investigators (Patrick Veres and Drew Rollins) are considering the possibility of collocating the Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA) campaign (Warneke et al. 2021) near La Jolla in June 2023. AEROMMA plans to make airborne measurements of marine cloud chemistry in the EPCAPE region in June 2023. Their focus will be investigating the implications of the recent discovery of a new dimethyl sulfide (DMS) oxidation product in the atmosphere (Veres et al. 2020). NASA ER-2 investigators may also be interested in scheduling overpasses for Aerosol, Cloud, Convection and Precipitation (ACCP) suborbital measurements.

Multi-frequency radar methods are routinely used to derive precipitation drop sizes. However, they are fundamentally limited at the low end by radar frequency. Current operational radars operate below 100 GHz or ~3 mm wavelength. Higher-frequency radar operated in combination with the ARM W- and Ka-band radars would permit more precise sizing into the drizzle regime of precipitation. Co-PI Lebsock is coordinating with NASA to bring the experimental G-band VIPR (Vapor In-Cloud Profiling Radar), which operates at 175 GHz, during the April-June IOP. Coordinated observations with the KAZR or SACR will demonstrate for the first time the possibilities for these advanced microphysical retrievals in drizzling stratocumulus regimes.

4.4 Data Management Plan

The investigators have a long, established record of collaboration and data sharing with other investigators on multi-investigator projects similar to EPCAPE, including past DOE ARM deployments such as AWARE, MASRAD, and others. Observations and simulations by the Russell group that were funded by federal and state grants have been posted to UCSD digital archives (Frossard et al. 2017a, b, J Liu et al.,2018b, 2017, Modini et al. 2017, Russell et al. 2016, 2017, 2018, Saliba et al. 2019, Sanchez et al. 2017b, 2017c, Takahama and Russell 2016). Any individual or composite data sets that may be generated as a result of the analysis conducted for this project will be made available to the scientific community on request. Project participants will archive and make available on request all analysis products from observations used for the publications that result from this project. Specifically, guest instruments in the Russell or AMF vans will be expected to also post their measurements within a year of completion of the project. New code developed as part of this project will be made available to DOE and others on request if not posted as part of the digital archives. Compilation of these data and corresponding results will be advertised through regular presentations at scientific conferences and through peer-reviewed journal publications.

Data Archives. Data resulting from this project will be published and made openly available to the research community and the public through several sites. Publications and presentations resulting from this award will properly reference the ARM Data Center as the source of data used in this research. Additional publications, archives, and products will depend on both data availability and the outcome of data analysis proposed as part of this project.

Publication. We will comply with the open-access data policy in accordance with DOE regulations. All data resulting from this project will be published and made openly available to the research community and the public through several mechanisms: (1) PI products will be archived and made available as part of the ARM website; (2) PI products and associated analysis will be stored on the curated UCSD digital archives; (3) Publications using results of this project will include links to the available data.

5.0 Science

Three DOE campaigns have been mounted in northeastern Pacific cloud regions (MASRAD, MAGIC, ACAPEX), and in the Atlantic (where clouds have some similar characteristics) there is the ARM ENA observatory and two additional field campaigns have occurred (Aerosol and Cloud Experiments in the

Eastern North Atlantic [ACE-ENA] and LASIC). To show how EPCAPE will differ from these and other past field campaigns, we summarize studies of stratocumulus clouds in the northern hemisphere (plus LASIC, Table 3) and discuss a few of the findings to date from those studies below.

Table 3. List of similar marine stratocumulus field campaigns in the Northern Hemisphere (*plus LASIC).

Campaign	Platform/ Location (Period)	Objectives/Focus	Example Reference
Eastern North Pacific			
DYCOMS-II (DYnamics and Chemistry of Marine Stratocumulus-II)	NCAR C-130 flights 300 miles offshore from San Diego (July 2001)	Persistent drizzle of nighttime shallow stratocumulus	Stevens et al. 2003
MASRAD (MArine Stratus Radiation Aerosol and Drizzle)	ARM deployment at Point Reyes (March-September 2005)	Relationship between mesoscale structure, aerosols, cloud microphysics, drizzle, and radiation in stratus clouds	Miller et al. 2005
SOLEDAD (Stratocumulus Observations of Los Angeles Emissions-Derived Aerosol Droplets)	Scripps deployment with Environment Canada (May-June 2012)	Effect of size distributions and chemical composition on cloud droplets, closure between measurements and detailed microphysics parcel model	Sanchez et al. 2016
MAGIC (Marine ARM GPCI Investigation of Clouds)	AMF2 on ship Spirit (September 2012-October 2013)	Stratocumulus-to-cumulus transition on cruises at points in the annual cycle	Zhou et al. 2015
CIRPAS Twin Otter (including MASE [Marine Stratus Experiment], E-PEACE [Eastern Pacific Emitted Aerosol Cloud Experiment], NICE [Nucleation in California Experiment], BOAS [Biological and Oceanic Atmospheric Study], FASE [Fog and Stratocumulus Evolution Experiment], MACAWS [Marine Aerosol Cloud and Wildfire Study])	Aircraft observations near the central California coast (2005-2018)	Various aerosol-cloud interaction studies with particle size distributions and composition measurements	Russell et al. 2013, Sorooshian et al.2019
Calwater-2/ACAPEX (ARM Cloud Aerosol Precipitation Experiment)	ARM AMF2 and the ARM Aerial Facility (AAF) Gulfstream-1 (G-1) aircraft offshore; ground site at Bodega Bay (January-March 2015)	Structure of atmospheric rivers; long-range transport of aerosols in the e. North Pacific; aerosol influence on clouds and precipitation on the West Coast	Thompson et al. 2016
Atlantic Ocean			
ACE-2 (Aerosol Characterization Experiment-2)	C-130 flights in eastern North Atlantic (June-July 1997)	Properties, processes, and effects of aerosol types in the marine boundary layer	Raes et al. 2000

ENA (Eastern North Atlantic, including CAP-MBL [Clouds, Aerosol, and Precipitation in the Marine Boundary Layer] and ACE-ENA)	Graciosa (2009-10); ENA ground sites (2012-present); AAF G-1 during IOPs (2017, 2018)	Boundary-layer structure, vertical distributions, and horizontal variability of low clouds and aerosol	Wood et al. 2015, Zheng et al. 2018
NAAMES (North Atlantic Aerosols and Marine Ecosystems Study)	NASA C-130 flights and *R/V Atlantis* (November 2015, May-June 2016, September 2017, March-April 2018)	Interactions between marine ecosystems, clouds, and aerosols in the North Atlantic	Saliba et al. 2019
LASIC* (Layered Atlantic Smoke Interactions with Clouds)	AMF1 at Ascension Island (June 2016-October 2017)	Cloud adjustments to the presence of shortwave-absorbing aerosol	Zuidema et al. 2018

MAGIC (September 2012-October 2013). Marine ARM GPCI (Global Energy and Water Cycle Experiment (GEWEX)-Cloud System Study (GCSS)-Pacific Cross-section Intercomparison) Investigation of Clouds consisted of the deployment of the second ARM Mobile Facility (AMF) on a container ship. MAGIC comprised 40 six-day transects between the Port of Los Angeles and Honolulu. A key scientific component of MAGIC was the characterization of the stratocumulus-to-cumulus-transition, precipitation, and thermodynamic structure over the open ocean (Zhou et al. 2015). In addition, MAGIC provided a unique data set for the quantification of aerosol-cloud interactions (Painemal et al. 2017), with retrievals yielding stronger linear correlations between cloud microphysics and CCN than those reported in McComiskey et al. (2009) using data collected at Point Reyes. This is likely associated with the deployment of more advanced instruments (e.g., a 3-channel MWR) and the development of novel microphysical retrievals that combine data from radars, lidars, and sun photometers (Fielding et al. 2015). MAGIC data were also instrumental for assessing precipitation (Y Zheng et al. 2020b) and systematic shortwave biases (Ahlgrimm et al. 2018) in climate models.

MAGIC was primarily oriented to understand boundary-layer cloud processes, with a moving platform that hampered the characterization of a (stationary) cloud diurnal cycle, especially near the coast. There are no continuous sub-cloud TKE measurements from MAGIC because no Doppler lidar was deployed, so these data cannot provide a baseline TKE profile. Quantitative chemical composition and a more comprehensive aerosol characterization were not included in MAGIC, preventing further insights into the factors that explain covariability between CCN and cloud droplet number concentration.

MASRAD (March-September 2005). The ARM deployment to Point Reyes in 2005 included MASRAD, which was the basis for model and satellite comparisons and evaluations as well as for a cloud turbulence study (Ching et al. 2010, de Boer et al. 2013, McComiskey and Feingold 2012, Minnis et al. 2011, Oreopoulos et al. 2012). CCN spectra have been included in three separate analyses (Hudson and Noble 2014a, b, Noble and Hudson 2015). Berkowitz et al. (2011) used AMS measurements to analyze aerosol composition for two different regimes during the July 7 to 29 sampling period, one of which was marine and the other that included local coastal influences and higher ammonium concentrations (likely associated with local agricultural sources). They showed a substantial contribution of sea salt (20%) and marine sulfate (35%) to fine particle mass during the marine conditions (see Table 1 in Berkowitz et al. [2011]). This result relied on assumptions about average sea spray particle diameter in the use of IMPROVE fine particle (PM2.5) filter measurements of Na, since AMS does not measure refractory components like the Na and Cl that constitute sea salt. Our proposed submicron filter measurements of Na and Cl by XRF provide support for improved quantification of salt contributions as well as specific information on sea spray mode sizes.

McComiskey et al. (2009) used MASRAD results to derive an average aerosol-cloud interaction (ACI) expressed in terms of cloud droplet number concentration (N_d), that is, $ACI_N = dln(N_d)/dln(a)$ where a is an observed proxy for aerosol abundance, in this case the CCN number concentration NCCN. Their average Point Reyes value is $ACI_N = 0.48$, where in this formulation a value of 1.0 would represent all aerosol particles being activated to cloud droplets. McComiskey et al. (2009) also show that ACI_N is more readily detected at lower ranges of liquid water path (LWP), which include optically thin clouds. For LWP greater than ~150 g m^{-2} there is higher variability in ACI_N that reflects precipitation scavenging of aerosol in addition to droplet activation. Schmeisser et al. (2017) used MASRAD spectral aerosol properties to characterize Point Reyes as a clean marine site alternately influenced by maritime and (polluted) continental air masses, often showing large particles low in shortwave absorption. Wang (2007) determined how temporal variability in the CCN spectrum influences the mean cloud albedo. Wang et al. (2008) made a first-order assessment of the influence of organic components on CCN concentrations. Hudson and Noble (2014a) used MASE data (Lu et al. 2007) to show that a larger range in particle sizes can nucleate stratus cloud drops than was previously believed. MASRAD data have been used extensively to validate and improve radiometric and remote-sensing techniques to retrieve cloud properties, including cloud LWP and precipitable water vapor (PWV) from MWRs (Turner et al. 2007), LWP and droplet effective radius r_e from AERI data in conjunction with MWR data (Turner 2007), and cloud optical depth from MFRSR data (T Wang and Min 2008). We will use these techniques in our proposed analysis of EPCAPE. Ultimately MASRAD and MASE data have contributed to subsequent and more ambitious efforts such as scale and temporal sampling issues with determining aerosol indirect effects (McComiskey and Feingold 2012), evaluating satellite remote-sensing validation (Lin et al. 2009, Noble and Hudson 2015, Witte et al. 2018), and assessing simulations of aerosol-cloud interactions in global climate models (de Boer et al. 2013). Since the Point Reyes deployment was one of the earliest applications of the ARM AMF concept (Miller et al. 2005), this proposed deployment will have additional and improved instrumentation and VAPs for cloud, radiation, and aerosol characterization that will allow us to address more specific scientific questions.

LASIC (June 2016-October 2017). The ARM deployment to Ascension Island in 2016-17 has produced multiple research articles focused on the optical properties and cloud effects of the smoky aerosol found in that region (Gordon et al. 2018, Mallet et al. 2019, Shen et al. 2019, Zhang and Zuidema 2019, Zuidema et al. 2016, 2018). The first of these articles explained the scientific background of the uncertainties that motivated LASIC and other campaigns in the region (Zuidema et al. 2016). Two articles provided comparisons to model simulations of radiative effects (Gordon et al. 2018, Mallet et al. 2019). The remaining three articles investigated the role of smoke in affecting the diurnal cycle of boundary-layer clouds (Zhang and Zuidema 2019), the single-scattering albedo of aerosol from August to October (Zuidema et al. 2018), and the regional CCN concentration (Shen et al. 2019). Two additional recent studies have also used AERONET (Aerosol Robotic Network) measurements (Holben et al. 1998) at Ascension Island to evaluate satellite retrieval algorithms and models (Brown et al. 2018, de Graaf et al. 2019).

By comparing the Ascension Island column AERONET measurements to a global model with organic and black carbon aerosol absorption, Brown et al. (2018) found that the unique mixture of large, non-absorbing sea salt particles and smoke particles was not well predicted by the model, in part due to the limited measurements available after cloud screening. The particular absorption characteristics of this type of mixture are characterized by a recent classification (Cappa et al. 2016) but are not well represented in global models, again highlighting the need to better characterize the chemical and optical properties of the aerosol mixtures that are present at different locations. The La Jolla EPCAPE measurements will sample a very different range of aerosol types and concentrations, revealing a mixture of marine, shipping-related, and urban sources and likely sporadic episodes of biomass burning. The biological marine sources differ substantially between the two regions as well, reflecting a productive coastal ocean ecosystem in an upwelling area rather than a mid-tropical region.

ENA (October 2013-present). The Clouds, Aerosol and Precipitation in the Marine Boundary Layer (CAP-MBL) experiment conducted in 2011 (Wood et al. 2015) was a precursor to the installation of a permanent ARM Eastern North Atlantic (ENA) atmospheric observatory on Graciosa, Azores. Numerous peer-reviewed journal articles have documented a myriad of topics related to the structure (Cadeddu et al. 2020, Ghate and Cadeddu 2019, Ghate et al. 2015, Giangrande et al. 2019, Remillard et al. 2012), microphysics (P Wu et al. 2020b), and evolution (Kazemirad and Miller 2020) of marine boundary-layer clouds in this important region. Aerosol concentrations, processes, and influences have also been extensively documented (Gallo et al. 2020, GJ Zheng et al. 2020a, 2018). Observations from ENA are being used to quantify the stabilizing effect of drizzle in the sub-cloud layer (Yang et al. 2018) and to better understand the connections between CCN and cloud microphysics (Yang et al. 2019). Recent modeling efforts have demonstrated that the deepening-warming hypothesis proposed by Bretherton and Wyant (1997) operates in the post-cold frontal environment at ENA and that the transition from solid stratocumulus to cumulus clouds in the region is driven primarily by the surface fluxes until the marine boundary layer becomes decoupled. Once decoupled, cloud-top processes are important determinants of cloud properties. It is important to note that the boundary-layer clouds sampled at ENA are more representative of an extratropical regime, strongly forced by midlatitude weather disturbances, rather than subtropical stratocumulus cloud regimes. Surprisingly, despite numerous field campaigns near the California coast, long-term deployments comparable to ENA are non-existent over the northeastern Pacific.

CIRPAS Twin Otter Campaigns. Figure 4 provides a brief summary of approximate CCN-related variables for low supersaturation in the Eastern Pacific and shows that CCN exceeding 200 cm^{-3} are frequent in the Eastern Pacific. These accumulation mode concentrations appear to be generally larger than those at ENA (Wood et al. 2017, GJ Zheng et al. 2020a), possibly due to the lower frequency of rain, the lower efficiency of scavenging, the greater proximity to large sources, or a combination of all of these.

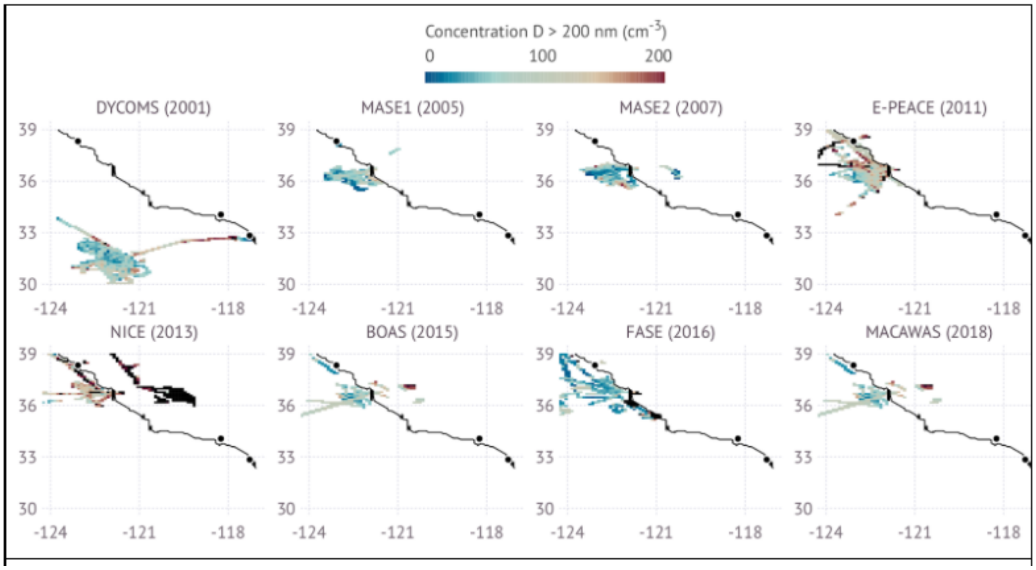

Figure 4. Observed aerosol number concentration for particle diameters >200 nm during various eastern Pacific field campaigns. Particle diameters >200 nm correspond approximately to CCN for supersaturations below 0.1%, depending on the hygroscopicity. The color scale is capped at 200 cm^{-3} to show that this value is frequently exceeded in the Eastern Pacific. Data are from the passive cavity aerosol spectrometer probe (PCASP) and screened for aircraft altitude <500 m. Data from all research flights are pooled and averaged on a pixel-by-pixel basis. The three black circles show, from northwest to southeast, the locations of Bodega Bay Marine Laboratory, Los Angeles, and La Jolla.

5.1 Scientific Focus

The focus of this project is to characterize the extent, radiative properties, aerosol interactions, and precipitation of stratocumulus clouds in the Eastern Pacific across all four seasons at a coastal location, the Scripps Pier and the Scripps Mt. Soledad sites in La Jolla, California. An important enhancement to this study will be the collection of simultaneous in-cloud aerosol and droplet measurements to investigate the differences in these cloud properties during regional polluted and clean marine conditions. The combined observations will provide an unprecedented set of constraints for the following questions:

1. Cloud and Aerosol Climatology: What are the seasonal and diurnal cycles of marine stratocumulus cloud and aerosol properties on the northeastern Pacific coast?
2. Cloud Radiative Fluxes: How do cloud properties, including the ratio of direct-to-diffuse radiation, change as coastal clouds are advected inland?
3. Aerosol-Cloud Interactions: Will retrieved cloud properties reflect the regional signatures of aerosol?

Each of these questions reflects a topic of current controversy in the literature that cannot be addressed without the type of comprehensive data set provided by EPCAPE. The discussion below illustrates some of the large variety of scientific questions that are embedded in each of these three topics, allowing a rich scientific landscape for investigations with this data set.

5.1.1 Q1—Cloud and Aerosol Climatology: What are the seasonal and diurnal cycles of marine stratocumulus cloud and aerosol properties on the northeastern Pacific coast?

Cloud and aerosol climatologies provide a complement to ENA studies in which similar analyses can be undertaken in a different cloud regime with substantially less frequent synoptic changes and in a very different aerosol regime with a nearby megacity source. Characterizing the separate climatologies of clouds and aerosols is an essential pre-requisite to characterizing the types of aerosol-cloud interactions. Here we will investigate both seasonal and diurnal cycles in those climatologies.

Seasonal Cycles. Marine stratocumulus is a persistent feature of the Southern California coastline, 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). However, the process-study focus of these investigations means that these studies provide only snapshots of the diurnal and annual cycles rather than the complete view that is needed to characterize the current climatology of the region. Testing whether the process-based knowledge that we have obtained from these earlier studies is sufficient when incorporated in global models requires a sufficiently long and accurate measurement record to provide statistical overlap. The detailed characterization of the full annual cycle of clouds and their properties is the first and most basic objective that will fulfill 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.

- What is the variability in cloud fraction and rain and drizzle frequency and intensity in the marine stratocumulus clouds at the Eastern Pacific coast on seasonal time scales?
- What are the key controlling factors and properties associated with meteorological conditions for marine stratocumulus clouds at the coast?
- How does the contribution of turbulence to coastal stratocumulus clouds change across different seasons?
- How well do different models represent coastal stratocumulus cloud evolution and properties?

The deployment of AMF1 will also provide an unprecedented characterization of the annual cycle of aerosol size distributions and hygroscopicity. The limited-duration prior measurements from 2012 (Figure 5) show that the pier site is generally more polluted than Mt. Soledad, likely associated with local activities. These measurements at the pier show a persistent accumulation mode between 100 and 200 nm that is absent at the mountain site, providing an important contrast between the more persistent background air aloft and the significantly higher concentrations at the pier. For this reason, the filter measurements provided by the Russell group at the pier will be run with conditional sampling (that is, turning the filter pumps off during spikes in particle concentrations). Online measurements will likely require de-spiking similar to what we have done in past ARM deployments (Gallo et al. 2020, J Liu et al. 2018a, 2018b). The dynamic range between nearly zero and 500 cm^{-3} at Mt. Soledad provides the opportunity to measure the full range of aerosol effects (Modini et al. 2017). Both sites have some evidence of occasional modal growth, but the ARM HTDMA is required to provide constraints on the hygroscopicity of condensing species. Previous Twin Otter aircraft campaigns were all farther north and do not provide local airborne observations. In addition, there are very limited ship-based aerosol observations in the vicinity offshore (Russell et al. 2016).

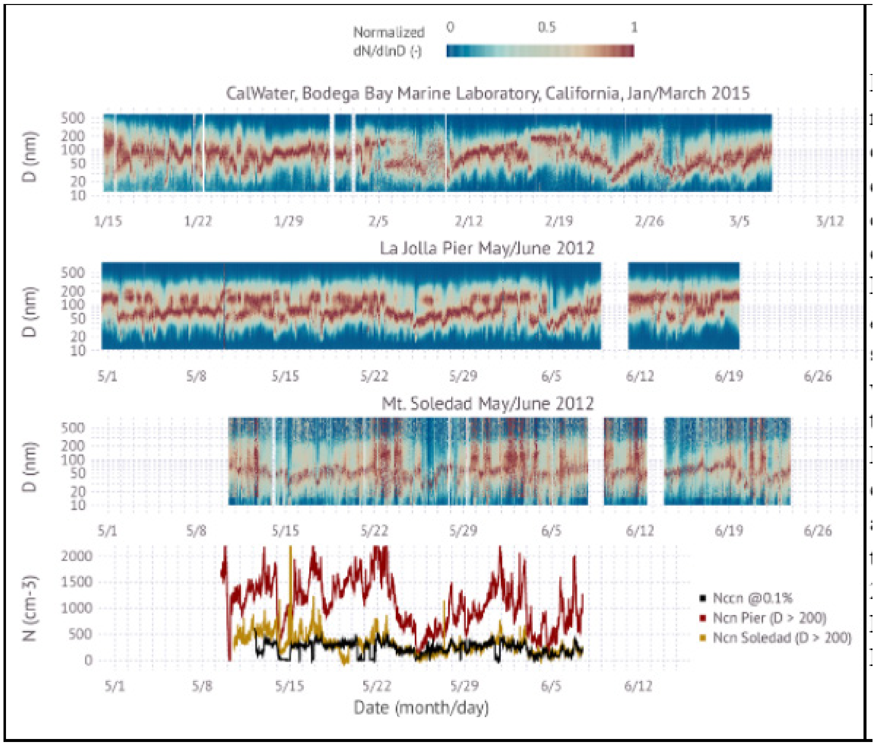

Figure 5. Aerosol number size distributions and concentrations observed during the SOLEDAD campaign in La Jolla in May-June 2012 (Modini et al. 2017). Two scanning DMA systems were operated, one at the pier and the other at Mt. Soledad. For comparison, also shown are measurements from the ACAPEX/CalWater 2015 campaign at Bodega Bay Marine Laboratory.

The 12-month data set proposed here will provide a much more complete constraint on global models, providing the ability to test the validity of modeled emissions inventories and transport of particles on 1-2-day trajectories from LA/LB (S Liu et al. 2011) and on 2-5-day trajectories from Monterey and other coastal regions (Hawkins and Russell 2010). Moreover, the 12-month duration also enables quantification of the less frequent back trajectory regimes, such as those during Santa Ana winds and other easterly sources (Day et al. 2010). Important open questions that could be addressed with this data set are:

- What is the seasonal frequency and relative contribution of aerosols from LA/LB to Scripps Pier?
- How do the contributions of photochemical oxidation and cloud processing to the aerosol size distribution change with season?
- How does the warming contribution of absorbing aerosols from LA/LB port activities change with season?
- How much do giant CCN and turbulence contribute to droplet spectral broadening? (Feingold et al. 2002, Witte et al. 2019)
- How well do large-scale models (e.g., E3SM) predict aerosol properties relevant to CCN activation (aerosol amount, size distribution, composition, and hygroscopicity) and their associations with different air masses in this region?

- How large are the biases in the modeled CCN activation spectra that are caused by biases or limitations in the modeled aerosol (including structural limitations), and how sensitive (or insensitive) are simulated clouds to any model biases in activation spectra? In other words, what are the main model weaknesses when it comes to simulating aerosol, and how much do they actually matter?

Diurnal Cycles. Another critical opportunity is to characterize the diurnal cycle of coastal clouds and aerosol size distributions. 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, 1993, Bretherton et al. 2007). The following open research questions are of interest to several co-investigators:

- What is the diurnal cycle of coastal marine stratocumulus clouds, precipitation, and boundary-layer decoupling?
- How does the diurnal cycle of coastal stratocumulus clouds modulate the longwave and shortwave fluxes at the surface? To what extent is sub-cloud turbulence set by cloud-top radiative cooling versus surface turbulent fluxes?
- Is the diurnal cycle of coastal stratocumulus cloud properties mainly controlled by meteorological conditions (e.g., LWP) or do other factors like aerosol play a role?
- Are the differential heating rates of the land-sea boundaries characterized well enough to accurately predict modulation of climate change in coastal areas?

The 12-month deployment provides more than 350 days of measurements to challenge model simulations. The fidelity of models to simulate the short time-scale variability of the diurnal cycle offers a constraint on their ability to simulate long-term cloud property changes associated with a warming climate. Similarly, the aerosol diurnal cycle at the pier has been shown to constrain photochemical and cloud processing of aerosol (S Liu et al. 2011), a critical feature of the diurnal cycle that affects both particle size and composition. This characterization would also allow for seasonal regional comparisons. Open questions on this topic include:

- What does the diurnal cycle of the aerosol size distribution show us about the frequency and importance of photochemically induced particle growth?
- Is there evidence for new particle formation associated with entrainment from above the marine boundary layer?
- How does the recirculation of aerosol from alternating onshore and offshore flow affect the size of accumulation-mode particles and their ability to serve as CCN?

5.1.2 Q2—Cloud Radiative Fluxes: How do cloud properties, including the ratio of direct-to-diffuse radiation, change as coastal clouds are advected inland?

Solar photovoltaic cells are an increasing source of energy for the power grid in California, and their reliability as a power source depends on accurate predictions of cloud cover over inland areas of southern California (among other parameters), where large solar farms provide increasing sources of clean energy. Much of the cloudiness over inland areas follows cloudiness at the coast, suggesting that it could be a good predictor for inland clouds on hourly time scales. However, existing weather observations fail to provide the constraints needed to predict inland cloud cover and to quantify cloud radiative properties.

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 (E 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 individual processes that shape the cloud structure and optical properties to be identified, and 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 using the comprehensive suite of relevant observations that is available from AMF1.

Many of the processes responsible for altering marine and coastal cloud structure are only observable with specialized remote sensors combined with suitably high-resolution, coincident measurements of thermodynamic and wind structure. Results from current and past research conducted by ASR investigators using AMF1 have shown the importance of cloud radar, Doppler lidar, MWR, RWP, comprehensive CCN and aerosol observations, and complementary measurements of the surface energy balance in detailing the process-level evolution of the marine and coastal boundary layers. The AMF1, which will be deployed on the Scripps Pier, is uniquely suited for this type of experiment and its measurements have been used in concert with models of various types to study cloud evolution.

The role of wind speed in the coastal stratocumulus dissipation is complex because it can differ greatly from one day to another, but also because wind shear at the bottom and top of the boundary layer affect the boundary-layer turbulence and cloud fraction (an effect that EPCAPE investigators are already studying). Wind profiler observations will be a great asset to better understand how different features of the wind speed profile (timing in the day, variability, predominant wind direction, wind shear) affect the timing of the dissipation as well as the spatial features of the clouds, which could also be cross-checked with measurements from a TSI, radars, and lidars. Cloud base and top heights derived from ARM ground-based lidars and radars could also be used as a complementary measurement to tune satellite products that usually have poor resolution in the boundary layer. Accurately predicting cloud dissipation time would also benefit from radiosonde profiles prior to sunrise, as this is a critical time for positioning solar panels and back-up energy streams. Continuous measurements of cloud thickness, heat fluxes, and wind speed could greatly improve these predictions.

Identifying the most important factors in cloud dissipation is challenging because many parameters are strongly correlated (Zapata et al. 2020). For example, parameters derived from numerical weather prediction (NWP) models (including Bowen ratio and divergence), estimated with bulk models (e.g., ocean heat fluxes), and direct measurements (wind speed) have tremendous effects from co-variability on modeled dissipation. A similar approach could be performed with the much more comprehensive data set provided by AMF1 observations with more accurate resulting retrievals, thereby highlighting and explaining sources of error in the cloud dissipation time.

Open research questions include:

- How does inland cloud cover depend on turbulence, cloud microphysical, and cloud radiative properties?
- How might multilayer cloud scenarios impact cloud presence and persistence?
- Do aerosols, decoupling, and sedimentation effects provide important additional controls on cloud dissipation?
- Are there net feedback effects of cloud optical properties on surface upwelling?
- How does the coastline modulate the TKE when the flow is onshore?
- What is the balance between cloud-top radiative properties and changes in the sub-cloud drizzle evaporation rate (and its stabilizing impact on the TKE profile)?

Quantifying the specific role of orographic forcing in modulating the TKE budget is a difficult issue. Aircraft data from other experiments in the region such as the Cloud System Evolution in the Trades (CSET; Albrecht et al. 2019) could be used, but they are piecemeal. Large-eddy simulations (LES) could shed light on the basic question of the TKE profile far removed from the coastline. High-resolution simulations (non-LES) at 1-km resolution can be used to resolve changes in cloudiness, but they still rely on parameterized sub-grid-scale turbulence, which limits their viability at the cloud-aerosol process scale.

Quantifying Cloud Radiative Properties. Most photovoltaic arrays consist of single panels oriented at a defined angle and separated somewhat from each other to avoid shadowing effects at low solar elevation angles and during winter. More sophisticated arrays may track the sun in either two or three dimensions, but they represent only a small fraction of the current array network. Fixed-angle (one-dimensional) photovoltaic arrays are most efficient in clear skies when the panels in the array are oriented orthogonal to the direct solar beam. As cloudiness increases, energy in the direct solar beam decreases while energy in the diffuse radiation field increases. 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 it is 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 use characteristics of a particular region are also important.

The specific radiative characteristics of clouds throughout their evolution can also affect solar cell efficiency. Before a coastal stratocumulus layer completely dissipates, there is a period when the cloud layer thins enough to allow the formation of a broken cloud field (for periods ranging from minutes to hours) (Zapata et al. 2019). This broken cloud field causes strong solar irradiance enhancement events that can affect solar equipment, which often is wasted and not converted to energy. The moment when the cloud field transitions from overcast to broken is not clearly defined nor understood, especially in the presence of coastal orography. Cloud thickness could be a relevant factor, but there is no evidence to confirm that hypothesis. Lidar and TSI measurements, for example, could be used to answer this question. Research questions on this topic include:

- How does the direct-to-diffuse ratio change as clouds move inland along the southern California coastline?
- How do boundary-layer structure, aerosol properties, and local circulation modulate the evolution of the direct-to-diffusion ratio?
- What are the implications of cloud evolution on solar photovoltaic arrays along the southern California coastline and beyond, and how does this evolution mesh with the energy demand profile?
- To what degree and on what time scale do aerosol interactions affect solar resources?

5.1.3 Q3—Aerosol-Cloud Interactions (ACI): Will retrieved cloud properties (drop size and number) reflect the regional signatures of aerosol?

A coastal site is intrinsically a very challenging location for ACI studies because of the orography and the co-variability between the meteorology and the aerosol (e.g., the polluted air mass is typically warmer and drier than the clean air mass). The coastal ACI questions are different (and, in many aspects, more challenging) than open-ocean scenarios, but it is vital to answer them because of regional climate impacts, such as the contribution of fog and drizzle to the local water budget and the contribution of cloud radiative effects to heatwave mitigation. Furthermore, we need to understand how these cloud regimes will change under aerosol reduction and climate change scenarios simulated by models. A classical approach provides a framework for separating ACI by physical mechanisms into the Twomey effect (cloud brightening) and the cloud "lifetime" effect (changes in precipitation, LWP, and cloud fraction) (Quaas et al. 2008). These aerosol effects can be translated into surface temperature changes (primarily by the Twomey effect) and water budget changes (primarily by the lifetime effect).

To address these questions, observations and modeling efforts will have to be used synergistically to get useful scientific results. The well-characterized aerosol, cloud, and turbulence data sets that are targeted forQ1 make it possible to probe ACI at the process level, including activation, evaporation, and precipitation. ACI proceed via a number of interacting physical mechanisms whose effects frequently cannot be measured individually (Stevens and Feingold 2009). ACI studies therefore rely on statistical associations between observable quantities, where care must be taken when inferring causation from correlation (Feingold et al. 2003, Gryspeerdt et al. 2019, 2016, 2017, 2014, Quaas et al. 2008, 2010, Sorooshian et al. 2009). Modeling studies, where individual processes can be modified in isolation, are an essential tool for causal inference (Mulmenstadt and Feingold 2018). The combination of modeling and the measurements proposed here provide an unprecedented opportunity to confront models with a set of process-oriented observables that constrain parameterized physics in a meaningful way (Lee et al. 2016, Mulmenstadt et al. 2020) using the comprehensive AMF1 instrumentation operated for more than 350 days to provide detailed turbulence, cloud, radiation, and aerosol property observations (including the cloudiest season of March to July).

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 are able to 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 in 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 ends up being the larger contributor to the global mean radiative forcing (Bellouin et al. 2020) and to the surface energy budget.

Two questions that assess model abilities to represent aerosol effects on cloud brightening in the coastal environment are: (1) How well do models represent vertical motions (mean flow and turbulence) resulting from the coastal terrain? (In particular, what resolution is required in numerical weather prediction (NWP) and cloud-resolving models for a statistically accurate prediction?) (2) How well do sub-grid turbulence and sub-grid orography schemes perform in coarser-resolution general circulation models such as E3SM? If models are capable of correctly simulating updraft statistics, then are they capable of reproducing the droplet number concentration (and size distribution) if initiated with the observed CCN and thermodynamic profiles? If so, this demonstrates model skill relevant to predicting CCN in future scenarios. For example, if E3SM predicts the aerosol correctly (which could be addressed with regionally refined model (RRM) simulations, as in Q1), then does it also predict the cloud responses correctly, given accurate thermodynamic and aerosol boundary conditions? This question could be addressed with single-column model (SCM) simulations forced with conditions obtained from the RRM and could be compared with LES.

Following this type of model evaluation, a number of important questions can be addressed:

- Which aspects of model errors in aerosol simulation matter most to the cloud properties that are most important for the coastal transition region?
- Can changes in aerosol properties (size, composition, hygroscopicity) be related to changes in cloud properties?
- Are there sufficient ranges of aerosol sources to distinguish between sources?
- How are aerosols processed in a cloud and what is the role of entrainment and detrainment? If above-cloud particles are detrained droplets, then comparing measurements at the pier to Mt. Soledad can provide insights on the chemical and physical processes that take place. Do these processes feed back onto the cloud properties?
- Do ACI metrics change as a function of deepening and shoaling boundary layer (Possner et al. 2020)?
- Can we separate the roles of aerosol and meteorology in determining cloud properties (including cloud droplet number, liquid water path, precipitation rate, boundary-layer depth, decoupling, diurnal cycle)?
- Can retrieved sub-cloud turbulence and activation theory accurately predict observed and retrieved cloud droplet number concentration for a given cloud LWP and large-scale meteorological forcing (Sena et al. 2016)? This type of closure study can be difficult to achieve using only retrievals of cloud droplet number concentration, but the fog monitor and other proposed in-cloud instrumentation for Mt. Soledad will enhance our ability to address this objective.

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 of which falls to the surface, but much evaporates before reaching the surface, thereby 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 a 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).

Many global models determine drizzle rates using autoconversion schemes that are poorly constrained, causing predicted cloud properties to vary widely between schemes (Dionne et al. 2020). Models that represent activation correctly (based on comparison to observations, as discussed above) may still not necessarily represent the "rapid adjustments" by drizzle suppression or enhanced evaporation correctly because these processes involve different model physics. If the models represent drizzle suppression correctly, it is possible to evaluate the dependence of the Albrecht and Ackerman effects on various conditions and to estimate the effect on the coastal water and energy budgets due to precipitation, LWP, and cloud fraction change. These effects describe possible relationships between the change in LWP due to the reduced drizzle sink and the change in CCN, involving the complex interplay of processes with different time scales. For example, faster updraft speeds associated with coastal orography could mean there is less time for collision-coalescence to operate which could limit drop growth (Ovchinnikov et al. 2013), while other studies suggest the opposite including the possible "lofted drizzle" phenomenon (Takahashi et al. 2017).

Specifically, the AMF1 observations can be compared to E3SM in both SCM and RRM mode. The RRM grid that will be default for E3SMv2 has a 25-km resolution in the continental U.S. and around the coasts (in the atmosphere), so it should better resolve the clouds at the coast compared to the low-resolution grid in v1 (100 km) and is less expensive than running at 25 km globally. The RRM in v2 will also have a refined grid in the ocean around the coastlines, and hence it will resolve ocean eddies (and thus heat transport) better. The SCM is fast and cheap to run and is appropriate for comparisons with LES and for benchmarking against case studies with known forcings. In addition to E3SM, the EPCAPE AMF1 data set would allow the statistical evaluation of the GISS ModelE3 coupled stratiform aerosol-cloud physics, similar to what is planned for E3SM. Satellite retrievals and additional global models will be used to extend these results based on the physics and regional context. With this approach, we expect it will be possible to address the following questions:

- Is it possible to disentangle the covariability of meteorology and aerosol perturbation? Do polluted air masses also tend to be dry and warm as found at more northerly latitudes in the northeastern Pacific coast? (Atwood et al. 2019)
- How does aerosol mediate the diurnal cycle of precipitation? Does this vary depending on either aerosol amount or CCN spectrum (activation curve as a function of supersaturation) associated with different air mass regimes?
- What is the role of aerosol in controlling drizzle fluxes from the cloud layer and how does the drizzle redistribute moisture and heat in the sub-cloud layer?
- Do models initialized with the measured aerosol properties reproduce the observed ACI evolution along Lagrangian tracks from the coast into the stratocumulus regions offshore (Christensen et al. 2020)?

6.0 Relevancy to the DOE Mission

The relevance of this campaign to the ARM mission is its strategic location in an accessible and economically important region of the world that lacks long-term observations of its frequent, persistent, and climatically important coastal stratocumulus cloud cover. The location affords excellent siting for both in situ and remote-sensing observations below and in-cloud locations with relatively low local influences. The clouds lie in one of the largest regions of upwelling-driven stratocumulus layers that are likely most impacted by aerosol indirect effects, but climate models do not accurately simulate the processes that control their radiative effects. Further, the coastal orography incites significant uncertainties related to cloud turbulence and hence updraft velocities and drop size distributions. Finally, the aerosol in the region ranges from a clean marine background to frequent intrusions from the large and numerous, regionally homogeneous and well-characterized, surface-based pollution sources of the Los Angeles-Long Beach urban port megacity; this range of conditions provides a large dynamic range of aerosol conditions for investigation.

Characterization of this important coastal cloud region and the aerosol impact on its characteristics will improve the understanding of aerosol indirect effects and its representation in DOE's E3SM model as well as other global climate models. Specifically, the layered, low-level, upwelling-driven nature of the stratocumulus clouds in this region will provide an important contrast to the ARM ENA site, contributing a more complete picture of cloud properties globally. In addition, the San Diego region will provide the opportunity to build on what was learned at ENA, apply the additional complexities of coastal orography, and mix in the combination of marine and polluted conditions. Moreover, the current AMF1 capabilities will allow us to expand on the more limited instrumentation and operations provided by MASRAD and MAGIC.

The relevance of this campaign to the decadal vision is that it extends ARM measurements to a diverse climate regime, that of coastal upwelling-driven stratocumulus, allowing an improved understanding of the key atmospheric phenomena that drive the aerosol indirect effect globally. As the ARM decadal plan notes the importance of studies in areas with significant urban development, this region serves to address this objective. The 12-month data set will provide sufficient duration and resolution to be used for testing and improving global and regional representation of clouds and climate, as well as helping the myriad of local predictions of solar and wind power utilities on which tomorrow's economy will rely. This duration is essential to provide the robust statistics and variability needed for aerosol-cloud interactions, and the multi-season duration will make this data set more useful for climate model evaluations than many of the previous northeastern Pacific studies.

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