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Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL)

Science Plan

for the 2009/2010 Deployment of the ARM Mobile Facility to Graciosa Island, the Azores, NE Atlantic

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Executive Summary

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 that 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 the 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 often evaporates before reaching the ocean surface and which 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, we are far from achieving a quantitative understanding of these processes sufficient to serve as a reliable foundation for developing parameterizations that will adequately predict aerosol indirect effects and the low cloud response to climate perturbations. This is especially true of the interactions between cloud, aerosol, and precipitation. In addition, these processes take place in an ever-changing synoptic environment that can confound interpretation of observations from a short time period.

The ARM Mobile Facility (AMF) will be deployed on Graciosa Island (the Azores, 28°W 39°N) for approximately 21 months (Apr 2009-Dec 2010) to study processes controlling the radiative properties (thickness, coverage, and microphysics) of marine boundary layer (MBL) clouds over the remote subtropical Northeast Atlantic Ocean (NEA). The NEA is a region of persistent but diverse subtropical marine low cloud. In the summer, the Azores are ideally located to sample the transition from the 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 (the 1992 Atlantic Stratocumulous Transition Experiment [ASTEX]) that sampled clouds in the NEA, and featured one of the first successful deployments of millimeter radars to study MBL clouds. In particular, ASTEX encountered both pristine MBLs advected from the central North Atlantic and aerosol-rich MBLs advected from Western Europe and North Africa. Thus, we anticipate that the AMF will sample an attractive range of MBL cloud and aerosol conditions.

In conjunction with detailed collocated aerosol measurements during the deployment period, the data from the deployment will be used in multiple ways to answer the following key scientific questions:

- Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the NEA? 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 NEA cloud cover and its radiative impacts?
- Can we find observational support for the Twomey effect in clouds over the NEA?
- 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?

- Are observed transitions in cloud mesoscale structure (e.g., from closed cellular to open cellular convection) influenced by the formation of precipitation?

These questions will be addressed with the AMF as a central pillar in a research structure that will include collocated aerosol measurements and multi-scale modeling work. Synthesized long-term data from the AMF will be used to initialize, constrain, and validate numerical models including large-eddy simulation, single-column, and regional and global atmospheric models as an important component of the proposed work.

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1. Scientific Background

Clouds in the subtropical marine boundary layer strongly influence the current regional and global climate system (e.g., Klein and Hartmann 1993). Their extensive nature results in high albedo, while their longwave impact at the top-of-atmosphere (TOA) is small. Therefore, regions with extensive low clouds exert a strong negative effect on TOA net radiation (Figure 1). This is particularly true over the subtropical and midlatitude oceans (Klein and Hartmann 1993) where stratocumulus is typically the dominant cloud type and where the annual mean low cloud coverage exceeds 50%.

Understanding how low clouds respond under future climate forcings is an extremely challenging and important problem. Over the last 15 years it has been repeatedly demonstrated that differences in the low cloud sensitivity to increasing sea surface temperature (Cess et al. 1989, 1996), the seasonal cycle (Zhang et al. 2005), greenhouse gases (Colman 2003; Williams et al. 2003; Wyant et al. 2005; Bony and Dufresne 2005), and aerosol properties (Ghan et al. 2001; Williams et al. 2001; Menon 2004; Lohmann and Feichter 2005) are a major reason why climate model predictions of future climate disagree. **It is therefore imperative that we better understand the processes controlling the formation, maintenance, and dissipation of low clouds so that we can improve their representation in climate models.**

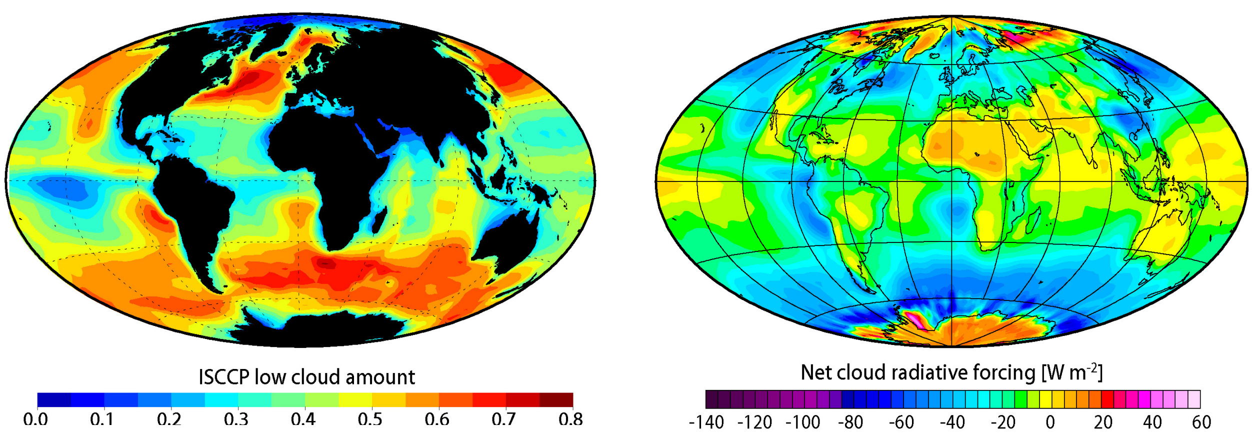

Figure 1. Low cloud effect on net TOA. Left: Coverage of low clouds from the International Satellite Cloud Climatology Project (ISCCP); Right: Net TOA cloud radiative forcing from the Earth Radiation Budget Experiment (ERBE). All values are annual means.

The radiative properties of MBL clouds depend upon their *macrophysical* properties (e.g., thickness and coverage), and their *microphysical* properties. Figure 2 shows the geographic variations in cloud droplet concentration over the North Atlantic. Near continental Europe and North America, the enhancement of reflected shortwave radiation due to the small droplet effective radii (high cloud droplet concentrations) associated with aerosol-rich polluted airmasses is roughly 15% of the mean over the region. Thus aerosol variations may exert a strong control on the cloud radiative forcing. While the synoptic scale variability of *macrophysical* properties of low clouds (e.g., cloud cover, liquid water path) has received considerable attention (e.g., Klein and Hartmann 1993; Klein 1997; Norris et al. 1998; Xu et al. 2005), technological limitations have largely precluded observations of the *microphysical* variability of marine low cloud on these scales. It is becoming apparent that there is considerable day-to-day variability of cloud droplet concentration in the subtropical MBL (e.g., Brenguier et al. 2000; Stevens et al. 2003; Bretherton et al. 2004) that is related to variability in CCN availability (Snider et al. 2003). Further, it is now known that cloud microphysical properties can influence the production of light precipitation (e.g., see Wood 2005), which can serve as a potentially important feedback in the cloudy MBL (Ackerman et al. 2004). **However, no long-term records exist that can be used to link cloud, precipitation, and aerosol microphysical variability in the remote cloud-capped MBL.**

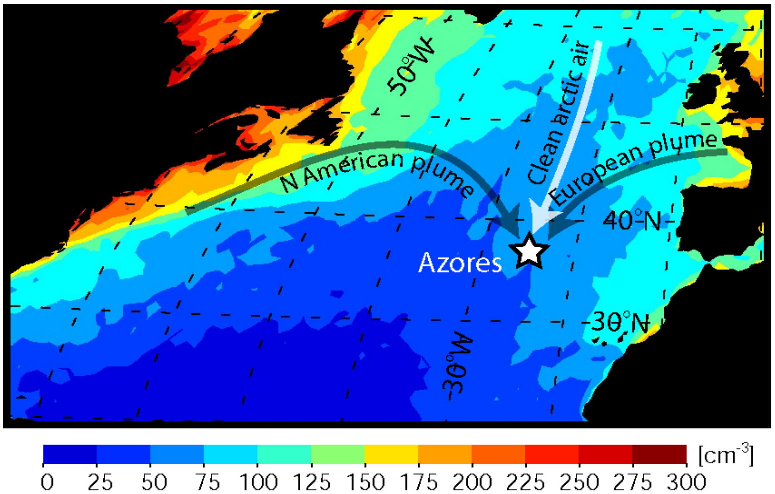

Figure 2. Moderate resolution imaging spectroradiometer (MODIS) annual mean cloud droplet concentration for overcast warm clouds over the North Atlantic. The Azores typically experiences relatively clean conditions with northerly flow, but with periodic episodes of continentally influenced polluted airmasses. The location is therefore ideal for capturing a wide range of aerosol conditions.

Satellite analyses (Matsui et al. 2006; Kaufman et al. 2005; Matheson et al. 2005; Mauger and Norris 2007) suggest that the links between aerosol and cloud microphysical and radiative properties are complex and can vary regionally. Microphysical variations in subtropical low clouds over the NEA and other subtropical low cloud regions are likely to be correlated with variations in large-scale meteorological forcings (e.g., lower tropospheric stability, Mauger and Norris 2007) as well as with aerosol properties suggesting that a long data record is needed to separate the influence of aerosols upon cloud properties from meteorological influences. It is important therefore that we devise strategies to account for the general rule that aerosol properties often will be accompanied by significant meteorological changes due to synoptic variability.

Increased aerosol concentrations may reduce cloud droplet size for fixed liquid water content and therefore increase cloud optical thickness (the *Twomey effect*, or *first indirect effect*). Model estimates of the strength of the Twomey effect are at odds with satellite estimates (e.g., Lohmann and Lesins 2002) indicating problems with our understanding of aerosol-cloud interactions or with the satellite retrievals. Reduced droplet size also may reduce coalescence rates resulting in precipitation suppression and a thickening of the cloud, an effect that models show is a significant feedback enhancing the Twomey effect (Albrecht 1989; Pincus and Baker 1994). However, recent modeling studies (Ackerman et al. 2004; Wood 2007; Bretherton et al. 2007) show that feedbacks involving the influence of precipitation upon turbulence in the MBL, and entrainment of free-tropospheric air into the MBL, make this feedback more complicated than originally thought. These studies have generated testable hypotheses that can be evaluated using long-term measurements of aerosols, clouds, precipitation, and their corresponding meteorological context. **Traditional intensive field studies alone cannot generate the long data record needed to isolate the effects of aerosols upon cloud optical properties and to statistically evaluate the quality of satellite retrievals and models of aerosol-cloud interaction.**

Recent observations (Stevens et al. 2005; Sharon et al. 2005; Comstock et al. 2005, 2007) demonstrate that strong precipitation is associated frequently with changes from closed to open cellular convection in the remote MBL. This transition has a marked influence on cloud coverage (Wood and Hartmann 2006). Modeling work (Rand 1995; DeLobbe and Galle 1998; Stevens et al. 1998; Savic-Jovcic and Stevens 2008) concludes that relatively small changes in precipitation efficiency can lead to abrupt changes in the mesoscale structure that are consistent with observations. Often these transitions form initially as pockets of open cells (POCs) embedded in overcast stratocumulus decks (Stevens et al. 2005), which tend to be associated with low cloud droplet concentrations (Petters et al. 2006, see also Figure 3). Wood et al. (2007) suggest that both microphysical and macrophysical processes favoring increased drizzle may lead to these transitions, making it a challenge to separate the influences of increased cloud thickening due to synoptic forcing from those due to aerosol processes. Satellite data (Wood et al. 2007) indicate that the initial formation of POCs occurs almost exclusively at night, mirroring the diurnal cycle in precipitation (Figure 4). During ASTEX, similar aerosol and cloud macrophysical transitions were seen in the NEA (Albrecht et al. 1995). **An AMF deployment provides a unique opportunity to better characterize the impact of precipitation on transitions between high and low cloudiness regimes.**

The formation of precipitation can lead to a depletion of cloud water (e.g., Stevens et al. 1998) and is a significant sink for cloud condensation nuclei (CCN, Mechem and Kogan 2006; Wood 2006). These potential feedback processes are complicated further because precipitation formation results in latent heating in the cloud layer and evaporation beneath it, which can affect the dynamical structure of the MBL in ways that remain poorly understood (Turton and Nicholls 1987; Stevens et al. 2005; Caldwell et al. 2005; Savic-Jovcic and Stevens 2008; Xue et al. 2007). Processes that affect precipitation formation, such as elevated CCN concentrations, also can affect entrainment (Ackerman et al. 2004) thus leading to important feedbacks that include both key processes. Observations during ASTEX (e.g., Miller and Albrecht 1995) documented mesoscale structures composed of precipitating cumulus detraining into 'anvils' of stratocumulus, strongly precipitating stratocumuli (Bretherton et al. 1995), and sharp transitions from precipitating to non-precipitating boundary layers (Albrecht et al. 1995). However, ASTEX was not long enough to quantitatively assess the climatological significance of these observations.

Active remote sensing using cloud radars and lidars is shedding new light upon physical processes that drive MBL clouds, particularly in the production of precipitation, which frequently occurs in the form of drizzle (e.g., Frisch et al. 1995; Vali et al. 1998; Stevens et al. 2003; O'Connor et al. 2005; Bretherton et al. 2004; Comstock et al. 2004, 2007; VanZanten et al. 2005). In large part because of these studies, it is becoming clear that precipitation in MBL clouds is a more common phenomenon, and more energetically important (Caldwell et al. 2005) than was previously thought. When these findings are fused with the fact that precipitation occurs frequently over much of the subtropical oceans (Petty 1995), and that model results indicate that modest amounts of precipitation can significantly influence low cloud extent and thickness, it becomes clear that there is a greater need to better understand and quantify the processes controlling precipitation and its effects in MBL clouds over the remote oceans.

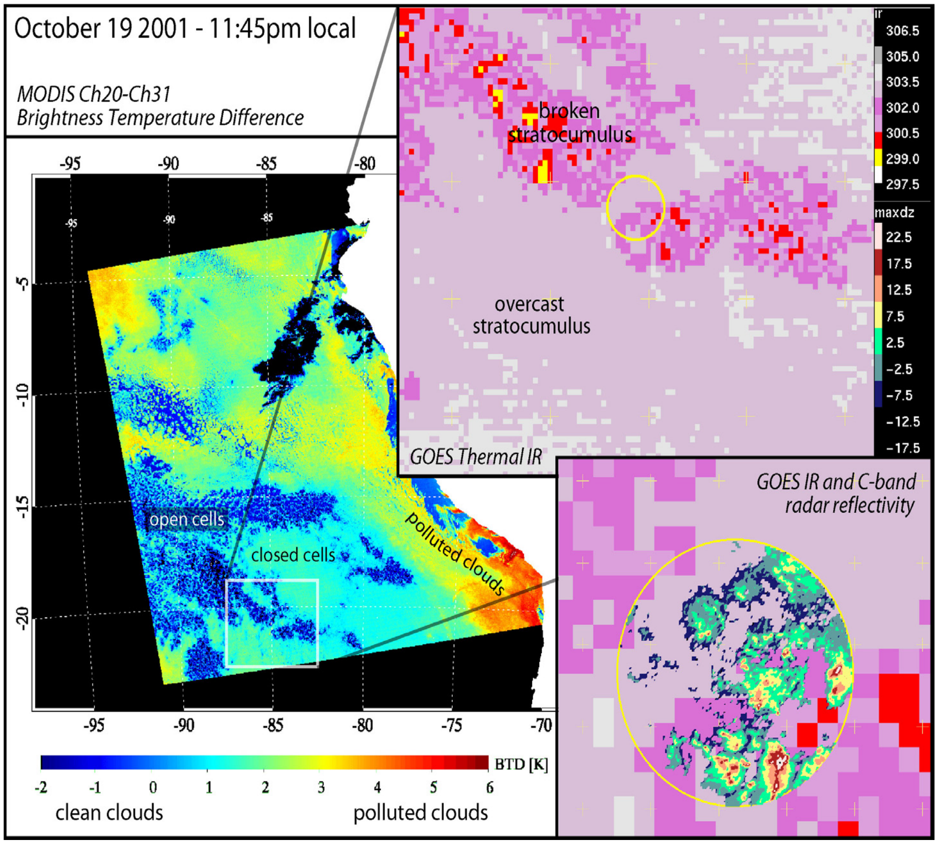

Figure 3. MODIS satellite image from October 19, 2001 (right), during the EPIC field campaign (main) showing night-time Ch20-Ch31 brightness temperature difference. Blues and reds indicate clouds with low and high cloud droplet concentration respectively. Open and closed cellular convection is also delineated. Upper inset shows GOES thermal infrared, which can also be used to determine broken stratocumulus (open cells). Lower inset shows composite of shipborne C-band radar and GOES thermal infrared. In this case, heavier drizzle is associated with the open cellular regions.

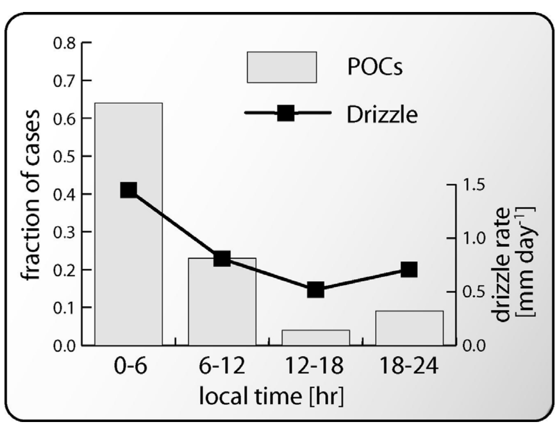

Figure 4. The diurnal cycle of the initial formation of pockets of open cells in otherwise overcast stratocumulus during Sep-Oct 2001. The data are from GOES over the SE Pacific subtropics (Wood et al. 2007). Also shown is the diurnal cycle of cloud base precipitation rate from EPIC 2001.

Cloud microphysical properties may be important modulators of drizzle production (Gerber 1996; Pawlowska and Brenguier 2003; Bretherton et al. 2004; Comstock et al. 2004; VanZanten et al. 2005; Wood 2005), which introduces a role for anthropogenic aerosols to modulate the dynamical and structural coverage of low clouds (Kaufman et al. 2005). A 14-day time series from the East Pacific Investigation of Climate (EPIC) cruise to the SE Pacific stratocumulus region (Figure 5, from Bretherton et al. 2004) shows surface and cloud base precipitation rate estimated using C-band radar, cloud liquid water path (LWP) estimated using a microwave radiometer, and cloud droplet concentration estimated using a surface remote sensing retrieval method (Dong and Mace 2003). The measurements, which will be readily available from an AMF deployment, show that drizzle is common in the subtropical MBL and that most of it evaporates before reaching the surface. In addition, the precipitation at cloud base is modulated strongly by liquid water path, especially on a diurnal timescale, with most precipitation falling during the night. However, precipitation appears to be suppressed during periods of high cloud droplet concentration. **Other than limited duration data from a few cruises, we have almost no record detailing the frequency and magnitude of precipitation in the remote cloud-capped MBL and its variability on diurnal-seasonal timescales**. A longer record would provide invaluable data to better characterize the interactions between cloud microphysical and macrophysical properties and drizzle.

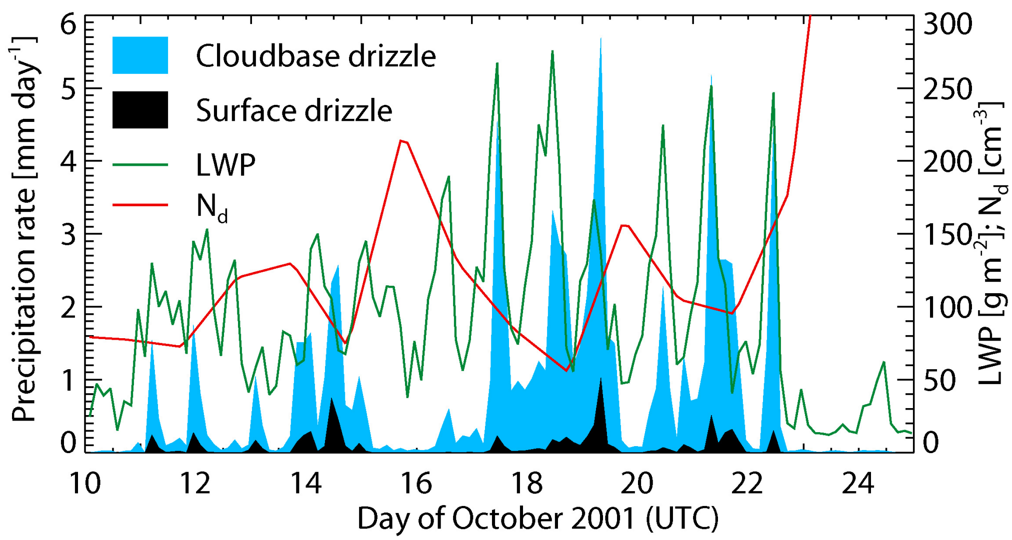

Figure 5. Time series from the EPIC 2001 field campaign showing cloud base and surface precipitation, together with estimates of cloud liquid water path (LWP) and droplet concentration N_d (from Bretherton et al. 2004).

We need a quantitative understanding of processes by which cloud and precipitation processes are modulated by aerosols and by large-scale forcings in the MBL. This understanding will serve as a foundation for developing parameterizations that will predict adequately the low cloud response to climate perturbations. These processes interact with one another and take place in an ever-changing synoptic environment that can confound interpretation of observations from a short time period. Perhaps even more importantly, most of our state-of-the-art observational studies of boundary layer clouds have taken place in regions that are either over land, or close to land, where the cloud morphology and mesoscale organization is substantially different from that over the remote ocean (Wood and Hartmann 2006). We have very few intensive observations of low clouds and the MBL over the remote oceans, and our climatology of low clouds in these regions is limited to volunteer and meteorological shipborne observations (Warren et al. 1988; Petty 1995), and satellite data sets (e.g., Rossow and Schiffer 1991; or the NASA Earth Observing System program). While extremely valuable for advancing our knowledge of the climatology of clouds over the oceans, the information that satellite data sets provide over the remote oceans needs validation.

The development of active cloud remote sensing technology in the last twenty years is providing a unique opportunity to improve our understanding of cloud physical processes. **The ability of sensitive radars to detect clouds gives us an ability to be able to make detailed, quantitative, high resolution measurements of clouds that extend for long periods of time.** These cloud radar measurements have been central to the success of the Atmospheric Radiation Measurement (ARM) Program (Ackerman and Stokes 2003). While these measurements will not replace detailed in situ studies with aircraft, they constitute a new and useful observing concept that provides quantitative measurements necessary to evaluate both high- and low-resolution models of the atmosphere.

2. Science Questions

In this section we present four sets of key scientific questions and describe how we plan to address each with AMF deployment and other synergistic activities.

- Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the NEA? 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 NEA cloud cover and its radiative impacts?
- Can we find observational support for the Twomey effect in clouds over the NEA?
- 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?
- Are observed transitions in cloud mesoscale structure (e.g., from closed cellular to open cellular convection) influenced by the formation of precipitation?

2.1 Which synoptic-scale features dominate the variability in subtropical low clouds on diurnal to seasonal timescales over the NEA? 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 NEA cloud cover and its radiative impacts?

The long duration data set from the AMF deployment will make it possible to address issues related to the synoptic variability of cloud and aerosol macrophysical and microphysical properties. Graciosa Island is influenced by both pristine and continentally influenced airmasses, and we will use the data to examine contrasts in both macrophysical and microphysical properties as a function of the degree of anthropogenic pollution. Graciosa is situated in a region of strong aerosol gradients that will result in a strong sensitivity of microphysics to small synoptic scale meteorological changes. This makes it an ideal site to examine the synoptic variability of aerosols and clouds. We will use compositing and trajectory methods using reanalysis data to characterize synoptic variability by incorporating reanalysis data sets to identify and control for variability of influential large-scale meteorological variables such as lower tropospheric stability (Klein and Hartmann 1993), inversion strength (Wood and Bretherton 2006), mid-tropospheric subsidence rate (Bony et al. 2004), and free-tropospheric moisture (Ackerman et al. 2004). Cloud microphysical measurements will be made using the surface-based retrievals of Dong and Mace (2003), which were developed using previous ARM data. These will be compared with satellite effective radius and droplet concentration estimates from MODIS.

Specifically, we will attempt to determine whether aerosol and cloud microphysical variability is a strong contributor to the synoptic variability in cloud shortwave radiative properties. In addition, we will ask whether shortwave radiation is modulated most strongly by cloud thickness, cloud coverage, cloud particle size, or cloud internal inhomogeneity. These are challenging problems and particularly important for cloud parameterization. We will use satellite data sets such as geostationary operational environmental satellite (GOES), MODIS, and Clouds and Earth's Radiant Energy System (CERES), in conjunction with the AMF to address these questions. Airmass histories will be determined by a combination of trajectory analysis and the PICO-NARE free-tropospheric chemical measurements, which include anthropogenic tracers such as carbon monoxide and ozone.

Regional model simulations, such as those carried out by René Garreaud at the Universidad de Chile, will be used to examine the synoptic variability. We will also compare observed relationships between cloud macrostructure and the synoptic conditions directly with general circulation models to determine to what extent biases in the GCM representation of clouds are related to those in meteorological variables such as humidity and boundary layer depth.

2.2 Can we find observational support for the Twomey effect in clouds over the NEA?

To address this question, we will measure aerosol and cloud properties using a wide array of ground-based remote sensors such as those associated with the AMF (Feingold et al. 2003). This approach allows one to observe columns of the atmosphere with range-resolved measurements of below-cloud aerosol and in-cloud microphysics. The study will use AMF and other data to quantitatively measure surface aerosol physical and cloud-nucleating properties (Surface Aerosol Observing System), sub-cloud aerosol extinction (MPL and HRDL), cloud liquid water path (MWR), cloud optical depth (NFOV and MFRSR), radar reflectivity (94-GHz radar), cloud droplet effective radius (MWR, MFRSR, e.g., Dong and Mace 2003), and boundary layer dynamics (HRDL). These measurements will be used to investigate the relationship between cloud condensation nucleus concentrations and cloud properties such as cloud droplet effective radius, cloud optical depth, and cloud droplet concentration. The fact that so many parameters can be measured simultaneously, and over an extended period of time, will allow us to categorize the data into various subsets and determine the most important parameters in a statistically meaningful way. This perspective will produce valuable data for evaluation of aerosol effects on clouds that will be complementary, and of direct benefit to the satellite remote-sensing community. The HRDL and MPL vertical profiles of aerosol optical properties below clouds will be essential to understanding how representative the surface aerosol measurements are of conditions at cloud base.

The Twomey effect will be assessed by comparing the relationships between the surface cloud condensation nucleus concentration and the cloud optical thickness at fixed values of the liquid water path as in Feingold et al. (2003). A key goal will be to assess why a much weaker relationship between aerosol and cloud microphysical properties is indicated in the satellite measurements than is expected from simple theory and represented in climate models (Breon et al. 2002; Lohmann and Lesins 2002).

The aerosol-cloud closure studies will be strengthened and evaluated using in situ data from the FAAM BAe-146 aircraft during the planned intensive operational period (IOP) during summer 2009. The BAe-146 carries a full suite of cloud microphysical probes and will include a suite of aerosol physicochemical measurements.

2.3 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?

Precipitation estimates from the AMF (95-GHz radar) will be made using the methodology of Frisch et al. (1995). In addition, we will explore the combined radar/lidar measurements of O'Connor et al. (2005) that combine the 6th and 2nd moments of the drizzle drop population below clouds to extract additional information on the evaporating drizzle drop size distribution. The precipitation estimates will be used to examine how important precipitation processes are as an energetic forcing on the MBL. The data will be used to answer the following questions regarding its variability: Is MBL precipitation important only during certain seasons, or is it important throughout the year? Is precipitation modulated on a synoptic timescale by the cloud macrophysical and microphysical variability as discussed in science question 2.1 above? What is the diurnal cycle of precipitation, and how is it related to the diurnal cycles of the radiative forcing, cloud liquid water path, and aerosol? Can we generalize relationships derived from recent field campaign data (ACE-2, DYCOMS, EPIC, and RICO) that relate precipitation strength to the depth of the cloud layer and the large scale meteorological structure? Does precipitation constitute a significant sink for aerosol on diurnal to synoptic timescales?

Using the aerosol and cloud microphysical measurements that will be made to assess science question 2.1 above, we will examine relationships between precipitation, aerosols and cloud microphysical and macrophysical properties as discussed in the scientific background section (Section 1).

Process modeling work using large eddy simulation with both bulk and bin microphysics will be used to interpret the observed relationships. The directly measured and derived parameters from the AMF data set will provide accurate boundary conditions with which to initialize these models.

2.4 Are observed transitions in cloud mesoscale structure (e.g., from closed cellular to open cellular convection) influenced by the formation of precipitation?

Closed cellular convection is the prevalent structural type during the summer months at Graciosa Island. Trade cumulus conditions are also common during the summer, and these clouds often organize themselves into mesoscale open cellular patterns. Repeated inspection of satellite imagery indicates that it is common, in the region near Graciosa Island to find the early stages of the transition from closed to open cells, which quite commonly typifies the transition from stratocumulus to trade cumulus. We will attempt to address with the AMF data whether these transitions tend to be associated with precipitation as suggested in Stevens et al. (2005) and whether accumulation mode aerosol depletion (Petters et al. 2006) is a cause or an effect of the transitions. The long AMF record, which will capture more transition events than existing studies have been able to, will be invaluable in this regard. The scanning X-band radar data will be used to characterize the cellular nature of the precipitation field, and to understand its vertical variability. Satellite data from MODIS and GOES will be used to determine the shallow convection type using the method of Wood and Hartmann (2006), and this characterization will be used as a basis for compositing AMF and scanning radar data.

Hourly GOES and daily MODIS satellite data, along with the scanning X-band radar, will be used to place the AMF observations into a broader context and to clearly identify the stratocumulus cloud structural types (open cell, closed cell). Modeling work will also be important in attempting to better understand the physics of precipitating MBL cloud systems and the rapid transitions from closed to open cells.

3. Site and Location

3.1 The ARM Mobile Facility

The suite of state-of-the-art active and passive remote sensors associated with the ARM Mobile Facility (AMF) will be used to derive cloud and precipitation macrophysical and microphysical properties together with marine boundary layer and lower tropospheric structure and physical, optical, and cloud nucleating properties of aerosols at the surface. Table 1 and Figure 7 in Section 6.2 detail the key ARM Climate Research Facility (ACRF) instrumental requirements and the physical parameters that will be derived using them. Table 2 details the additional measurements that will be provided to complement the AMF deployment.

An important component of the deployment will be the continuous operation of a sensitive scanning W-band radar that will be colocated with the AMF deployment on Graciosa for a substantial fraction of the total AMF deployment period. The radar to be used is currently being built and tested for eventual use by the ARM community.

The scanning capability will be to define the horizontal variability of clouds and precipitation upwind from the island that can be used to put the temporal variability from the high-resolution, upward-facing W-band observations into perspective. Sampling out to 10 km or less upstream will be useful. A simple routine scanning sequence of PPI and RHI scans focusing on areas upstream from the island during either intensive observational periods or during the entire observation period will be sufficient.

The scanning W-band will provide important mesoscale context to the AMF vertically pointing instrumentation. Key additional information that the scanning capability will provide includes improved quantification of the precipitation field and its associated kinematics, which has proven highly useful during the EPIC 2001 field campaign in the SE Pacific (Bretherton et al. 2004). A second important use of the W-band radar will be to make assessments of the island effects

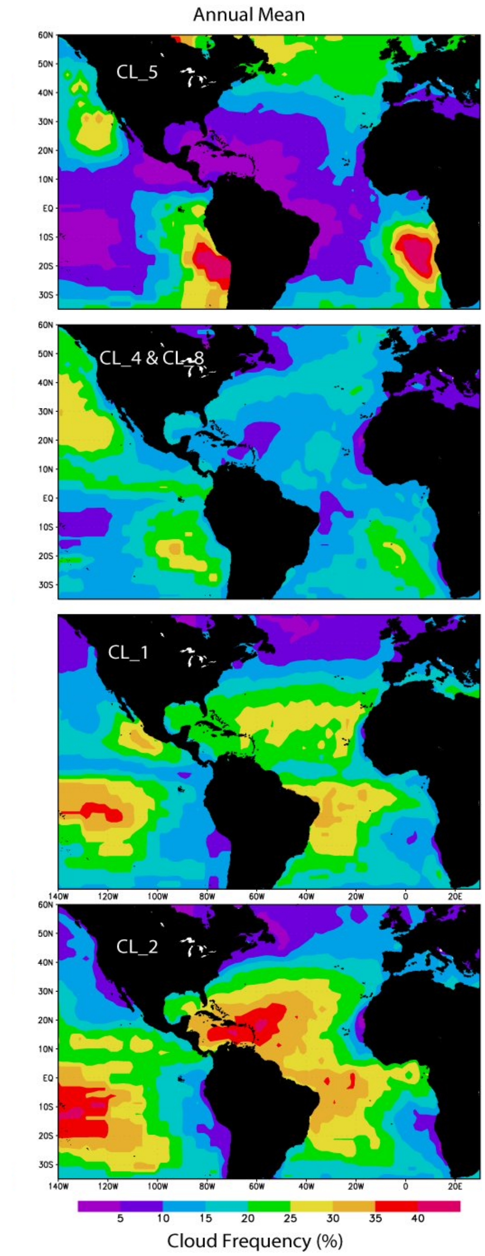

Figure 6. Annual mean frequency of occurrence of (from top) stratocumulus, stratocumulus with cumulus beneath or formed from spreading cumulus, small cumulus, and large cumulus.

on the precipitation by building a climatology of the precipitation as a function of height and distance upwind of Graciosa. This radar will be operated in both PPI and RHI scans to examine the horizontal and vertical structure and kinematics of the precipitation field. It is historically noteworthy that ASTEX featured one of the first deployments of a scanning short-wavelength (K_a -band) Doppler radar to study boundary-layer clouds (Kropfli and Kelly 1995) and demonstrated its potential to scan across the mesoscale features of the NEA cloud field.

3.2 Graciosa Island in the Azores

To make the observations necessary to address the key science questions, the AMF will be deployed on Graciosa Island in the Azores Islands in the NE Atlantic subtropical Ocean. Graciosa (28°W 39°N) is one of the few subtropical Eastern Ocean sites that is sufficiently remote to be clear of direct continental influence (1300 km from Europe), and is small (4×8 km) and low enough (<400 m) that the clouds are not expected to be strongly influenced by its presence (typical MBL depths are 1000-2000 m).

Surface meteorological and remote sensing measurements were made successfully from a similar island (Santa Maria) in the Azores during the Atlantic Stratocumulus Transition Experiment (ASTEX) in 1992 (Albrecht et al. 1995; Miller and Albrecht 1995). Graciosa has a good infrastructure and a dock for shipping the AMF equipment. Low cloud cover at Graciosa is 50% with a relatively weak seasonal cycle. Winds are predominantly subtropical trades from the north and east. Stratus, stratocumulus, and cumulus are present throughout the year at Graciosa (Figure 6). The predominant cloud type is stratocumulus, which is present 36% of the time (Warren et al. 1988). Trade cumulus occurs 30% of the time. Other cloud types are relatively rare, but occasionally include bad weather stratus and fog during the winter, and cirrus associated with the tails of midlatitude disturbances, also generally in the winter months. Graciosa is ideally suited to study the transitions from overcast stratus/stratocumulus to broken trade cumulus. Transitions from closed to open cellular structures are observed in this region. Also of particular interest from a microphysical perspective is the strong airmass variability arriving at Graciosa Island, which includes pristine arctic airmasses that have been transported through midlatitude oceanic regions to the north and cleaned by precipitation; airmasses that have been circulating around the Azores high pressure system over the ocean for several days; markedly polluted continental airmasses from both North America and Europe. Figure 2 gives a broad sense of the airmass origins, although we note that this figure highly simplifies what can be complex patterns of airmass transport in the North Atlantic region.

The Intercontinental Transport of Ozone and Precursors (ITOP) experiment, the European contribution to the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) 2004 experiment, revealed considerable variability in aerosol composition and origin in the Azores region. Extensive pollution plumes containing sulfates and organics were sampled at low level whose source was the north eastern United States (see also Figure 2), and biomass burning aerosol from wildfires in Canada and Alaska are common during the summer months. This makes the Azores a particularly interesting site for studying the effects of aged aerosols on marine boundary layer cloud.

4. Expected Scientific Results

This study will provide new long-term data on low clouds in a meteorological regime that is poorly sampled but extremely important climatologically. The data set generated will provide unprecedented data on the interaction between aerosols, clouds, precipitation, and climate, sampling a statistically representative set of open-ocean boundary-layer cloud regimes, and will be extremely useful for the design and evaluation of parameterizations for climate models. The international collaboration generated through the proposed deployment will have long-term benefits for atmospheric science research. All data sets from the deployment will be made available for ARM researchers to use, and ultimately all researchers. We will work in conjunction with ARM to create user-friendly and accessible data sets for use by the scientific community.

Other beneficiaries of the data sets will include scientists working on satellite-based retrievals of cloud and other atmospheric properties. The NASA Aqua and Terra satellite cloud and aerosols products remain poorly validated over the remote oceans, and retrievals from marine stratocumulus clouds, especially broken clouds, remain uncertain. The data set also will provide a good opportunity to evaluate low cloud retrievals from CloudSat and MODIS, and MBL depth estimates from GPS/COSMIC.

5. Synergistic Activities

In addition to bringing considerable expertise in the observation and theoretical understanding of MBL cloud systems, the coinvestigators are involved in synergistic field experiments, satellite analysis and modeling programs. The data from the synergistic activities will be made available to members of the ARM science team through bilateral arrangements with the various agencies leading the synergistic components, the details of which are described below.

5.1 Surface Based and Aircraft Measurements of Chemistry, Aerosols and Clouds (Hugh Coe, University of Manchester)

The Atmospheric Physics Group at the University of Manchester has many years' experience in the field of cloud and aerosol field measurements. The group participated in the second Aerosol Characterization Experiment (ACE-2) and ACE-ASIA, has made long term aerosol and chemistry measurements at rural sites in the north of England, and participated in the 2004 Intercontinental Transport of Ozone and Precursors (ITOP) experiment, the European contribution to the ICARTT 2004 experiment, which included aircraft measurements based out of the Azores. Funding will be sought from the UK Natural Environment Research Council (NERC) to make a suite of surface chemistry and aerosol measurements to enhance the standard AMF suite during an IOP, which would take place during summer 2009. The IOP would involve both ground-based and aircraft measurements using the Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 jet, which is jointly operated by the UK universities and The Met Office. NERC has recently initiated a thematic program with dedicated resources to target specific problems in the area of aerosol-cloud-climate interactions. This IOP would complement the AMF observing system and would include important in situ cloud and aerosol measurements designed to (a) provide validation of ground-based remote sensing retrievals of cloud properties; (b) allow the testing of hypotheses related to cloud-aerosol-precipitation interaction in the MBL.

5.2 Pico International Chemical Observatory, a Component of the North Atlantic Regional Experiment (PICO-NARE)

Ongoing measurements of atmospheric chemistry in the lower free troposphere (FT) over the Azores are being maintained by Richard Honrath of Michigan Technological University (http://www.cee.mtu.edu/~reh/azores/pico) and Paulo Fialho at the University of the Azores on Terceira Island. The objective of this project to make direct measurements over the North Atlantic of pollutants transported from North America and Europe, as well as characterization of pristine free-tropospheric airmasses. Since most intercontinental transport occurs in the free troposphere, these measurements must be made above the marine boundary layer (>2 km). Measurements have been made since 2001 from the summit of Pico and are expected to be continued through 2009. These measurements are used to determine the frequency and magnitude of transport events that disperse ozone and carbon monoxide. Additional measurements have been made by researchers from Portugal and the United States, to the extent possible within the station's space and power constraints. The site is operated by Michigan Technological University and funded by NOAA. For the AMF deployment during 2009, we hope to leverage these measurements, including the regular trajectory analyses that are being carried out in collaboration with ECMWF and FLEXPART (Owen et al. 2006).

5.3 The Center of Climate, Meteorology and Climate Change (CMMG) at the University of the Azores

The Center of Climate, Meteorology, and Climate Change (CMMG) at the University of the Azores runs a network of oceanic buoys around the Azores Islands. These data will be made available to CAP-MBL researchers. One buoy is located just offshore of Graciosa, and will provide sea-surface temperature measurements during the AMF deployment. The CMMG also have a meteorological research station situated at the top of Pico mountain (collocated with the Pico International Chemical Observatory, see above), which is run in conjunction with NOAA. The Portugese Institute of Meteorology will deploy a baseline surface radiation network (BSRN) site at Terceira Island in collaboration with the CMMG, which will be available to AMF researchers.

5.4 Azores AERONET Site

An Aerosol Robotic Network (AERONET) site (Holben et al. 2001) is operated continually on the Island of Pico in the Azores (75 km to the SSW of Graciosa) using sunphotometry to provide information about the aerosol loading and size distribution through the tropospheric column. This, together with the PICO-NARE observations, will be used to provide important chemistry/aerosol context for the AMF deployment. In conjunction with the AMF micropulse lidar, the AERONET data will provide important constraints on the characterization of the vertical extent of pollution plumes over the Azores region. This site discontinued observations in 2006, but discussions are underway with the U.S. AERONET program to reinstate them during 2009.

5.5 Satellite and Reanalysis Data Sets

Several of the co-investigators have experience in the analysis of satellite measurements of MBL clouds. Incorporation of satellite data to complement the AMF deployment is essential for placing the single-site measurements in a broader context. The chief satellite data sets we will use are from GOES, Terra and Aqua (which include MODIS, AMSR, CERES, and AIRS), Cloudsat and CALIPSO, TRMM, and COSMIC. The AMF data will form an unrivaled test bed for validation of microphysical retrievals cloud (effective radius, drizzle, liquid water path) and MBL (boundary layer depth) properties.

Satellite data also will provide important mesoscale context for the remote sensing measurements made with the AMF. Cloud morphology characterizations, such as those made by Wood and Hartmann (2006), will be applied to MODIS and GOES data to objectively determine mesoscale convection type. MODIS and GOES IR data, along with Quikscat winds and microwave SSTs (AMSR) will be used to investigate the development of advection products (cloud top height, temperature and water vapor) from satellites.

CloudSat will be used to characterize the horizontal extent of precipitating features. An integrated satellite data set will be produced for the duration of the AMF deployment.

Reanalysis data sets including those from NCEP/NCAR, ECMWF, and NASA will be used to produce forcing data sets for model initialization. In addition, we will use reanalysis to produce back trajectories to examine the origins of airmasses arriving at Graciosa.

5.6 Modeling Activities

Co-PIs Bretherton, Garreaud, Feingold and Stevens all have extensive numerical modeling experience. Bretherton was the lead PI on the United States CLIVAR Low-latitude Cloud Feedbacks Climate Process Team (CPT). This is a multi-institution NSF/NOAA-sponsored project (Oct 2003-Sep 2006) to try to better understand the differences in cloud feedbacks on climate sensitivity in three leading US climate models (NCAR, GFDL, and NASA-GMAO), and to use recent findings from observations and process models to reduce uncertainties in climate sensitivity by improving the representation of cloud microphysics, turbulence and moist convection, and radiative transfer in cloudy atmospheres in these models. He is also on the Scientific Steering Committee of the NCAR Community Climate System Model. Bretherton and Stevens are active participants of the GEWEX Cloud System Study (GCSS) Boundary Layer Cloud Working Group (BLCWG), which aims to improve physical parameterizations of clouds, other boundary layer processes, and their interactions. The group conducts careful intercomparisons between observational or laboratory case studies, one-dimensional GCM single-column-model (SCM) results, and 3D large-eddy-simulation models of cloud-topped boundary layers. It is our aim to produce at least one case study for the BLCWG from the AMF deployment. This will probably differ from the conventional case studies in being a comparison over a longer intensive observational period of a few weeks or so, to utilize the long-term measurements. Three types of model framework and the questions we hope to address by comparing them to the AMF data are:

Large eddy simulation: What level of complexity in model resolution/domain size, and parameterizations of cloud microphysics and of cloud-aerosol interaction is required to adequately simulate precipitation processes and their feedbacks on cloud radiative properties for the suite of marine cloud-topped boundary layers seen over the NEA? Averaged over the statistical distribution of clouds sampled at the AMF, does the LES suggest that CCN variability is playing an important role? Our strategy is to develop long column advective and surface forcing data sets (e.g., Zhang et al. 2001) and run the System for Atmospheric Modeling LES (Khairoutdinov and Randall 2003) for long time periods to test its skill in simulating the AMF observed cloud statistics at Graciosa Island and its sensitivities to relevant model microphysical parameters, as is being done at the Southern Great Plains (SGP) site. This LES is particularly appropriate because it is essentially identical to that used in the ARM-supported superparameterization approach to climate modeling of Randall and colleagues (e.g., Khairoutdinov et al. 2005; Wyant et al. 2006), and is already extensively used by Bretherton (e.g., Bretherton et al. 2005, 2006).

The LES will also a critical tool in the use of AMF observations to separate the respective roles of aerosols and large-scale meteorology in determining the cloud optical properties over the NEA.
The model output from the long-term LES simulations will be analyzed by compositing results as a function of their aerosol properties and their lower tropospheric stability and/or subsidence rate. We will then perform sensitivity studies to changes in aerosols and meteorology around this ever-changing base state, to examine aerosol sensitivity at different locations within the observed aerosol-cloud-

precipitation “phase space.” These results will enable us to determine which aspects of the subtropical MBL are most sensitive to changes in CCN concentrations.

Large domain LES such as those by Savic-Jovcic and Stevens (2007) will be used to examine whether large domains are necessary to capture the observed statistics of cloud optical properties over the NEA.

Single-column models: The same strategic approach for the LES will be used with at least one single-column version of a climate model, the NCAR single-column CAM3, of which Bretherton’s group already makes extensive use. In the framework of the ARM Cloud Parameterization and Modeling and GCSS Boundary Layer Cloud Working Group intercomparisons, other interested LES and single-column modeling groups will also be invited to examine particularly interesting sampling periods.

Mesoscale and global models: Can we skillfully forecast the synoptic variability of low cloud and cloud-radiative forcing over the NEA and especially at the AMF at timescales of 1-7 days, using current climate models run in forecast mode as in the CAPT project, or using nested regional models such as the Weather Research and Forecasting (WRF) model forced at the model domain boundaries by global reanalyses? Is aerosol variability important to the cloud forecast, and to the overall space-time distribution of cloud radiative forcing, as suggested by Kaufman et al. (2005)? Bretherton et al. (1995) showed that the ECMWF operational forecast model at the time of ASTEX could not simulate the synoptic cloud variability observed during that experiment, but great strides in parameterizing boundary layer cloud have been since made. Models such as the NCAR CAM climate model have begun to incorporate interactive aerosol transport as an option, and are developing their parameterizations to allow the predicted aerosol to interact with cloud microphysics. This will allow us to address the second question above.

Central to the regional modeling effort is the use of the Weather and Research Forecast (WRF) model to simulate the circulation over the northeast Atlantic during the whole period of the field campaign. We plan to initialize the model a few weeks before the field campaign and then perform a continuous integration of 9 months forced by reanalysis data at the lateral boundaries. The horizontal resolution over the larger domain will be set at 27 km, and we will use at least one inner domain (6 km horizontal resolution) centered over Graciosa Island. Selected case studies will be simulated with the MesoNH model at high resolution (better than 1 km) using a variety of different parameterization options to investigate model sensitivity to physics.

The EC-Earth model will be run by collaborators in Portugal, with a focus on using long-duration simulations to examine synoptic, seasonal, and interannual variability.

Diagnostic studies that will be based on regional and GCM simulations include:

1. Comparison between observed and simulated vertical profiles (T, q, winds) and cloud-derived properties (e.g.,, cloud fraction, cloud base, LWP) to assess the ability of models to simulate variability of circulation and cloudiness in time-scales from diurnal to seasonal.
2. Testing different PBL parameterizations for selected periods of time against the AMF observational data.
3. Analysis of the MBL response (e.g.,, MBL depth) to synoptic forcing. If the model is capable to simulate the synoptic variability of the cloud deck, this will be a strong indication of a more prominent role of the circulation (e.g.,, vertical velocity) rather than microphysical effects in determining the cloud properties.

4. Analysis of the observed cloud response (as per macrophysical properties) to the origin of air masses arriving to Graciosa. To conduct this analysis, we will determine backward trajectories (3-5 days) using WRF results taking advantage of the high vertical and horizontal resolution of the model.
5. Analysis of the island effect. While we expect that such effects are small (given the modest topography of the island), they can't be ruled out. We will perform several no-topography, no-island experiments (intergrations of a few weeks), that will be contrasted with the control runs to asses the island-effect under different synoptic scenarios. The results of this analysis will shed light on the interpretation of the observations as well.

6. Resources and Project Management

6.1 Resources

The ARM Mobile Facility will be deployed from April 2009-December 2010. The suite of state-of-the-art active and passive remote sensors associated with the AMF will be used to derive cloud macrophysical and microphysical properties together with marine boundary layer and lower tropospheric structure. The Surface Aerosol Observing System is also a critical component. Table 1 and Figure 7 detail the key ACRF instrumental requirements and the physical parameters that will be derived using them.

In addition, a specific requirement that would greatly benefit the work is e*nhanced BBSS sampling for specific periods within the deployment.* During EPIC 2001, soundings were taken every three hours which permitted an unprecedented evaluation of the strong diurnal cycle in the remote marine boundary layer. For several periods we would like to supplement the twice or four times daily soundings that will form the routine ACRF measurements, with additional BBSS sounding data.

We are working with collaborators at the University of the Azores regarding the AMF deployment. Bruce Albrecht at the University of Miami has experience working on Santa Maria (an island in the Azores with similar infrastructure to Graciosa) during the 1992 ASTEX field campaign, and has sited radars and ground-based instrumentation there before. Resources on Graciosa are expected to be sufficient with seaport access, and no particularly difficult negotiations need to be made as the Azores is administered by Portugal, an European Union nation. The site has some power capability but this is being provided mainly by generators. We will work with the AMF deployment team throughout to ensure the success of the deployment.

6.2 Project Management

The project will be managed by PI Wood at the University of Washington, who will work with the Co-PIs and ACRF to develop a set of key observational data sets that will achieve the goals set out above. Numerical modeling work will be carried out at the University of Washington (Bretherton), NOAA ESRL (Feingold), UCLA (Stevens), the Universidad de Chile (Garreaud) and at the University of Lisbon (Soares) and a single set of observationally-derived model initialization products (forcing data sets) will be developed by the group in coordination with the PI.

Co-PI Coe, in collaboration with the other Co-PIs and collaborators in the UK, will continue planning and development of the field deployment of the BAe-146 during summer 2009. Funding to carry out the analysis and modeling work involved in the project will be sought from both the DOE Atmospheric Radiation Measurement (ARM) Program, and from other agencies.

Table 1. Key instrumentation requirments for the AMF deployment.

Instrument	Important Derived Parameters
94-GHz Profiling Radar	(i) Cloud and precipitation vertical structure (ii) Cloud top height (iii) Drizzle drop size distribution using both Doppler spectral measurements (Frisch et al. 1995) and with MPL below cloud base (O'Connor et al. 2005)
Micropulse Lidar (MPL)	(i) Cloud occurrence, (ii) Precipitation profiling below cloud base (with radar) (iii) Aerosol properties in MBL and above MBL (clear skies)
Microwave Radiometer (MWR)	(i) Cloud liquid water path (ii) Column water vapor path
MultiFilter Rotating Shadowband Radiometer (MFRSR) and Narrow Field-of-View Radiometer (NFOV)	(i) Cloud visible optical thickness. Will be used to infer cloud microphysical properties (droplet concentration, effective radius) in combination with MWR (ii) Aerosol optical properties in clear skies
Marine Atmospheric Emitted Radiance Interferometer (MAERI).	Cloud liquid water path estimates for thin clouds (combined with MWR, following Turner 2007)
Total Sky Imager (TSI)	Cloud coverage and type
Ceilometer (VCEIL)	(i) Cloud base height (ii) Cloud cover
Balloon-borne Sounding System (BBSS)	(i) Atmospheric profile structure (ii) MBL depth (iii) Inversion strength
Eddy Correlation Systems (ECOR)	Surface turbulent fluxes of latent and sensible heat
Surface Meteorological Instruments	Surface temperature, humidity, pressure, winds
Sky Radiometers	Downwelling shortwave and longwave radiative fluxes used to constrain the surface energy budget
Surface Aerosol Observing System	Aerosol physical properties (total concentration, scattering and absorption), CCN characteristics

Table 2. Key additional instrumentation and observational data sets.

Instrument [Provider]	Important derived parameters
Scanning W-band radar [being developed for ARM]	Light precipitation and cloud horizontal and vertical structure
Ground-based chemistry [Hugh Coe, University of Manchester, UK]	(i) Aerosol size resolved chemistry (inorganic, organic) (ii) Aerosol hygroscopic growth
BAe-146 aircraft deployment [coordinator Hugh Coe, University of Manchester]	(i) Cloud and drizzle microphysical properties (ii) Turbulence and meteorology measurements (iii) Aerosol and gas phase chemistry suite, CCN, aerosol mass spectrometry

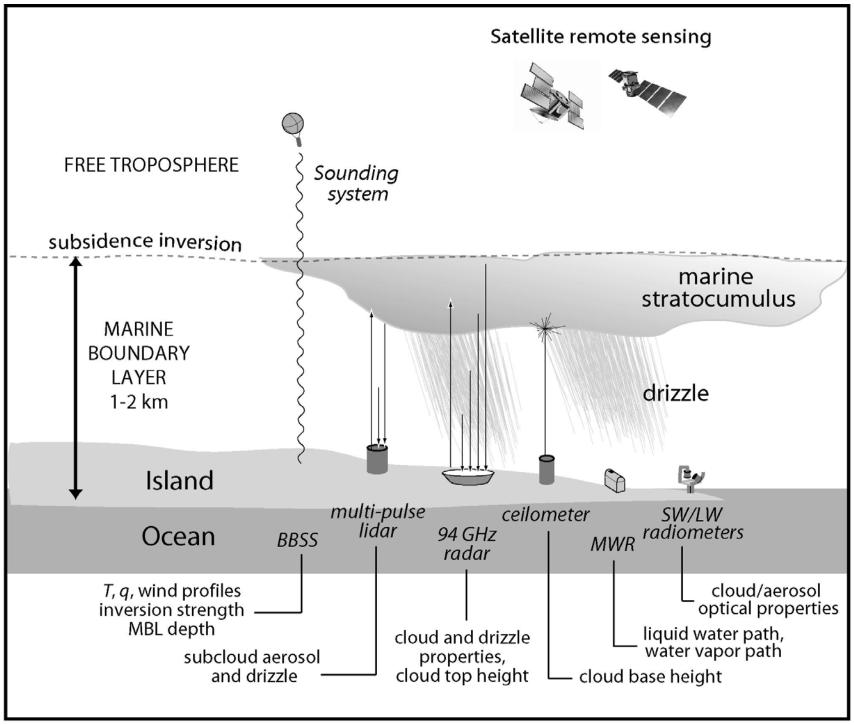

Figure 7. Schematic showing key instruments to be used in the AMF deployment.

6.3 Relevancy to DOE Long-term Goals

"Deliver improved climate data & models for policy makers to determine safe levels of greenhouse gases for the Earth system. By 2013, substantially reduce differences between observed temperature and model simulations at subcontinental scales using several decades of recent data."

The Intergovernmental Panel on Climate Change (IPCC) has identified the response of clouds to climate change as being a major source of uncertainty in climate models. Many of the processes that govern the behavior of clouds in numerical models occur on scales smaller than a typical climate model grid box and it is therefore an important challenge to parameterize clouds in a physically consistent manner.

Marine boundary layer clouds are particularly important in the global climate system, not only as passive modulators of solar radiation, but as interactive systems that influence and modulate sea surface temperature and the strength of the trade winds on seasonal-interannual timescales. Their microphysical properties are important, strongly sensitive to anthropogenic aerosol, and poorly understood, especially over the remote oceans. The data from the AMF deployment will constitute the first climatology of the high-resolution vertical structure of cloud and precipitation properties of low clouds at a remote subtropical marine site. These data will give us particularly important new information about the structure and variability of the remote marine boundary layer system and the factors that influence it. The AMF and synergistic data sets created within this study will be extremely important in the validation and testing of cloud parameterizations for the large-scale numerical models required to long-term goals of the DOE in delivering improved climate predictions to policy makers.

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