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# Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL) Final Campaign Report

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# Acronyms and Abbreviations

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| AMF | Atmospheric Radiation Measurement Mobile Facility |
| ARM | Atmospheric Radiation Measurement |
| CAP | Clouds, Aerosol, and Precipitation |
| CCN | cloud condensation nuclei |
| ENA | Eastern North Atlantic |
| MBL | Marine Boundary Layer |

# Contents

# 1.0 Problem Statement

The extensive coverage of low clouds over the subtropical eastern oceans greatly impacts the current climate. In addition, the response of low clouds to changes in atmospheric greenhouse gases and aerosols is a major source of uncertainty, which thwarts accurate prediction of future climate change. Low clouds are poorly simulated in climate models, partly due to inadequate long-term simultaneous observations of their macrophysical and microphysical structure, radiative effects, and associated aerosol distribution in regions where their impact is greatest. The thickness and extent of subtropical low clouds is dependent on tight couplings between surface fluxes of heat and moisture, radiative cooling, boundary layer turbulence, and precipitation (much of which evaporates before reaching the ocean surface and is closely connected to the abundance of cloud condensation nuclei). These couplings have been documented as a result of past field programs and model studies. However, extensive research is still required to achieve a quantitative understanding sufficient for developing parameterizations, which adequately predict aerosol indirect effects and low cloud response to climate perturbations. This is especially true of the interactions between clouds, aerosol, and precipitation. These processes take place in an ever-changing synoptic environment that can confound interpretation of short time period observations.

The Eastern North Atlantic (ENA) Ocean is a region of persistent, but diverse, subtropical marine low clouds. In summer, the Azores are ideally located to sample the transition from overcast stratocumulus regime to the broken trade cumulus regime; the winter frequently experiences maritime frontal clouds. Context for this deployment is provided by a major prior field experiment (Atlantic Stratocumulus Transition Experiment [ASTEX] 1992) that sampled clouds in the ENA and featured one of the first successful deployments of millimeter radars to study marine boundary layer (MBL) clouds.

In conjunction with detailed collocated aerosol measurements during the deployment period, additional data from the deployment were utilized to address the following key scientific questions:

1. Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the ENA? Do physical, optical, and cloud-forming properties of aerosols vary with these synoptic features? How well can state-of-the-art weather forecast and climate models (run in forecast mode) predict the day-to-day variability of ENA cloud cover and its radiative impacts?
2. Can we find observational support for the Twomey effect in clouds over the ENA?
3. What is the variability in precipitation frequency and strength in the subtropical cloud-topped MBL on diurnal to seasonal timescales, and is this variability correlated with variability in aerosol properties?
4. Are observed transitions in cloud mesoscale structure (e.g., closed cellular to open cellular convection) influenced by the formation of precipitation?

These questions were addressed with the support of the Department of Energy's Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) in a research structure that included collocated aerosol measurements and multiscale modeling work. Synthesized long-term data from the AMF were used to initialize, constrain, and validate numerical models including large eddy simulation, single column, and regional and global atmospheric models.

# 2.0 Project Synopsis

The complex interactions among clouds, aerosols, and precipitation are major sources of uncertainty in our ability to predict past and future climate change (Lohmann and Feichter 2005, Stevens and Feingold 2009, Quaas et al. 2009, Isaksen et al. 2009). Marine low clouds are particularly susceptible to perturbations in aerosols because they are spatially extensive (Warren et al. 1988), optically thin, (e.g. Turner et al. 2007, Leahy et al. 2012) and often form in pristine air masses (Platnick and Twomey 1994). Increases in aerosol concentrations due to anthropogenic emissions lead to increased cloud droplet concentrations that increase cloud brightness by increasing the overall surface area of droplets. These aerosol indirect effects are the dominant contributor to the overall aerosol radiative forcing in most climate models, yet are extremely poorly constrained and can vary by a factor of five across models (Quaas et al. 2009).

Climate models indicate a major fraction of the global aerosol indirect radiative forcing signals are associated with marine low clouds (Quaas et al. 2009, and see Figure 3 in Kooperman et al. 2012), which are poorly simulated in climate models (Zhang et al. 2005, Wyant et al. 2010). A range of models from simple theoretical models to sophisticated cloud-resolving simulations all indicate the Twomey effect (increased cloud reflectance stemming from the reduction of drop size by condensation on a larger number of nuclei) is by itself insufficient to explain how low clouds respond to changes in aerosols. Models illustrate a significant fraction of the overall aerosol indirect effect may be related to precipitation suppression by aerosols and its impact on the turbulent kinetic energy and moisture budget of the boundary layer (Albrecht 1989, Ackerman et al. 2004, Lohmann and Feichter 2005, Penner et al. 2006, Wood 2007). Since a significant fraction of the precipitation falling from low clouds evaporates before reaching the surface (Comstock et al. 2004), additional complexity must be taken into account when determining how precipitation impacts cloud dynamical responses to aerosols.

Recent field measurements are revealing important information on the factors controlling precipitation rates in marine low clouds; particularly the role aerosols may play in precipitation suppression (Wood 2005, Geoffroy et al. 2008, Wood 2012, Terai et al. 2012). These studies indicate that based on a given amount of condensation or cloud thickness, precipitation from low clouds decreases with increasing cloud droplet concentration. Unfortunately, existing field data sets are statistically limited to a relatively low number of cases. As such, it has proven challenging to fully understand the role of precipitation suppression by aerosols. Spaceborne cloud radar overcomes some of these sampling limitations and provides evidence that light precipitation is susceptible to increased concentrations of droplets (e.g., Kubar et al. 2009, Wood et al. 2009) and aerosols (L'Ecuyer et al. 2009). However, current spaceborne radar data suffer limitations such as low sensitivity, low vertical resolution, and near-surface ground clutter contamination. In addition, spaceborne column-integrated aerosol optical property retrievals do not necessarily provide sufficient constraints on cloud condensation nuclei concentrations (Liu and Li 2014). Therefore, it is necessary to increase surface sampling of aerosol-cloud-precipitation processes using state-of-the-art remote sensing in conjunction with ground-based in situ measurements of aerosol optical and cloud-forming properties.

The ARM Climate Research Facility deployed the Clouds, Aerosol, and Precipitation in the Marine Boundary Layer field campaign (CAP-MBL, www.arm.gov/sites/amf/grw) to the island of Graciosa in the eastern Atlantic Ocean in response to the need for improved long-term, but comprehensive, measurements at a marine low cloud site. Graciosa is a small island (~60 km$^2$ area) situated at

39.1°N, 28.0°W in the Azores archipelago, located between the boundary of the subtropics and the mid-latitudes. As such, Graciosa is subject to a wide range of meteorological conditions, including periods of relatively undisturbed trade-wind flow, mid-latitude cyclonic systems and associated fronts, and periods of extensive low-level cloudiness. Measurements were made from April 2009 to December 2010.

CAP-MBL was designed to gather an extended record of high-quality data on clouds and aerosol properties in a remote marine environment, with the objective to improve cloud and aerosol treatments in climate models. An additional objective was to provide high-quality ground-based remote sensing and in situ data, to be used in conjunction with spaceborne remote sensing, for improved mapping and understanding of marine low cloud properties over remote oceans. The CAP-MBL's continuous record allows for greater statistical reliability in the observed relationships between aerosols, clouds, and precipitation than is possible with aircraft, yet retains the advantages of in situ sampling of aerosol properties difficult to constrain with satellite data.

# 3.0 Preliminary Results

Graciosa Island is situated between the boundary of the subtropics and mid-latitudes in the Northeast Atlantic Ocean. Analysis of AMF data show great diversity in meteorological and cloudiness conditions (Rémillard et al. 2012, Dong et al. 2014, Tselioudis et al. 2014). Low clouds are the dominant cloud type, with stratocumulus and cumulus occurring regularly. Approximately half of all clouds contained precipitation, detectable as radar echoes below the cloud base (Rémillard et al. 2012). State-of-the-art radar remote sensing is revealing the complex nature of warm rain formation in shallow marine clouds (Kollias et al. 2011, Luke and Kollias 2013). Radar and satellite observations reveal clouds with tops from 1-11 km contribute more or less equally to surface-measured precipitation at Graciosa (Wood et al. 2014). A wide range of aerosol conditions was sampled during the deployment, consistent with the diversity of sources indicated by back trajectory analysis. Preliminary findings suggest important two-way interactions between aerosols and clouds at Graciosa; with aerosols affecting light precipitation (Mann et al. 2014) and cloud radiative properties, and clouds being partially controlled by precipitation scavenging (Wood et al. 2014).

The clouds and aerosols sampled at Graciosa are being compared with short-range forecasts predicted by a variety of models. A pilot analysis with two climate and two weather forecast models illustrate fairly accurate reproductions of the observed time-varying vertical structure of lower-tropospheric clouds, but less accurate forecasts of cloud-nucleating aerosol concentrations.

# 4.0 Key Lessons Learned

The campaign was successful overall. Most instruments remained operationally efficient throughout the twenty-one months of data collection. Collaborators from the Regional Directorate of Science and Technology of the Government of Azores, the University of the Azores, and the Portuguese Meteorological Institute provided key logistical and operations support. This engagement with regional authorities and institutions was important for the logistical success of the deployment.

**Site:** The AMF instruments were deployed at Graciosa airport, situated within a few hundred meters of the island shore. The site location was appropriate due to being situated on the flattest part of the island. Graciosa is one of the smallest and flattest islands in the Azores, with maximum dimensions of 10 km and a maximum elevation of less than 400 m, therefore making it most appropriate for measurements designed to be representative of the open ocean. Nevertheless, there were a number of issues encountered with the site.

1. Despite its proximity to the ocean, there will likely be island influence on the clouds measured. There was island influence on surface temperatures measured at the site, due to the development of a shallow internal boundary layer as the air moved from the ocean over the island. Thus, it is challenging to accurately determine an appropriate ocean-relevant lifting condensation level, and conduct measurements of surface fluxes representative of the open ocean. Proposed solutions include situating a buoy offshore, but this could prove expensive. Evidence for a significant island effect on clouds measured at the site, compared with those offshore, is less clear, but a recent satellite study (Xi et al. 2014) suggests the possibility of relatively modest island impact on clouds.
2. Contamination from the infrequent air traffic requires consideration when processing aerosol data. In most cases, spike removal techniques can be used to remove short-term contamination due to aircraft and road traffic. If filter measurements are deployed in the future, assessment of the potential impact of contamination should first be undertaken.
3. It has been suggested that the proximity of the site to breaking ocean waves might lead to anomalously high coarse mode aerosol scattering. The degree to which this is true has not yet been ascertained. A possible study using short (<20 m) towers might help resolve this issue.

In addition to site considerations, there were a couple instrumental issues as well:

1. The atmospheric emitted radiance interferometer (AERI) instrument failure early on in the campaign (June 2009) required a part that could not be shipped internationally due to export controls.
2. The cloud condensation nuclei (CCN) instrument underwent a slow decline after roughly August 2009 due to inlet clogging. This continued until April 2010, when the issue was discovered and remedied. The clogging resulted in larger sized droplets at the higher percentage supersaturated values not reaching the detector. Optical particle counter detector inlet clogging was the result of dust particles from the ceramic bisque falling into the aperture. It was difficult to identify the problem from data alone due to a marked seasonal cycle in aerosol properties. In response, a correction has been applied that "calibrates" the flow rate in the CCN instrument through comparison of the high supersaturation CCN estimates against the CCN concentration. This appears to have resolved the problem, but future deployment of CCN instruments over long periods should consider this potential issue and employ frequent inspection and maintenance of the CCN. The AMF CCN bisque has twice been replaced since the Graciosa deployment. The bisque is quite fragile and susceptible to cracking during shipment, which makes shipment back to the United States for repairs rather difficult.

Finally, some scientific findings from CAP-MBL are important for consideration in future sampling from the long-term, fixed ARM ENA site, (which is currently being instrumented and should be fully operational by mid-late 2014). These include:

1. The planetary boundary layer is not fully coupled most of the time (Rémillard et al. 2012). Thus, surface CCN measurements may not be representative of the aerosols entrained into clouds. A new

two-lidar system will be deployed at the ENA site and efforts should be made to link the surface CCN with cloud base aerosol properties, using lidar profiling.

2. Given the frequency of cloud precipitation, it is important to ensure retrievals of cloud properties, using radars, are not contaminated.
3. Liquid in precipitating frontal clouds frequently attenuates the W-band radar. Longer frequencies will be needed to completely sample the precipitating clouds.

# 5.0 Publications/Manuscripts

Note: Publications preceded by * indicate publications using data from the CAP-MBL deployment.

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