DOE/ER-ARM-0501

Marine Stratus Radiation, Aerosol, and Drizzle (MASRAD) Science Plan

June 2005

M.A. Miller
Brookhaven National Laboratory
Earth System Science Division
Upton, New York

A. Bucholtz
Naval Research Laboratory
Monterey, California

B. Albrecht and P. Kollias
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Abstract

Marine stratus is one of the most prevalent and under sampled cloud types on earth and is an important component of the earth's climate system. Marine stratus is thought to be susceptible to infusions of anthropogenic aerosols that alter in-cloud microphysical processes and is known to have at least two stable modes: one with relatively large cloud droplets and relatively large drizzle rates and another with relatively smaller cloud droplets and little or no drizzle. Cloud condensation nuclei (CCN) may play a critical role in determining which mode is observed. Marine stratus clouds also exhibit a strong diurnal cycle due to a pronounced cloud and radiation feedback involving changes in the net radiative flux at cloud top.

The Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) will be deployed at Point Reyes on the central California coast to study the microphysical characteristics of coastal marine stratus during the Marine Stratus Radiation, Aerosol, and Drizzle (MASRAD) Experiment. MASRAD has two main scientific objectives: (1) to investigate the general relationship between cloud structure, aerosols, cloud microphysics, drizzle, and radiation in coastal marine stratus clouds; and (2) to investigate the specific effects of aerosols on the discrepancy between the measured and modeled amount of solar radiation absorbed by these clouds. These scientific objectives will be investigated by combining detailed cloud, drizzle, and radiation measurements from cloud radar and other sensors with detailed aircraft profiles of cloud microphysics and aerosols, and a comprehensive suite of coincident surface aerosol measurements. MASRAD will include deployment of two aircraft: the U.S. Department of Energy (DOE) Gulfstream G-1 (G1) aircraft sponsored by the DOE Atmospheric Sciences Program, and the Center for Interdisciplinary Remotely – Piloted Vehicle Studies (CIRPAS) Twin Otter that will be fielded jointly by the Naval Research Laboratory in Monterey and the California Institute of Technology. Both aircraft will be equipped with a comprehensive array of sensors to measure cloud microphysics, aerosol chemical and microphysical properties, CCN spectra, and turbulence. In addition, the Twin Otter will carry a comprehensive array of sophisticated, motion-stabilized radiometers capable of measuring both up- and downwelling radiation fields.

Contents

Figures

Tables

Marine Stratus Radiation, Aerosol, and Drizzle (MASRAD)

Science Plan

1. Introduction

Extensive sheets of stratus and stratocumulus clouds lie above the eastern boundary current upwelling regions over the world's oceans during summer. These clouds are some of the most prevalent on earth. They exert a large scale cooling effect on the ocean surface and are important components of the global energy budget. Nonetheless, relatively few detailed and comprehensive observations of marine stratus clouds exist despite their known importance in the climate system and potential susceptibility to anthropogenic emissions.

The mixing processes that sustain marine boundary layer stratus are primarily fueled by the net radiative flux at cloud top. This net flux has a strong diurnal signature modulated by solar radiation, which causes the cloud structure to undergo compensating changes. As the solar flux increases during the day, the net amount of cloud top cooling decreases such that there may not be sufficient turbulent kinetic energy to maintain a well-mixed state. This circumstance may lead to a suspension of the vertical mixing that supplies the clouds with water vapor from the ocean below, which may cause them to thin or to evaporate completely (Nicholls 1984; Albrecht et al. 1995; Miller and Albrecht 1995; Rogers et al. 1995; Miller et al. 1998a,b; Wood et al. 2002). This diurnal cycle is a powerful cloud and radiation feedback mechanism that impacts marine clouds over a wide area of the world's oceans. Near coastal areas, the subsidence rate at the top of the marine boundary layer may be modulated by land-sea breeze circulations or inertia-gravity wave activity, which may also contribute to the observed diurnal cycle (Bretherton et al. 2004).

Several microphysical processes are thought to operate in marine stratus clouds, depending on the specific location and conditions. Increases in anthropogenic sources of cloud condensation nuclei (CCN) can increase cloud albedo by increasing the concentration and size of cloud droplets (Twomey 1977), usually referred to as the first indirect effect of aerosol on climate. The Twomey effect is thought to give rise to a shortwave radiative forcing of climate by anthropogenic aerosols of order -1 W m^{-2}, where the negative sign indicates a cooling effect (ref: Chapter 5, IPCC 2001). Such a forcing is comparable in magnitude (and opposite in sign) to the longwave forcing by anthropogenic greenhouse gases. However, this forcing is considered to be quite uncertain, perhaps the most uncertain of the several identified forcings of climate change over the industrial period (ref: Chapter 6, IPCC 2001). Increasing the number concentration of smaller droplets may also suppress the production of drizzle and increase cloud lifetime, thereby increasing average planetary cloud cover (Albrecht 1989). Also, reduction in cloud cover caused by absorption of solar radiation in haze layers (Hansen et al. 1997; Ackerman et al. 2000) may be considered a "semi-direct effect." More recently, Liu and Daum (2002) demonstrated that anthropogenic aerosols exert an additional effect on cloud properties that is derived from changes in the spectral shape of the size distribution of cloud droplets in polluted air that acts to diminish the cooling impact of the first indirect effect.

The amount of cloud liquid water and the effective radius of the constituent cloud droplets are the dominant modulators of the surface and top-of-the-atmosphere-radiative fluxes and the profile of radiative flux divergence in marine stratus. Modeling studies show that cloud liquid water is generally the more important of these two forcing mechanisms. The response of cloud liquid water to changes in aerosol and cloud droplet concentrations is difficult to measure because the amount of aerosol and in-cloud mixing physics depends on meteorological conditions, thereby convolving the microphysical and meteorological signals. Theoretical models suggest that cloud liquid water should increase with aerosol loading, but observations are strongly divided on this issue. A recent modeling study suggests that the response of cloud water to the suppression of precipitation, the second indirect effect, is determined by a competition between moistening from decreased surface precipitation and drying from increased entrainment of overlying air (Ackerman et al. 2004). "Only when the overlying air is humid or droplet concentrations are extremely low does sufficient precipitation reach the surface to allow cloud water to increase with droplet concentrations. Otherwise, the response of cloud water to aerosol-induced suppression of precipitation is dominated by enhanced entrainment of overlying dry air. In this scenario, cloud water is reduced as droplet concentrations increase, which diminishes the indirect climate forcing." Hence, the behavior of the cloud liquid water within marine stratus clouds in response to changes in aerosol concentration remains a vexing issue that may involve complex feedbacks between the cloud and its environment.

The drizzle process itself is a subject of considerable debate in the literature. Recent theoretical studies provide competing plausible explanations for the physics of the drizzle process itself. One hypothesis for the movement of a non-precipitating stratus cloud to produce drizzle is the addition of so-called giant cloud condensation nuclei (GCCN) to the cloud (Feingold et al. 1999). Modeling studies suggest that 20 μm radius particles that exist in concentrations of between 10^{-4} and 10^{-2} cm^{-3}, depending on the ambient wind and sea state, are sufficient to move a non-precipitating stratus into a precipitating state at typical CCN concentrations of 50 to 250 cm^{-3}. This theory suggests that higher concentrations of GCCN are required at higher CCN concentrations. In contrast, a more recent theory based on an extension of aerosol droplet nucleation theory and stochastic droplet growth suggests that the precipitation process in marine stratus is initiated by a "barrier crossing" that depends on the concentration of CCN and cloud droplets (McGraw and Liu 2003). Thus, a debate remains as to the exact physics of the precipitation initiation process in marine stratus.

Indirect aerosol effects hypothetically operate in both marine and continental cloud systems, and there is a considerable body of evidence, though largely circumstantial, to substantiate this claim (Albrecht et al. 1989; Platnick and Twomey 1994; Feingold et al. 2003; Kim et al. 2003). Observational studies provide evidence that liquid phase continental stratocumulus clouds exhibit the characteristics associated with the first indirect effect (Feingold et. al. 2003), but the correlations between surface aerosol characterizations and cloud droplet effective radius in a recent study were found to be fairly weak (Kim et al. 2003). These weak correlations may be due to complicated vertical mixing structure that causes the surface aerosol measurements to be unrepresentative of those at cloud level, lack of explicit measurements of CCN, mitigating meteorological factors, or competing processes such as those described above. A recent study with an adiabatic cloud model suggests that the weakness of the observed signals could be due to the complicated cloud and aerosol interactions that occur in polluted air masses, which may mask the Twomey effect (Feingold 2003). This same modeling study suggests that the requirements for measuring the indirect effect over polluted continents may be more stringent than those over the cleaner oceans. Despite the weakness of the aerosol indirect effect signals in these continental clouds, evidence of the first indirect effect was indicated in these studies.

In contrast to continental liquid stratocumulus, maritime stratus and stratocumulus yield much stronger indications of first and second indirect effects (Platnick and Twomey 1994). The marine air masses that contain these clouds are normally pristine and, thus, are particularly susceptible to the intrusion of anthropogenic aerosol. Moreover, generally more clouds exist in the marine boundary layer because of the continuous availability of water vapor. Satellite images often show meso-beta-scale (100-300 km) patches of stratocumulus with similar properties surrounded by areas of much thinner cloud or trade cumulus. These regions of thin clouds are often referred to as rift zones. A comparison of microphysics and thermodynamics on opposite sides of a rift boundary in a recent study (Smith 2000; Sharon et al. 2004) indicated that these rifts form where low aerosol concentrations enhance drizzle production. Below-cloud aerosol concentrations within the rift zone were only one-sixth that observed beneath the background stratocumulus. Cloud droplets in rift clouds were 3-5 microns larger than droplets in the surrounding stratocumulus sheets and exhibited a broader size distribution, thereby suggesting a first indirect effect. Drizzle production was also greater within the rift zones, which suggests that the second indirect effect is also operating. In general, the marine boundary layer appears to present an opportunity for a more straightforward interpretation of observations related to aerosol indirect effects and a significantly wider dynamic range in indirect effects as compared to continental stratus.

Despite the importance of indirect effects in climate studies, they are characterized by large uncertainty because of the complexity of the constituent processes and the difficulty of obtaining relevant, comprehensive, and statistically significant observational data.

- Processes important in modulating the aerosol indirect effect likely occur on a wide range of size and time scales. Furthermore, it has been demonstrated that, to first order, the liquid water (and ice water) path determines the radiation-transfer characteristics of clouds. A recent modeling study suggested that the cloud droplet effective radius is most susceptible to cloud liquid water (Feingold 2003) and a recent observational study of liquid-phase continental stratus using surface-based remote sensors demonstrated that variance in the liquid water path (LWP) accounted for 97% of the variance of optical depth on some individual days, and 63% for the entire dataset (Kim et al. 2003). Therefore, any attempt to study the indirect effect and its impact on radiation must begin with a dutiful analysis of the LWP. Unfortunately, it is often difficult to filter the effects of LWP variability so as to detect the variability in cloud structure and radiation associated specifically with the indirect effects.

- Aircraft penetrations at specific times and heights may provide excellent correlations between the various microphysical elements of different indirect effects, but they cannot easily quantify the relationship between these measurables and the total integrated LWP of the cloud, which, as aforementioned, strongly modulates the radiative forcing at the surface. Moreover, aircraft observations don't provide a time series of sufficient length and scope to determine the climatological characteristics of the processes that they do observe and they may not sample the full range of processes that are operating in the cloud system.

In addition to the climatic implications of the aerosol indirect effects that operate in the marine boundary layer clouds, basic questions about the amount of solar radiation absorbed by clouds has been a subject of debate for many years (Stephens and Tsay 1990). The motivation for this debate has been the fairly consistent discrepancy between measurements and models, with many measurements showing clouds absorbing more solar radiation than given by model calculations. Within the past 10 yr, this debate has heated up due to a series of studies that showed much more solar absorption by clouds than previous studies indicated (Cess et al. 1995; Ramanthan et al. 1995; Pilewskie and Valero 1995; Valero et al. 1997; Zender et al. 1997), while other studies showed no indication of a discrepancy between measured and modeled absorption (Francis et al. 1997; Asano et al. 2000).

The Atmoshperic Radiation Measurement (ARM) Program takes an active role in this debate and has a long and productive history of studying the solar absorption of clouds and narrowing the gap between models and observations (Ackerman et al. 2003, O'Hirok and Gautier 2003, Valero et al. 2003). However, complete closure between models and observations is still lacking because all previous studies have suffered from one or more of the following flaws: insufficient case studies, insufficient characterization of the cloud, insufficient characterization of the aerosol throughout the atmospheric column, insufficient characterization of the surface albedo, and/or insufficient accuracy in the solar flux radiometer measurements. Ackerman et al. (2003), and others (O'Hirok and Gautier 2003; Valero et al. 2003) have hypothesized that these flaws, especially the lack of knowledge of the ambient aerosols, are the main reasons for the remaining discrepancy between models and observations of the solar absorption by clouds. The debate on this issue has therefore waned (Kerr 2003), but is still not completely resolved (Li et al. 2003).

2. Experiment Overview

The ARM Mobile Facility (AMF) will collect a 6-month sample of the spring and summer coastal marine stratus clouds at Point Reyes, California. The months chosen for analysis span the summertime peak in stratus frequency off the California coast. Results of an analysis of images from the moderate-resolution imaging spectroradiometer (MODIS) over an area approximately the size of a grid cell in a global climate model (GCM) off Point Reyes show that the cloud optical thickness and cloud frequency peak in July (Figure 1). Analysis of high resolution MODIS data from the area around the Point Reyes field reveals gradients in the cloud properties as the clouds move onshore, suggesting that they are representative of coastal marine stratus, rather than pure marine stratus (Figure 2).

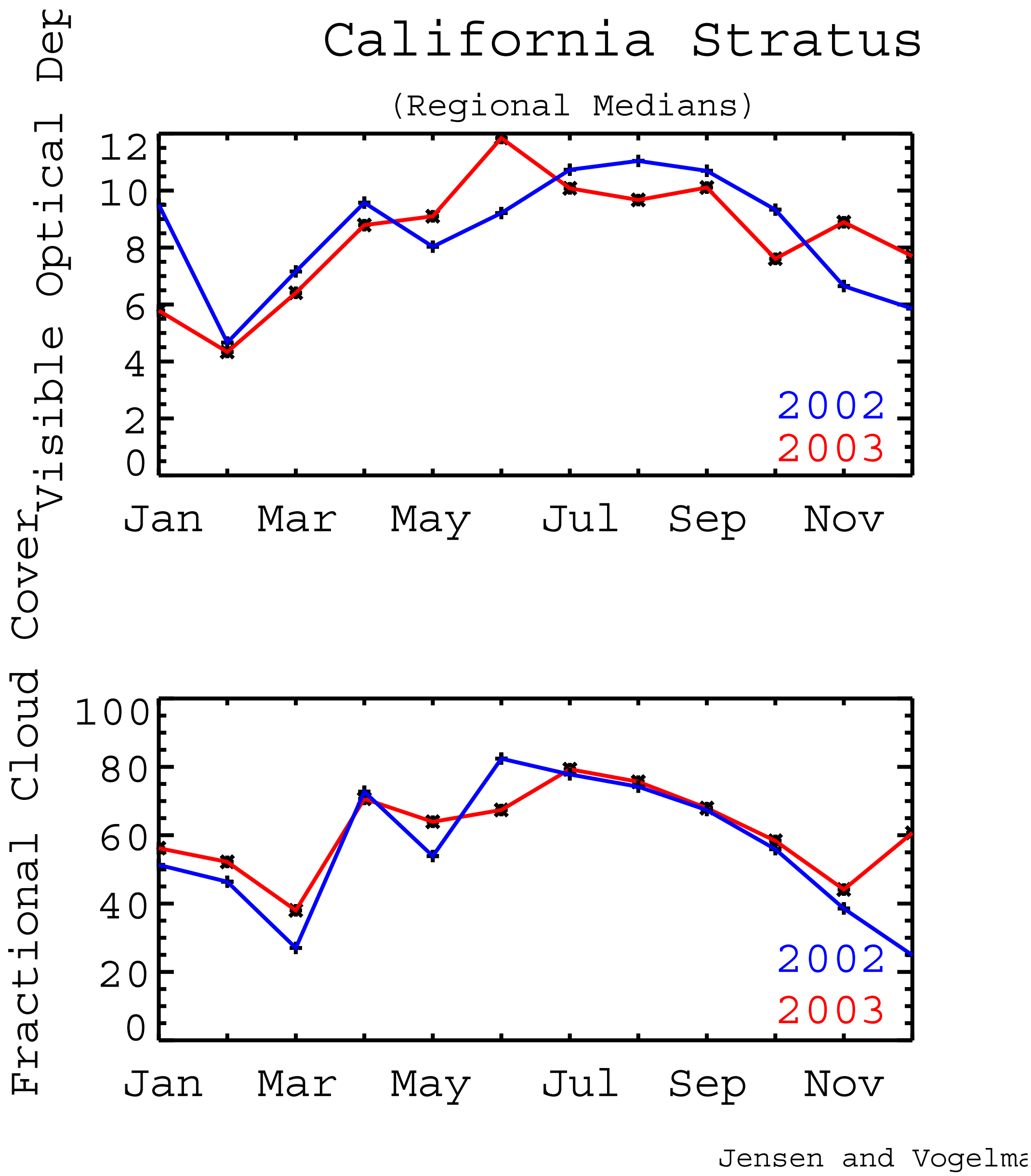

Figure 1. Regional satellite-derived cloud properties for California stratus in the vicinity of Point Reyes, California. The data are from MODIS and represent averages over an area that is approximately the size of a GCM grid cell.

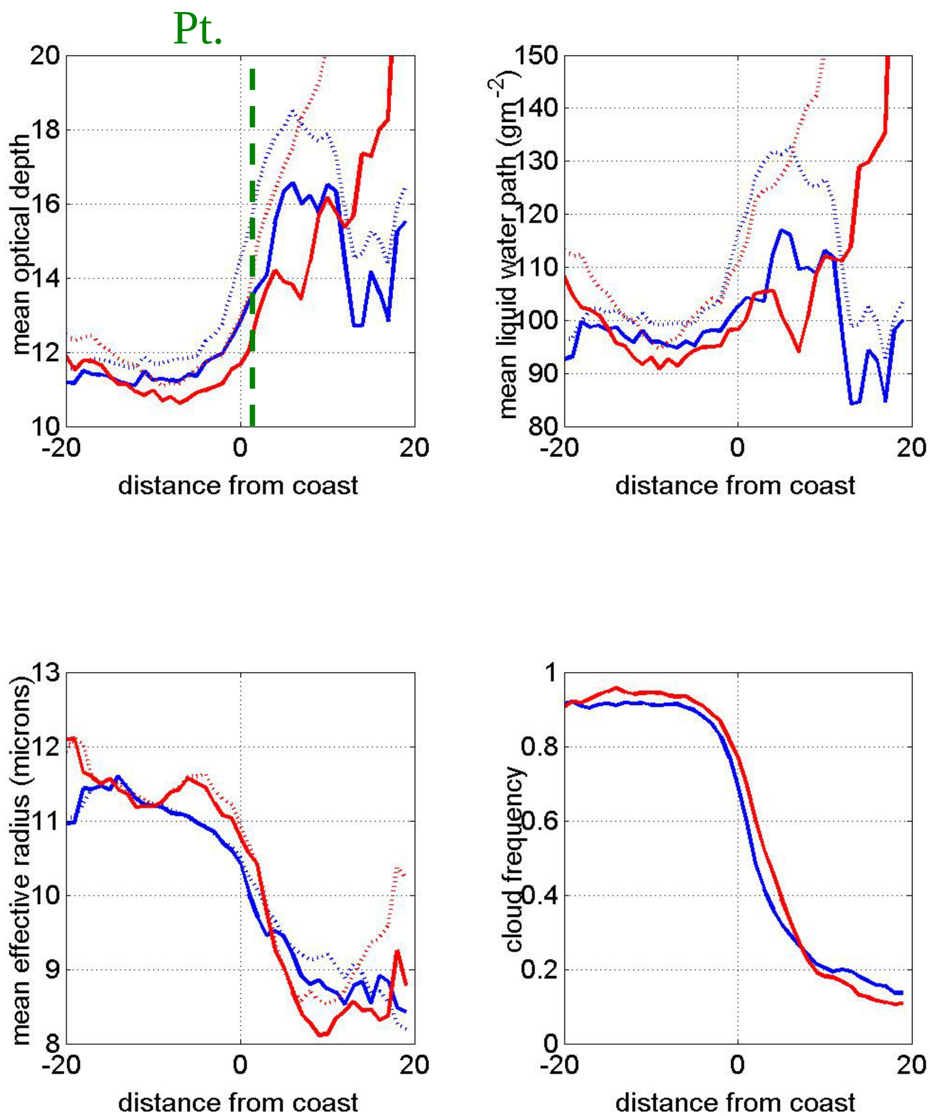

Figure 2. Shown are retrievals of MODIS Aqua (blue) and Terra (red) mean cloud optical depth, mean LWP (g m^{-2}), mean effective radius (µm), and cloud frequency in a 20-km wide rectangle of length 40-km. The rectangle is oriented such that its long axis is perpendicular to the coast and the intersection of the diagonals is centered on the Point Reyes site. The dashed lines are the cloud property retrievals weighted by cloud fraction such that completely overcast scenes receive the highest weighting. (M. Jensen and A. Vogelmann at Brookhaven National Laboratory provided this figure.)

The AMF is being deployed at the site of a former telephone switching facility, hereafter referred to as the AT+T site. The site was selected due to close proximity to the shore (~1 mile; Figure 3), the geographic orientation of the Point Reyes peninsula and its propensity to be ensconced in coastal marine stratus (Figure 4), tenable infrastructure, acceptable air space constraints, and an accommodating Point Reyes National Park Service Administration. The geography of the Point Reyes site is characterized by an escarpment at the beach that rises into sand dunes, which give way to flat pastureland (Figure 5). The area around the AT+T site has a few remaining large tress surrounded by scrub bushes that are approximately knee-high.

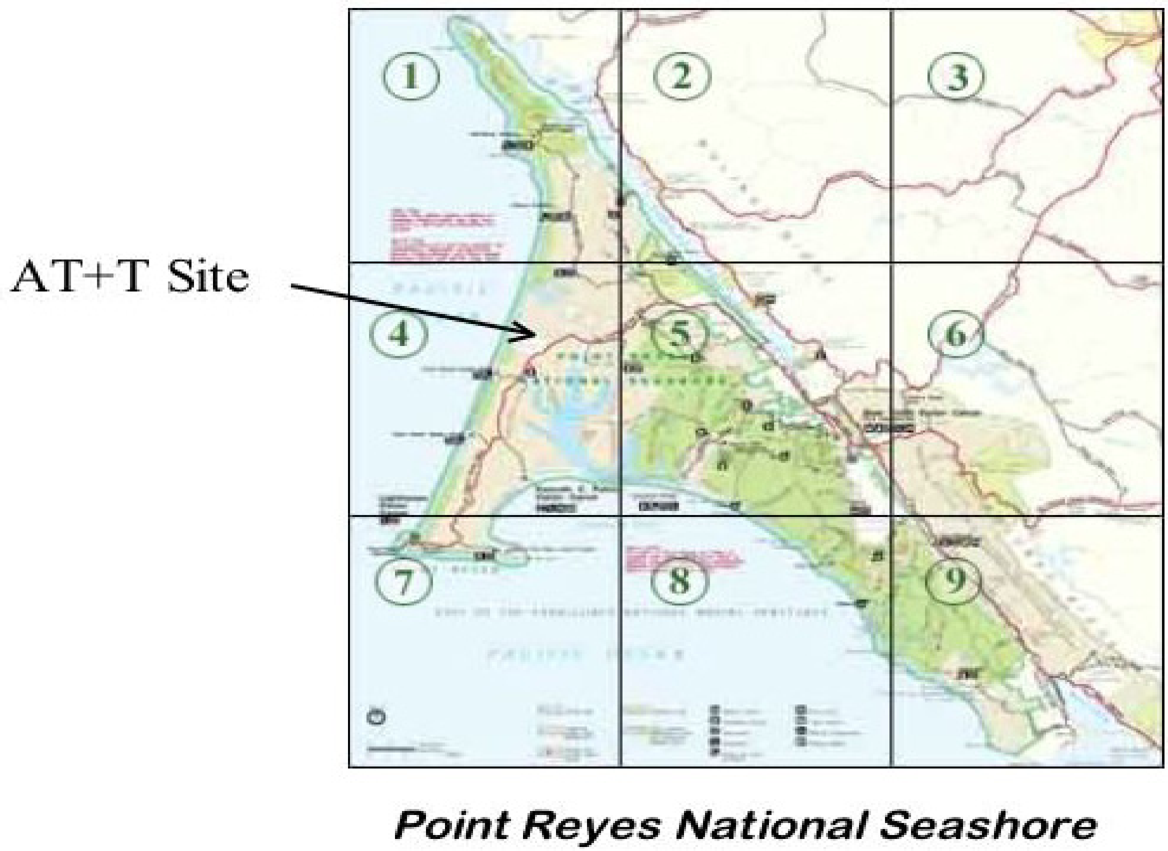

Figure 3. Geography of the Point Reyes National Seashore and location of the AT+T deployment site.

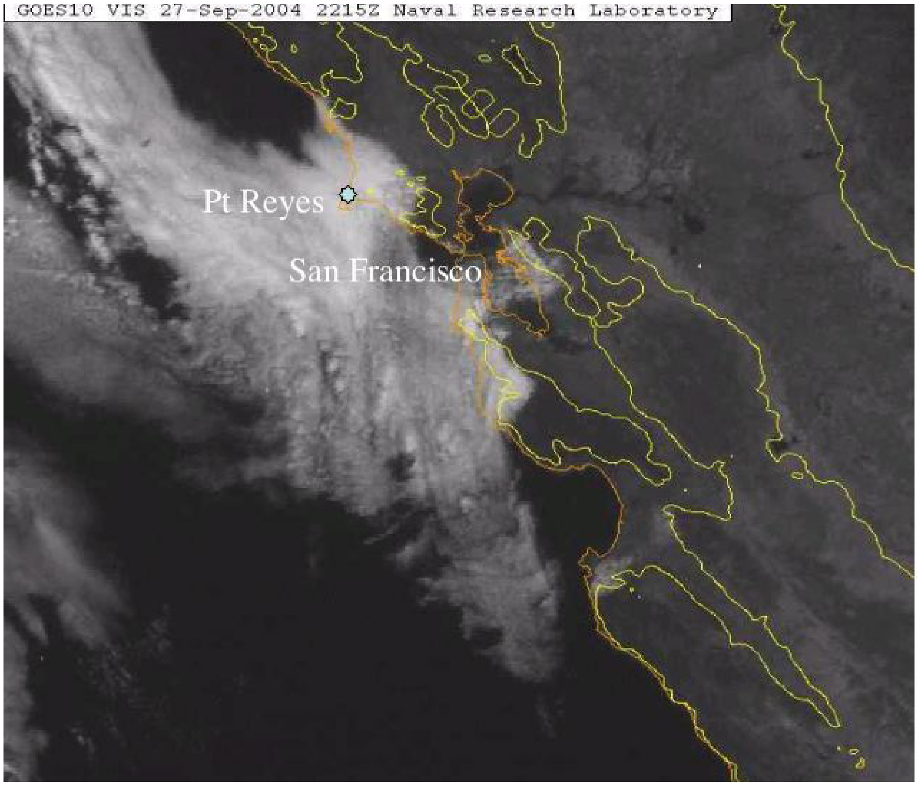

Figure 4. The Geostationary Operational Environmental Satellite infrared image of the Point Reyes area.

Figure 5. The photograph is an aerial view of the Point Reyes AT+T site from above the nearby ocean. The site is located at the small patch of trees in the center of the photograph. Copyright (C) 2002-2004 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.

The experimental approach is to collect continuous data with the AMF at Point Reyes and use sophisticated analysis of the surface-based remote sensors to create a continuous record of cloud microphysical structure through the study period. A continuous surface record of multiple supersaturation CCN measurements and other surface aerosol characterizations will augment these data. We will embellish the continuous record of microphysical and aerosol structure with an intensive measurement campaign during which aircraft will collect detailed profiles of cloud and aerosol microphysical structure, and additional aerosol instrumentation will be deployed at the Point Reyes AMF site. These profiles will be used to evaluate the surface-based retrievals from the AMF, to specifically link below-cloud and above-cloud aerosol structure with the in-cloud microphysical structure, and to allow spatial sampling. During this campaign, at least one aircraft will be equipped with a specialized, motion-compensated radiometer package that can be used to directly address the issue of solar absorption in stratus clouds, which is a fundamental unanswered question. The complete dataset will be used to study surface radiative forcing through radiative closure studies similar to those currently being conducted in ARM (i.e., the Broadband Heating Rate Project [BBHRP]; Mlawer et al. 2003) and to understand the diurnal cycle (assuming the latter is not profoundly impacted by the nearby continent).

The deployment of the AMF at Point Reyes, California, and accompanying efforts by the U.S. Department of Energy (DOE) Atmospheric Science Program (ASP) and the Office of Naval Research (ONR) affords the opportunity to gather a critical, long-term dataset that can advance our understanding of the marine stratus cloud system. Most of the known information about marine stratus has been gathered during experiments that are relatively narrow in scope or relatively short in duration. The deployment of the AMF at Point Reyes for a period of 6 months will provide one of the largest cloud microphysical datasets gathered to date. Most importantly, the opportunity to gather coincident aircraft data, particularly information about aerosol chemistry, radiation, and CCN, affords a serious opportunity to decipher many of the complex microphysical and radiative process that are associated with marine stratus and stratocumulus clouds. The Marine Stratus Radiation, Aerosol, and Drizzle (MASRAD) experiment is facilitated by technological innovations over the past decade that allow complex microphysical measurements to be made using surface-based remote sensors and more accurate radiation measurements from aircraft. Hence, the combination of the AMF and these new aircraft sensors enables bottlenecks in our ability to characterize marine stratus to be removed.

2.1 Science Questions

The MASRAD experiment contains many facets, but there are two main components. The first component is to quantify the cloud liquid water budget in coastal marine stratus and determine the controlling factors. An important aspect of this component is to understand how the aerosol distribution is linked to the cloud liquid water budget. Specific objectives of the MASRAD study are to determine the following:

1. What factors control the cloud liquid water budget in coastal marine stratus clouds?

2. What are the respective contributions of cloud liquid water and the Twomey effect in modulating the surface solar radiative forcing of liquid-phase boundary layer clouds?

3. Is the second indirect effect relatively more important than the Twomey effect in marine boundary layer clouds?

4. At what cloud LWP and CCN concentration does the Twomey effect dominate surface radiative forcing in boundary layer clouds?

5. How is the cloud coverage in boundary layer clouds related to aerosol concentration, particularly the concentration of CCN?

6. What is the cloud liquid water flux (drizzle rate) and drizzle droplet size distribution, and how does it depend on cloud CCN concentration, cloud liquid water content, and large-scale forcing?

7. How are in-cloud turbulence levels related to the liquid water flux, cloud droplet size distribution, and entrainment rates?

8. What role does the moisture gradient at the inversion play in the production of drizzle?

9. Do the characteristics of cloud microphysics and drizzle production in the Point Reyes area change from late spring to late summer, and if so, how and why?

10. What is the character of the radiative flux divergence profile in coastal marine stratus clouds?

The second component is an embedded experiment being performed by the DOE ASP. This experiment is known collectively as the Marine Stratus Experiment (MASE) and its objectives are as follows:

1. Examine relationships between aerosol properties—particle size distribution and composition—and CCN spectra (number concentration of CCN as a function of supersaturation), and between CCN spectra and the number and size distribution of cloud droplets.

2. Compare composition of particles forming droplets in ambient clouds to the composition of those remaining as aerosol particles in cloud interstitial air.

3. Characterize the effects of cloud macrophysical properties such as turbulence and ambient meteorology on cloud liquid water content, and microphysical properties such as droplet number concentration and droplet dispersion on the initiation of drizzle.

4. Gather in situ cloud data suitable for examination of the dependence of the autoconversion rate (rate of conversion of cloudwater to precipitation) on droplet size distribution and number concentration.

Deliverables from the DOE ASP's Marine Stratus Experiment (MASE) will include the following:

1. A publicly available comprehensive dataset of aerosol and cloud properties, including aerosol composition, size distribution, CCN spectra, optical properties, cloud droplet and drizzle number concentrations and size distributions, cloud updraft velocities, and turbulence.

2. An evaluation of parameterizations of warm rain initiation and rate suitable for inclusion in GCMs.

3. An assessment of the role of turbulence in the initiation of warm rain.

4. An evaluation of the role of chemical composition in determining the activation behavior of ambient aerosols.

These objectives combine well with the MASRAD objectives and greatly enhance the interpretation of the AMF time series through the use of in situ sampling. An additional project funded by the ONR (John Seinfeld, PI) will contribute to the MASRAD and MASE effort. This ONR effort has similar objectives and will provide additional resources to the project.

3. Platforms, Participants, and Science

The MASRAD experiment will be conducted in collaboration with MASE. Surface aerosol sensors and the Gulfstream G-1 (G1) research aircraft will be deployed to Point Reyes for MASE and in support of MASRAD. The ONR will also contribute to MASRAD through flights of the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter. Detailed measurement plans for the AMF, ASP G1, and ONR Twin Otter are described below.

3.1 Atmospheric Monitor Measurement Mobile Facility Measurements for Marine Stratus Radiation Aerosol Drizzle

The overarching goal of MASRAD is to investigate the general relationship between cloud structure, aerosols, cloud microphysics, drizzle, and radiation in marine stratus clouds. Accomplishing this goal requires a detailed analysis of the data from the surface-based remote sensors that are included in the AMF, particularly the 94-GHz Doppler radar that is equipped with spectral recording capability. These measurements can then be interpreted in the context of surface radiative forcing using techniques similar to those currently being used for ARM's BBHRP. Specifically, we will insert the cloud, aerosol, microphysical, and atmospheric thermodynamic state assays that we produce from the AMF sensors and aircraft profiles (when available) into a radiation transfer model. The resulting calculations of the surface and top-of-the-atmosphere radiative fluxes can be compared with data from the AMF radiometers and satellite radiances (when available) to establish the degree of closure of the calculated radiation profile. If closure is established, within reasonable uncertainties, some confidence in the computed heating rate profile is warranted.

The cloud microphysical properties will be determined from the AMF 94-GHz radar and the radiative properties from surface-based radiometers. The 94-GHz Doppler radar with spectral recording capability is an ideal instrument for indirect aerosol studies, provided the data are used in concert with comprehensive aerosol measurements from aircraft (particularly CCN measurements). Millimeter wavelength Doppler radars have high temporal and spatial resolution, extreme sensitivity and high velocity resolution. Due to their short wavelength, millimeter radars are capable of detecting very small droplets with diameters of 5-10 microns. Despite this advantage, millimeter radars have narrow beams that result in small sampling volumes. As a result, these radars provide excellent resolution in space and in time. Moreover, radar deployments over the past decade have produced radar sampling configurations that can be optimized for MASRAD indirect effect studies (Clothiaux et al. 1995; Clothiaux et al. 1998; Miller et al. 1998a,b; Clothiaux et al. 1999; and Kollias et al. 2004).

Parallel with the recent development of millimeter wavelength radars, retrieval techniques for the estimation of cloud and drizzle drop distributions were developed (Gossard 1988; Gossard 1994; Gossard et al. 1997; Frisch et al. 1995; and Babb et al. 1999). Radars that operate at 94-GHz provide a substantial advantage in that they allow specialized retrieval techniques of precipitation droplet size distributions and air motions based on Mie scattering (Lhermitte 1988). In the Mie scattering regime, the backscattering cross section as function of the raindrop diameter oscillates due to resonant electromagnetic multi-poles effects. Under precipitating conditions at 94-GHz, these oscillations are apparent in the observed Doppler spectrum and can be used as reference points for the retrieval of the vertical air motion and subsequently the droplet size distribution (Kollias et al. 2001, 2002; Firda et al. 1999).

The development of clouds radars has substantially advanced our capability to detect non-precipitating clouds and to measure their microphysical properties. Nonetheless, in-cloud turbulence has a profound impact on the integrity of the retrievals of cloud and drizzle droplet size distributions from the Doppler spectra. The terminal velocity of a cloud droplet is small, so that the droplets' vertical velocity is primarily due to air motion and turbulence. In addition, turbulence and wind shear broadening often overwhelm the droplet-size induced broadening of the Doppler spectrum. In such clouds, the mean Doppler velocity and Doppler spectrum width have strong contributions from turbulence (Kollias et al. 2001). Lately, our understanding of the contribution of cloud kinematics to the observed Doppler spectra from cloud radars has advanced. Given the scales of turbulence and up- and downdraft structures in non-precipitating clouds, an optimum radar signal dwell and processing strategy can be designed to minimize the effect of turbulence on the Doppler spectra. While the improvement on the interpretation of the mean Doppler velocity is small due to the overwhelming air motion contribution at any observable scale, we can significantly isolate the effect of turbulence on the Doppler spectrum and the related Doppler spectrum width to the cloud droplet size distribution broadening. Hence, it is feasible in most circumstances to retrieve a credible cloud droplet spectrum with a vertical resolution on the order of 30 m and a temporal resolution on the order of 2 s.

When clouds contain a bi-modal droplet distribution, additional techniques can be applied. The use of higher order Doppler moments, especially skewness, can be related to the existence of large drop (drizzle) in the radar resolution volume. Furthermore, a detailed Fast Fourier Transform (FFT; 512 or more) provides sufficient velocity resolution, given the narrow nature of the cloud Doppler spectra, to enable bi-modal peaks to be discriminated. Hence, the recording of optimum Doppler spectra from cloud radars for droplet-size distributions is based on short signal dwell (high temporal resolution of samples), a sufficiently large number of FFT points, and post-processing that includes multi-modal spectra and higher order moments. Doppler spectra collected from mm-wavelength radars at various experiments (e.g., the Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment [CRYSTAL FACE]) exhibited the *not as rare as assumed* presence of multi-modal Doppler spectra from non-precipitating clouds, especially mixed-phase clouds, cloud and drizzle droplet size distribution modes and large ice crystal generation in convective anvils. While the presence of such multimode Doppler spectra is a small portion of the observations, the merits from the analysis of such interesting cases could advance our understanding of cloud and precipitation processes.

The specific science questions relative to the aerosol indirect effect and its impact on radiative forcing that will be addressed in our proposal are***:***

1. What factors control the cloud liquid water budget in coastal marine stratus clouds?

   Surface-based millimeter cloud radar, microwave radiometers, and micropulse lidars will be used to construct a liquid water budget during the AMF deployment. From the spectral data collected by the 94-GHz, we will know the liquid water flux in-cloud and below-cloud. We can subsequently segregate the measured LWP into drizzle and cloud water components using the cloud radar (spectral processing). This information can be used to study the ambient factors that modulate the liquid water budget.

2. What are the respective contributions of cloud liquid water and the Twomey effect in modulating the surface solar radiative forcing of liquid-phase boundary layer clouds?

   Data from surface-based remote sensors will be used to estimate the cloud droplet size distribution (cloud radar spectral processing) and the liquid water budget on scales of less than 1-min. in overcast conditions. The measurements will be combined with observations of CCN and other aerosol measurements from aircraft and the surface. To ensure that the surface aerosol measurements are representated in the absence of aircraft or radiosonde data, the lifting condensation level at the surface will be compared with physical measurements of cloud base from lidar to determine the mixing state of the boundary layer. The cloud optical thickness will be measured at the surface using a multi-channel shadowband radiometer. The variance of cloud optical thickness can be correlated with the variances of the moments of the cloud droplet distribution, CCN concentration (and other aerosols), and LWP. These correlations should determine whether the droplet size distribution or LWP is modulating the surface radiation budget.

3. Is the second indirect effect relatively more important than the Twomey effect in marine and continental boundary layer clouds?

   Given the results from question (2), we can correlate the cloud LWP variance with the liquid water flux (drizzle) variance to determine how strongly the cloud radiative forcing is correlated with the occurrence of drizzle. The issue of cloud lifetimes and the occurrence of drizzle may be addressed by correlating the surface and aircraft CCN counts with the LWP. If drizzle suppression does lead to an increase in cloud liquid water, which is a symptom of enhanced cloud lifetime, it should be possible to detect this process using these two techniques.

4. At what cloud LWP and CCN concentration does the Twomey effect dominate surface radiative forcing in boundary layer clouds?

   This question should be easily addressed using the data analysis from questions (1)-(3). The crux of this question is to determine if thin marine clouds with low cloud liquid water contents are more susceptible to indirect aerosol effects, which is indicated by simple experiments with plane parallel cloud and radiation models.

5. How is the cloud coverage in boundary layer clouds related to aerosol concentration, particularly the concentration of CCN?

   Satellite analysis with temporal averages of cloud location from the surface-based sensors will be used to produce a best estimate of cloud fraction as a function of height and total cloud coverage (the integration of the contributions from all heights). These data will subsequently be correlated with aerosol measurements (CCN and others) from surface and from aircraft. Surface aerosol measurements will be filtered according to boundary layer mixing state as outlined in question (2).

6. What is the cloud liquid water flux (drizzle rate) and drizzle droplet size distribution, and how does it depend on cloud CCN concentration, cloud liquid water content, and large scale forcing?

   This question can be addressed using the analysis from questions (1)-(3) along with aerosol measurements (CCN and others) from surface and from aircraft. Large scale forcing will be quantified using the analysis data from a relevant weather forecasting model.

7. How are in-cloud turbulence levels related to the liquid water flux, cloud droplet size distribution, and entrainment rates?

   Some case studies using the analysis performed in earlier segments of the project will be used to link measurements made with the surface-based remote sensors with information about the background thermodynamic profile.

8. What role does the moisture gradient at the inversion play in the production of drizzle?

   Data from AMF radiosondes, aircraft profiles, and from the AMF remote sensors (particularly the profiling microwave radiometer) will be combined to establish the thermodynamic state of the column above the AMF. Particular emphasis will be placed on the moisture gradient at cloud top. Current modeling studies suggest a strong link between drizzle and above-cloud humidity, which can be evaluated with these data.

9. Do the characteristics of cloud microphysics and drizzle production in the Point Reyes area change from late spring to late summer, and if so, how and why?

   Spectral analysis of the data from the AMF 94-GHz radar will be used to quantify marine stratus cloud microphysics, as detailed above, and create a time series. This time series will be analyzed for the purpose of determining if the marine stratus in the region evolves in structure through the stratus season. If evolution is suggested, we will attempt to determine the causes.

10. What is the character of the radiative flux divergence profile in coastal marine stratus clouds?

    Closure experiments similar to those being conducted in ARM's BBHRP project will be performed using data from the AMF. These experiments quantify the radiative impacts of the coastal marine stratus on the clear atmosphere (the cloud forcing).

3.2 Surface Measurements for Marine Stratus Radiation Aerosol Drizzle and Marine Stratus Experiment

The AMF instruments will be deployed at Point Reyes. Table 1 lists each instrument and any comments related to the operation of the instrument for MASRAD.

Table 1. Clouds and Radiation

Instrument	Measurement	Resolution	Comments
Atmospheric emitted radiance interferometer (AERI)	absolute infrared spectral radiance in 1.3° field-of-view; temperature and vapor profiles	3-19.2 microns with 3.3-36 nm resolution Time: <1 min	Rapid sample mode
95-GHz cloud radars (WACR; and FM-CW)	effective reflectivity Doppler spectrum	Resolution: 30 m Temporal: 2 s	Minimum detectable signal: -50 dBz at 2 km
Micropulse lidar (MPL)	Backscatter intensity: 523.5 nm	Resolution: 15 m Time: 30-60 s	Maximum height: 18 km
Microwave radiometer (MWR)	Brightness temperature (5 channels), cloud liquid water path, precipitable water vapor	Time: 20 s	Minimum detectable LWP: 30 gm^{-2}
Profiling microwave radiometer (MWR-P)	Brightness temperature (12 channels), cloud LWP, temperature, and water vapor profiles	Time: 5 min	Variable vertical resolution
Laser ceilometer	Cloud base height	Time: 30 s	
Zenith-pointing infrared thermometer (IRT)	Cloud base temperature	Time: <1 min	Cloud must be a blackbody (emissivity = 1)
Rawindsondes	Pressure, temperature, relative humidity, winds	Time: every 4 hr	Vertical resolution: variable

Table 1. (cont'd)

Instrument	Measurement	Resolution	Comments
Multi-filter rotating shadowband radiometer	Aerosol optical thickness, aerosol Angstrom Exponent, cloud optical thickness	Time: 20 s	Channels: 415, 500, 615, 673, 870, and 940 nm with 10 nm width
Downwelling radiation (SKYRAD)	Direct, diffuse, and global broadband shortwave (solar), longwave (infrared), irradiances for downwelling components.	Time: 1 min	
Narrow field-of-view radiometer (NFOV)	Cloud radiance and optical thickness	Time: <1 min	
PSU dual spectrometer system	Cloud optical depth retrieval is based on the two radiance and flux method	Time: <1 min	
Upwelling radiation (GNDRAD)	Broadband shortwave (solar) and longwave (infrared) irradiances	Time: 1 min	
Surface-pointing infrared thermometer	Surface skin temperature	Time: <1 min	
Total sky imager	hemispheric sky images for daylight hours	Time: ~30 s	solar elevation > 5° to 10°
Surface meteorology	surface wind speed and direction, temperature, relative humidity, barometric pressure, and rain-rate	Time: 1 min	
Fog detector	Fog occurrence and precipitation type	Time: 1 min	
Eddy correlation	surface turbulent fluxes of momentum, sensible heat, latent heat	Time: one-half hour	Mounted at 1 m to facilitate small footprint
915 MHz wind profiler	Wind profile, precipitation Doppler spectrum	Time: 6 min Resolution: 75 m	

3.2.1 Surface Aerosols (PIs: J. Ogren, C. Berkowitz, R. Halthore, A. Laskin, A. Strawa, J. Wang, A. Wexler, and B. Andrews)

As part of the AMF deployment to Point Reyes, a suite of instrumentation will be installed to measure the chemical, physical and optical properties of aerosol particles at the site. DOE's new Aerosol Science Program funds several of the participants. Point Reyes has been called one of the foggiest places on earth, and while that may be hyperbole, this provides an excellent opportunity to study the inter-relationship between aerosol particle and cloud droplet properties using a surface-based observing platform. In addition to the cloud/aerosol research, several other complementary aerosol projects are also taking place at the site including (a) an intercomparison of the Cadenza cavity ring down technique (funded by NASA) and use of the particles/soot absorption photometer (PSAP) for measuring light absorption, (b) coordinated ultrafine and chemistry aerosol particle measurements, and (c) measurement of aerosol optical, physical, and chemical properties during cloud-free conditions at a marine site. The measurements and specific scientific questions addressed are described below.

A major focus of the Aerosol Science Program research is the interaction between clouds and aerosol particles. To study this, a counter-flow virtual impactor (CVI) will be used to selectively sample cloud drops. The CVI takes advantage of the higher inertia of the cloud drops to draw them through a slight counter-flow into the system while smaller particles are unable to overcome the counter-flow. Downstream of the CVI the cloud drops will be evaporated and the resulting CCN will be fed to aerosol instrumentation to characterize their optical, chemical, physical (size, number and shape) and cloud activation properties. In parallel with the CVI system, a second aerosol inlet with an upper cut-off size of 5 µm will sample the interstitial aerosol (i.e., the particles which have not activated to cloud droplets). Instrumentation downstream of this interstitial inlet will be similar to that downstream of the CVI and will also include an SMPS for sizing the particles and a humidograph for assessing hygroscopic growth of the aerosol. By running these two inlet systems in tandem, the following scientific questions can be addressed:

- What are the differences in chemistry between interstitial and activated aerosol?
- What role do organics play in aerosol formation and activation?
- How do clouds change the optical properties of the aerosol?
- How do the CCN spectra differ between interstitial and activated aerosol?
- Can CCN closure be obtained?

While the research described above focuses on aerosol-cloud relationships, many of the deployed instruments will sample continuously, thus providing characterization of cloud-free summertime aerosol at Point Reyes. This dataset will be used to address the following scientific questions:

- How do light absorption measurement methods compare under a variety of sampling conditions (e.g., the influence of particle size on instrument performance)?

- What are the chemical, optical, and physical properties of the aerosol at a marine site during fog-free conditions?

- What can be learned about the chemical species and processes controlling homogeneous aerosol nucleation processes in the coastal marine boundary layer?

A number of different types of models, covering processes ranging from radiative transfer to marine aerosol microphysics to cloud droplet formation will be used to interpret the measurements. Results from this study will be relevant to improving the parameterization of aerosol forcing (direct and indirect effect) in climate models.

The aerosol observations collected during MASRAD will be accomplished in two stages. The first stage will be the installation of aerosol instrumentation that will collect a continuous time series during the experiment. This first stage instrumentation was installed in early March 2005. A second stage of instrumentation will be installed in July 2005.

3.2.1.1 Stage 1: March 2005

At its meeting in December 2004, the ARM Aerosol Working Group recommended that an in situ aerosol observing system be included in the AMF Aerosol Observing System (AOS). The AMF AOS should use sampling protocols identical to those used for the AOS at the ARM Climate Research Facility's (ACRF's) Southern Great Plains site, so that the data from the two systems are quantitatively comparable. The recommended instruments for the AMF AOS are:

1. Integrating Nephelometer (TSI 3563, operated at low relative humidity [RH]): The nephelometer measures total scattering (between 7° and 170°) and backscattering (between 90° and 170°) by aerosol particles at three wavelengths: blue (450 nm), green (550 nm) and red (700 nm). This nephelometer is maintained at a humidity of 50%.

2. Integrating Nephelometer (TSI 3563, operated at RH scanned from ~40%-90%): This is a second nephelometer that samples air at a variety of controlled humidities ranging from 20% to 90%. This instrument will not be deployed to Point Reyes in March.

3. PSAP (Radiance Research, 3-wavelength): The PSAP is a filter-based method that measures light absorption by particles at a single wavelength: green (565 nm). Particles are collected on a filter and light transmission through the filter is monitored continuously.

4. CNC (TSI 3010): The CNC measures the total number concentration of condensation particles of diameter in the size range of 10 nm to 3 µm.

5. Multiple-Supersaturation CCN Counter (Droplet Measurement Technologies): Measures the total number of CCN at several different supersaturations simultaneously.

The current fiscal year's budget for ARM does not include funding for procurement of the AMF AOS. The basic system that CMDL will deploy at Point Reyes can be viewed as a prototype for the AMF AOS. All of the instruments above, except the RH scanning TSI 3563, were deployed by CMDL and ARM in March 2005 at Point Reyes.

There will be additional aerosol instrumentation deployed on an intermittent basis at Point Reyes by the University of California at Davis (Anthony Wexler, PI). The instrumentation that will be deployed includes the following:

1. Micro-Orifice Uniform-Deposit Impactor (MOUDI): Size fractionates an aerosol sample over the range from 0.056-18 µm by uniformly impacting particle deposits for chemical analysis.

2. Rapid Single Particle Mass Spectrometer (RSMS): RSMS aerodynamically focuses one particle size at a time to the source region of a mass spectrometer and employs a 193 nm excimer laser to desorb and ionize the particle components. The ions are analyzed in a dual time-of-flight mass spectrometer and the spectrum is digitally recorded. Spectra are

only saved if the ion peak in the spectrum is above a threshold. Aerodynamic particle sizes ranging from about 40 to 1300 nm are detected. The deployment of this instrument is subject to funding availability.

3. Aerodynamic Particle Sizer (APS): Measures the aerodynamic diameter and light scattering intensity. It provides the size distribution for particles with an aerodynamic diameter of 0.5 to 20 µm. It also measures light-scattering intensity in the equivalent optical size range of 0.37 to 20 µm.

3.2.1.2 Stage 2 Deployment: July 2005

CMDL's Aerosol Science Program-funded research project will measure the scattering and absorption of particles in two complementary fractions within clouds: those particles that are scavenged by the cloud droplets and those particles that are not scavenged. The hypothesis to be tested is that particle size and chemical composition control both the radiative properties of the particles and their propensity to act as CCN, which leads to systematic differences in the radiative properties of cloud-scavenged particles compared to their unscavenged cousins. A CVI will be used to separate droplets larger than about 5 µm from the surrounding air, and a radial impactor will provide a sample of particles smaller than that size.

The NCAR CVI (Noone et al. 1988; Twohy et al. 1997) is an airborne instrument that can be used for studies of aerosol/cloud interactions, cloud physics, and climate. At the CVI inlet, cloud droplets or ice crystals with an aerodynamic diameter larger than about 5 µm are separated from the interstitial aerosol and impacted into dry nitrogen gas. This separation is possible via a counterflow stream of nitrogen out the CVI tip, which assures that only larger particles (cloud droplets or ice crystals) are sampled. Because droplets or crystals in a sampling volume of about 200 l/min are impacted into a sample stream of approximately 10 l/min, concentrations within the CVI are significantly enhanced. The water vapor and non-volatile residual nuclei remaining after droplet evaporation are sampled downstream of the inlet with selected instruments, which may include a Lyman-alpha or similar hygrometer, a condensation nucleus counter, an optical particle counter, filters for chemical analyses, or user instruments.

The sample stream from the CVI and the stream containing smaller particles will be dried, and identical measurements will be made on both fractions. The analytical instrumentation will include an integrating nephelometer, 3-wavelength PSAP, and CPC.

A hygrometer will be used downstream of the CVI to measure the liquid water content of the sampled droplets.

3.3 Aircraft Measurements During the Marine Stratus, Radiation, Aerosol, and Drizzle and Marine Status Experiment

The ASP G1 and the ONR-funded Twin Otter will participate in this experiment. Coordination between the two aircraft is being discussed at the time of this writing and it is anticipated that several missions will be constructed that use both aircraft.

3.3.1 Aerosol Effects on the Amount of Solar Radiation Absorbed by Clouds

One of the scientific objectives of MASRAD is to quantify the effects of aerosols on the discrepancy between the measured and modeled amount of solar radiation absorbed by marine stratus clouds. The AMF surface measurements of the physical and radiative properties of marine stratus clouds will be combined with in situ, vertical profile aircraft measurements of the physical and radiative properties of the clouds, and aerosols, to fully characterize the atmospheric column in order to rigorously compare models and observations of the solar absorption by marine stratus. The Naval Postgraduate School (NPS) CIRPAS Twin Otter research aircraft is equipped with a comprehensive suite of in situ cloud, aerosol, and radiometric instrumentation that we will use in this study. Of particular interest is a state-of-the-art, stabilized platform for making highly accurate radiometric measurements from the Twin Otter. Developed through collaboration between CIRPAS, the Naval Research Laboratory (NRL), and Sandia National Laboratories, through an ONR Small Business Innovation Research (SBIR) grant with Sonoma Design Group, the stabilized platform keeps the radiometers level as the airplane pitches and rolls. This eliminates one of the biggest sources of error and the most time-consuming data reduction step in airborne radiometer measurements.

Deploying the AMF to Point Reyes and combining its surface measurement capability with the in situ CIRPAS Twin Otter aircraft measurements affords us the opportunity to address all of the flaws (see above) of previous studies: Persistent, nearly plane-parallel, marine stratus are a ubiquitous feature of the central California coast in the summer affording numerous case study opportunities. The combined AMF and Twin Otter measurements will characterize the cloud and aerosol throughout the atmospheric column providing the necessary input for accurate and complete radiative transfer calculations. The ocean has a low, constant surface albedo minimizing that complicating factor. Finally, the Twin Otter solar radiometer measurements above and below the cloud from the newly developed stabilized platform will provide solar absorption data of unprecedented accuracy.

The intended scientific result from this scientific objective is therefore a complete and robust characterization of the microphysical and radiative properties of the clouds and aerosols throughout the atmospheric column in order to fully assess the discrepancy between measurements and models of the amount of solar absorption by marine stratus clouds. This characterization may lead to an improved understanding of the diurnal cycle of marine stratus and its dependency on cloud microphysics and aerosols.

3.3.2 Aircraft Operations Plans

G1 flights will be planned on the basis of forecast or prevailing meteorological conditions, specifically the presence of cloud layers over 100 nautical miles of the near coastal Pacific Ocean. All flights will be conducted during daylight hours. Under appropriate meteorological conditions, flights over the ARM site located at Point Reyes National Seashore will be emphasized. A map showing the proposed track of the aircraft over this facility is given in Figure 6. This track may be flown from 1 to 4 hr depending on conditions. As possible, flights will include below-cloud (provided cloud-base is > 400 ft msl), in-cloud, and above-cloud passes. Depending on prevailing conditions, these passes may be repeated multiple times. Flights further away from the coast (up to 200 nm) are also planned, both in conjunction with

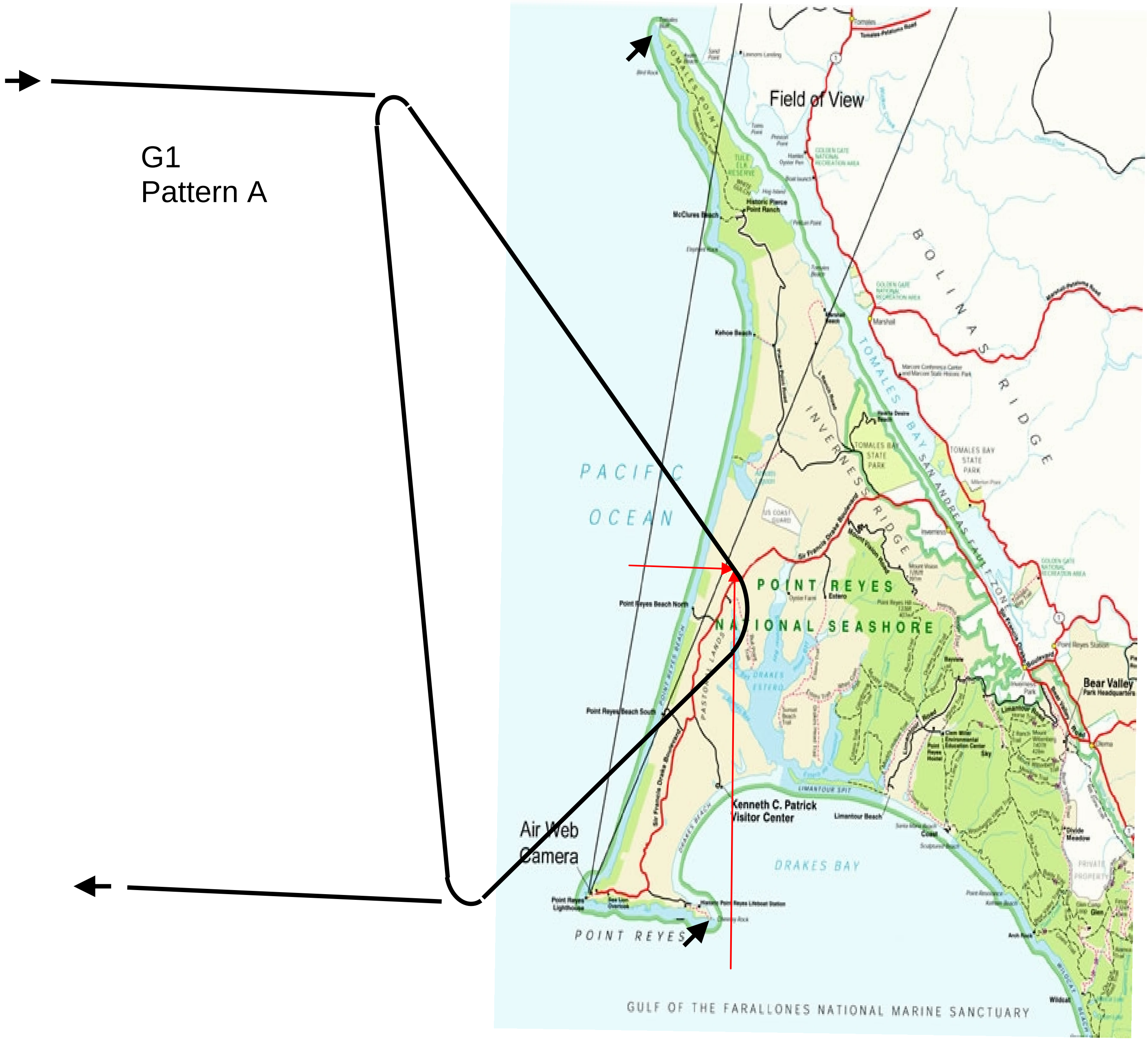

Figure 6. Flight pattern of the G1 aircraft.

flights over Point Reyes and independently. Such flights will be conducted in uncontrolled airspace, or in Military Operations Areas (MOAs). Flight altitudes will range approximately between 300 ft above the ocean surface to no higher than 10,000 ft. It is anticipated that these flights will be made below-cloud, at multiple altitudes in-cloud, and just above cloud top.

Instruments that are intended for deployment on the G1 during the study are listed in Table 2. Consistent with the focus of this experiment on cloud/aerosol interactions, the only trace gas instrument that will be flown during the study is an O_3 detector.

The G1 fights will be conducted in coordination with the Twin Otter that has a similar complement of instrumentation except that the Twin Otter will also carry a sophisticated complement of radiometers to measure up- and down- welling radiation fields.

An example of a joint flight might be to fly both aircraft over the Point Reyes site. The G1 would sample below and in cloud, and the Twin Otter would measure up- and downwelling radiation above clouds. Combination of the surface data with the data from the two aircraft would allow a complete closure experiment, from aerosol and CCN properties to cloud radiation fields.

3.4 Single-Column Modeling

A number of modeling groups have expressed interest in conducting single-column climate model runs for the MASRAD experiment period, particularly the July aircraft-augmented observation period. Efforts will be made to supply relevant forcing data for the period and to work with these groups to evaluate the diagnosed clouds. These efforts should result in evaluation studies that are similar to those from the 2000 Cloud Intensive Operational Period that were recently published by the ARM Cloud Parameterization and Modeling Group.

Table 2. Instruments to be flown on the G1 during MASE.

Measurement	Instrument	PI
Cloud microphysics	DMT CAPS Probe	BNL- G. Senum
Aerosol microphysics	PCASP	PNNL- J. Hubbe
Aerosol scattering	3-wavelength integrating nephelometer operating at a controlled (low?) relative humidity	PNNL- J. Hubbe
Aerosol microphysics	DMA system	BNL-J. Wang
Aerosol Absorption	Aethelometer	PNNL- J. Hubbe
Aerosol number concentration	CN counter	PNNL- J. Hubbe
CCN Spectra	DRI CCN Spectrometer	DRI- J. Hudson
CCN	2X DMT CCN Counter	BNL- J. Wang
Cloud liquid water content	Gerber probe	PNL- J. Hubbe
Aerosol composition	Particle into liquid sampler (PILS)	BNL- Y-N. Lee
Aerosol Composition	Aerodyne AMS	PNNL-M. Alexander
O_3	UV absorbtion	BNL-Springston
State parameters	Standard G1 instruments	PNNL- J. Hubbe
Winds and turbulence	5-port gust prob	PNNL- J. Hubbe

4. External Data and Resources

4.1 Aircraft Data

Aircraft data collected during MASRAD by the G1 and CIRPAS Twin Otter will be made available to the general community via the ARM/ASP External Data Center. These data will be released to the public after they have been processed and subject to quality control.

4.2 Satellite Analysis

Several groups have expressed interest in participating in MASRAD by analyzing satellite products. The NASA Langley group (P. Minnis, PI) is analyzing Geostationary Operational Environmental Satellite data to develop a climatologic summary of clouds in the Point Reyes region. In parallel, MODIS data for the region are being analyzed by the BNL Cloud Properties Group (A. Vogelmann and M. Jensen, PIs). Products being produced from MODIS data include surveys of the cloud LWP, cloud optical thickness, and cloud macrophysical and microphysical structure in the vicinity of Point Reyes. Preliminary analysis of MODIS data suggest that the clouds that are present over the location of the AT+T site are not structurally different from those found offshore.

4.3 Ocean Properties

The Bodega Bay Marine Laboratory, operated by the University of California at Davis, is located only 15 miles from the Point Reyes research site. This facility is an active ocean laboratory that collects oceanographic data from the ocean surrounding Point Reyes and operates a network of coastal radars (CODARs) in the area. An example of the current mapping from Bodega Bay is shown in Figure 7.

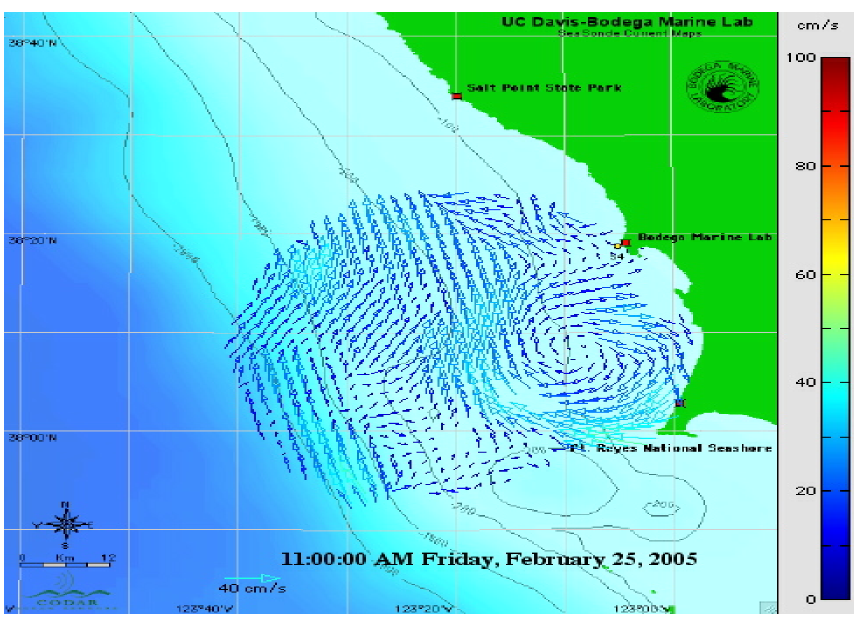

Figure 7. Data from the CODAR network operated by the Bodega Bay Marine Laboratory.

In addition to current mapping, Bodega Bay also operates a buoy that records the sea surface temperature and seawater characteristics. An example of data from this buoy is shown in Figure 8.

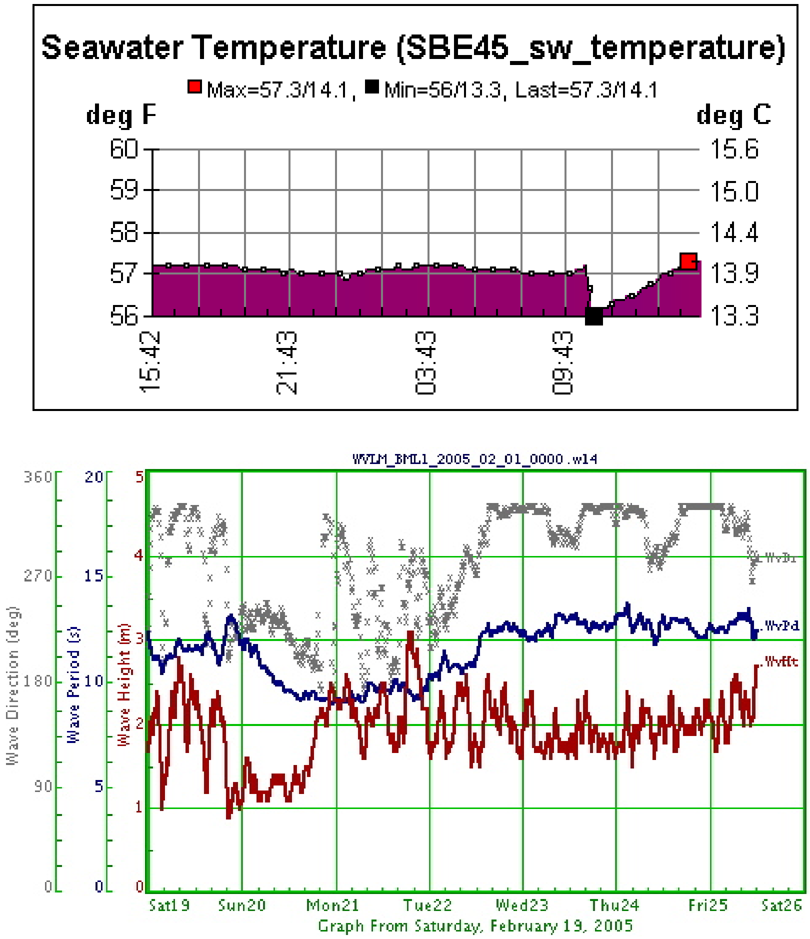

Figure 8. Seawater temperature and wave characteristics from Bodega Bay Marine Laboratory.

Ocean data collected by the Bodega Bay Marine Laboratory are accessible for download to the general public.

4.4 Numerical Weather Prediction Products

Arrangements have been made with the ARM External Data Center to archive Model Output Location Time Series (MOLTS) data from the Point Reyes vicinity. In addition to MOLTS, efforts will be made to archive Rapid Update Cycle and the European Centre for Medium-Range Forecasts analyses, especially in the period from May through September. The MOLTS box for Point Reyes will be 122W to 124W and 37N to 39N and is shown in Figure 9.

Figure 9. MOLTS coverage area for Point Reyes.

4.5 Data Processing Plan

The AMF site scientist will support the Point Reyes experiment by analyzing data from its surface-based remote sensors and aircraft. The baseline AMF data will process using standard ARM algorithms and protocols, but they will be complemented with state-of-the-art algorithms for analyzing the spectral signals from 94-GHz cloud radars. These algorithms produce highly constrained, continuous estimates of the cloud droplet size distribution, drizzle droplet size distributions, and in-cloud turbulence profiles. We determine optimal radar configurations for cloud and aerosol studies in the Point Reyes area based on past experience. These standard AMF products (cloud location and thermodynamic state characterizations) will be employed to forge links between the observed thermodynamic profile and cloud macroscale structure. We are particularly interested in the vertical structure of mixing within the boundary layer, which is often modulated by the in-cloud net heating rate profile. We expect to combine these data so as to address the variability of cloud fraction as a function of height and cloud coverage (the vertical integral of cloud fractional coverage as a function of height). Several ARM value-added procedures (VAPs) should be applied to the Point Reyes data. These procedures and the products that result are listed in Table 3. A comprehensive list of AMF datastreams and additional VAPs is found in Appendix A.

Table 3. VAPs that will be applied to the Point Reyes data.

Value-Added Procedure	Geophysical Variable or Quality Control Function
Active Remote Sensing of Cloud Location (ARSCL)	Best estimate of cloud location and radar reflectivity
Merged sounding	Best estimate of thermodynamic and wind profiles
Microbase	Baseline estimate of cloud microphysical structure
BBHRP	Radiative closure and heating rate profile analysis

5. Contact

M.A. Miller, miller@bnl.gov, (631) 344-2958

6. References

Ackerman, AS, OB Toon, DE Stevens, AJ Heymsfield, V Ramanathan, and EJ Welton. 2000. "Reduction of tropical cloudiness by soot." *Science* 288(5468):1042-1047.

Ackerman, AS, MP Kirkpatrick, DE Stevens, and OB Toon. 2004. "The impact of humidity above stratiform clouds on the indirect aerosol climate forcing." *Nature* 432, 1014-1017.

Ackerman, TP, DM Flynn, and RT Marchand. 2003. "Quantifying the magnitude of anomalous solar absorption." *Journal of Geophysical Research* 108(D9):4273, doi:10.1029/2002JD002674.

Albrecht, BA. 1989. "Aerosols, cloud microphysics, and fractional cloudiness." *Science* 245:1227-1230.

Albrecht, BA, MP Jensen, and WJ Syrett. 1995. "Marine Boundary Layer Structure and Fractional Cloudiness." *Journal of Geophysical Research* 100:14209-14222.

Asano, S, A Uchiyama, Y Mano, M Murakami, and Y Takayama. 2000. "No evidence for solar absorption anomaly by marine water clouds through collocated aircraft radiation measurements." *Journal of Geophysical Research* 105:14,761-14,775.

Babb, D, J Verlinde, and BA Albrecht. 1999. "Retrieval of cloud microphysical parameters from 94-GHz radar doppler power spectra." *Journal of Atmospheric and Oceanic Technology* 16:489-503.

Bretherton CS, T Uttal, CW Fairall, SE Yuter, RA Weller, D Baumgardner, K Comstock, R Wood, GB Raga. 2004. "The EPIC 2001 stratocumulus study." *Bulletin of American Meteorology Society* 85(7):967-977.

Cess RD, MH Zhang, P Minnis, L Corsetti, EG Dutton, BW Forgan, DP Garber, WL Gates, JJ Hack, EF Harrison, X Jing, JT Kiehl, CN Long, JJ Morcrette, GL Potter, V Ramanathan, B Subasilar, CH Whitlock, DF Young, Y Zhou. 1995. "Absorption of solar radiation by clouds: Observations versus models." *Science* 267(5197), 496-499.

Clothiaux, EE, MA Miller, BA Albrecht, TA Ackerman, J Verlinde, DM Babb, RM Peters, and WJ Syrett. 1995. "An evaluation of a 94-GHz radar for remote sensing of cloud properties." *Journal of Atmospheric and Oceanic Technology* 12:201-229.

Clothiaux, EE, KP Moran, BE Martiner, TP Ackerman, GG Mace, T Uttal, JH Mather, K Widener, MA Miller, and DJ Rodriguez. 1999. "The atmospheric radiation measurement program cloud radars, part 1: operational modes." *Journal of Atmospheric and Oceanic Technology* 16(7):819–827.

Clothiaux, EE, TP Ackerman, GG Mace, KP Moran, RT Marchand, MA Miller, and BE Martner. 1998. “Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites.” *Journal of Applied Meteorology* 39(5):645–665.

Feingold G, Cotton WR, Kreidenweis SM, and Davis JT. 1999. “The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties.” *Journal of the Atmospheric Science* 56(24): 4100-4117.

Feingold, G, WL Eberhard, DE Veron, and M Previdi. 2003 . “First measurements of the Twomey indirect effect using ground-based remote sensors.” *Geophysical Research Letters* 30(6):1287.

Feingold, G. 2003. “Modeling of the first indirect effect: analysis of measurement requirements.” *Geophysical Research Letters* 30, No.19.

Firda, JM, SM Sekelsky, and RE McIntosh. 1999. “Application of Dual-Frequency Millimeter Wave Doppler Spectra for the Retrieval of Drop Size Distributions and Vertical Air Motion in Rain.” *Journal of Atmospheric and Oceanic Technology* 16, 216-236.

Frisch, AS, CW Fairall and JB Snider. 1995. “Measurement of stratus cloud and drizzle parameters in ASTEX with a K_{α} –band doppler radar and microwave radiometer.” *Journal of the Atmospheric Sciences* 52(16):2788-2799.

Gossard, EE. 1988. “Measuring drop size distributions in cloud with a clear-air sensing Doppler radar.” *Journal of Atmospheric and Oceanic Technology* 5:640-649.

Gossard, EE. 1994. “Measurements of cloud droplet size spectra by doppler radar.” *Journal of Atmospheric and Oceanic Technology* 11:712-726.

Gossard, EE, JB Snider, EE Clothiaux, B Martner, JS Gibson, RA Kropfli, and AS Frisch. 1997. “The potential of 8-mm radars for remotely sensing cloud drop-size distributions.” *Journal of Atmospheric and Oceanic Technology* 13:76-87.

Francis, PN, JP Taylor, P Hignett, and A Slingo. 1997. “On the question of enhanced absorption of solar radiation by clouds.” *Quarterly Journal of the Royal Meteorological Society* 123:419-434.

Hansen, J, M Sato, and R Ruedy. 1997. “Radiative forcing and climate response.” *Journal of Geophysical Research* 102(D6):6831-6864.

Intergovernmental Panel on Climate Change (IPCC). 2001. “Climate Change 2001: The Scientific Basis.” Edited by JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, and D Xiaosu. Cambridge University Press, New York, pp. 944.

Kerr, RA. 2003. “Making Clouds Darker Sharpens Cloudy Climate Models.” *Science* 300:1859-1860.

Kim, BG, SE Schwartz, MA Miller, and Q Min. 2003. Effective radius of cloud droplets by ground-based remote sensing: relationship to aerosol." *Journal of Geophysical Research* 108(D23):4740-4758.

Kollias, P, BA Albrecht, R Lhermitte, and A Savtchenko. 2001. "Radar Observations of Updrafts, Downdrafts, and Turbulence in Fair Weather Cumuli." *Journal of Atmospheric Science* 58:750-1766.

Kollias, P, BA Albrecht, and FD Marks, Jr. 2002. "Why Mie? Accurate observations of vertical air velocities and rain drops using a cloud radar." *Bulletin of the American Meteorological Society* 83:1471-1483.

Kollias, P, EE Clothiaux, BA Albrecht, MA Miller, KP Moran, and KL Johnson. 2004. "The atmospheric radiation measurement program cloud profiling radars: an evaluation of signal processing and sampling strategies." *Journal of Atmospheric and Oceanic Technology* (Submitted).

Liu, Y, and PH Daum. 2002. "Indirect warming effect from dispersion forcing." *Nature* 419:580-581.

Lhermitte, R. 1987. "A 94 GHz Doppler radar for clouds observations." *Journal of Atmospheric and Oceanic Technology* 4:36-48.

Lhermitte, R. 1988. "Observations of rain at vertical incidence with a 94 GHz doppler radar: an insight of Mie scattering." *Geophysical Research Letters* 15:1125-1128.

Li, Z, TP Ackerman, W Wiscombe, and GL Stephens. 2003. "Have Clouds Darkened Since 1995." *Science* 302, 1150-1151.

McGraw R and Y Liu. 2003. "Kinetic potential and barrier crossing: a model for warm cloud drizzle formation." *Physical Review Letters* 90(1):018501.

Miller, MA, MP Jensen, and EE Clothiaux. 1998. "Diurnal cloud and thermodynamic variations in the stratocumulus transition regime: a case study using in situ and remote sensors." *Journal of Atmospheric Science* 55:2294-2310.

Miller, MA, J Verlinde, C Gilbert, G Lehenbauer, J Tongue, and EE Clothiaux. 1998. "Detection of non-precipitating clouds with the WSR-88D: a theoretical and experimental survey of capabilities and limitations." *Weather and Forecasting* 13:1046-1062.

Miller, MA, and BA Albrecht. 1995. "Surface-based observations of mesoscale cumulus-stratocumulus interaction during ASTEX." *Journal of Atmospheric Science* 16:2809-2826.

Mlawer, EJ, TR Shippert, CN Long, MA Miller, and coauthors. 2003. "Status of the broadband heating rate profile value-added product." In *Proceedings of the Fourteenth Atmospheric Radiation Measurement Program Science Team Meeting*, March 2004, Albuquerque, New Mexico.

Nicholls, S. 1984. "The dynamics of stratocumulus: aircraft observations and comparisons with a mixed-layer model." *Quarterly Journal of the Royal Meteorological Society* 110:783-820.

Noone, KJ, JA Ogren, J Heintzenberg, RJ Charlson, and DS Covert. 1988. "Design and calibration of a counterflow virtual impactor for sampling of atmospheric fog and cloud droplets." *Aerosol Science and Technology* 8j:235-244.

O'Hirok, W, and C Gautier. 2003. "Absorption of shortwave radiation in a cloudy atmosphere: Observed and theoretical estimates during the second Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE)." *Journal of Geophysical Research* 108(D14):4412.

Pilewskie, P, and FPJ Valero. 1995. "Direct observations of excess solar absorption by clouds." *Science* 267:1626-1629.

Platnick, S, and S Twomey. 1994. "Determining the susceptibility of cloud albedo to changes in droplet concentration with the advanced very high-resolution radiometer." *Journal of Applied Meteorology* 33:334-347.

Ramanthan, V, B Subasilar, GJ Zhang, W Conant, RD Cess, JT Kiehl, H Grassl, and L Shi. 1995. "Warm pool heat budget and shortwave cloud forcing: A missing physics?" *Science* 267:499-503.

Rogers, DP, X Yang, PM Norris, DW Johnson, GM Martin, CA Friehe, and BW Berger. 1995. "Diurnal Evolution of the Cloud-Topped Marine Boundary Layer. Part I: Nocturnal Stratocumulus Development." *Journal of Atmospheric Science* 52(16):2953–2966.

Sharon, T, B Albrecht, H Jonsson, P Minnis, M Khaiyer, T Van Reken, J Seinfeld, and R Flagan. 2004. "Aerosol and Cloud Microphysical Characteristics of Rifts and Gradients in Maritime Stratocumulus Clouds." *Monthly Weather Review* (Submitted)

Smith, NT. 2000. "Suppression of marine stratus clouds due to reduced cloud condensation nuclei." M.S. Thesis, Naval Postgraduate School, Monterey, California.

Stephens, GL, and SC Tsay. 1990. "On the cloud absorption anomaly." *Quarterly Journal of the Royal Meteorological Society* 116:671-704.

Twohy, CH, AJ Schanot, and WA Cooper. 1997. "Measurement of condensed water content in liquid and ice clouds using an airborne counterflow virtual impactor." *Journal of Atmospheric and Oceanic Technology* 14:197-202.

Twomey, S. 1977. "The influence of pollution on the short-wave albedo of clouds." *Journal of Atmospheric Science* 34:1149-1152.

Valero, FPJ, A Bucholtz, BC Bush, SK Pope, WD Collins, P Flatau, AW Strawa, and WJY Gore. 1997. "Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE): Experimental and data details." *Journal of Geophysical Research* 102:29,929-29,937.

Valero, FPJ, SK Pope, BC Bush, Q Nguyen, D Marsden, RD Cess, AS Simpson-Leitner, A Bucholtz, and PM Udelhofen. 2003. "The absorption of solar radiation by the clear and cloudy atmosphere during the Atmospheric Radiation Measurements Enhanced Shortwave Experiments (ARESE) I and II: Observations and models." *Journal of Geophysical Research* 108(D1):4016.

Wood, R, CS Bretherton, and DL Hartmann. 2002. "Diurnal cycle of liquid water path over the subtropical and tropical oceans." *Geophysical Research Letters* 29, 2092.

Zender, CS, B Bush, SK Pope, A Bucholtz, WD Collins, JT Kiehl, FPJ Valero, and J Vitko. 1997. "Atmospheric absorption during the Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE)." *Journal of Geophyiscal Research* 102:29,901-29,915.

Appendix A

Estimating the Impacts of the Inland Atmospheric Radiation Measurement Mobile Facility Site on the Marine Cloud Structure

Appendix A

Estimating the Impacts of the Inland Atmospheric Radiation Measurement Mobile Facility Site on the Marine Cloud Structure

The mixing ratio at the surface in the marine boundary layer must be known to compute the lifting condensation level (LCL), a critical thermodynamic variable that determines the cloud base and mixing structure. Time is required for a surface parcel to reach the LCL, so the clouds that lie immediately overhead at a specific site are likely to have been formed some distance upwind of the site. If we assume that the vertical velocity in a typical well-mixed marine boundary layer is on the order of 1 ms^{-1}, the horizontal wind speed is 10 ms^{-1}, and the LCL is 200 m, the surface parcel will cover a horizontal distance of 1.2 miles before it reaches cloud base. Therefore, any modifications to surface parcels made by the land surface as they come ashore would not impact the clouds above the site, though they could impact the structure of the subcloud layer.

Appendix B

Atmospheric Radiation Measurement Mobile Facility Datastreams and Value-Added Procedures

Appendix B

Atmospheric Radiation Measurement Mobile Facility Datastreams and Value-Added Procedures

Files to be ingested by the DMF

instrument class	**datastream name**
aeri	rldaeriM1.00
aeri	rldaerirawM1.00
aeri	rldaerich1M1.b1
aeri	rldaerich2M1.b1
aeri	rldaeriengineerM1.b1
aeri	rldaerisummaryM1.b1
gndrad	rldgndradM1.00
gndrad	rldgndrad20sM1.a0
gndrad	rldgndrad60sM1.b1
mfrsr	rldmfrsrM1.00
mfrsr	rldmfrsrM1.a0
mfrsr	rldmfrsrM1.b1
mpl	rldmplM1.00
mpl	rldmplM1.a1
mwr	rldmwrM1.00
mwr	rldmwrlosM1.b1
mwr	rldmwrtipM1.a1
mwrp	rldmwrpM1.00
mwrp	rldmwrprawM1.00
mwrp	rldmwrpM1.b1
skyrad	rldskyradM1.00
skyrad	rldskyrad20sM1.a0
skyrad	rldskyrad60sM1.b1
smet	rldsmetM1.00
smet	rldsmet60sM1.b1
sonde	rldsondeM1.00
sonde	rldsonderawM1.00
sonde	rldsondewnpnM1.b1
tsi	rldtsiM1.00
tsi	rldtsicldmaskM1.a1
tsi	rldtsiskycoverM1.b1
tsi	rldtsiskyimageM1.a1
twrcam	**rldtwrcam3mM1.a1**
vceil25k	rldvceil25kM1.00
vceil25k	rldvceil25kM1.b1

instrument class	**datastream name**
irt	**rldirtM1.00**
irt	rldirtM1.b1
irt	rldirt2sM1.b1
ecor	rld30ecorM1.b1
ecor	rldecorM1.00
"Routine Vaps" created at DMF	rldmfrsrlangleyM1.c1
	rldmfrsrlangplotM1.c1
	rldmplnor1campM1.c1
	rldlssondeM1.c1
	rld1swfanalskyrad1long M1.c1
	rldtsicldmaskM1.a1
	rldtsiskycoverM1.b1
	rldtsiskyimageM1.a1
	rldaeriprofM1.c1
	rldaerilblcloudsM1.c1
"PI", Vaps	These are at a developmental stage.
Dave Turner	rldaerilbldiffM1.c1
	rldaerilbldifflsM1.c1
	rldaerilblch1M1.c1
	rldaerllblch2M1.c1
	rldaerilblch1lsM1.c1
	rldaerilblch2lsM1.c1
	rldqmeaerilblM1.c1
	rldqmeaerilbllsM1.c1
	rldqmeaerimeansM1.c1
	mpl cloud optical thickness
	rldqmemwrcolM1.c1
	rld5mwravgM1.c1
	rldqmemwrprofM1.c1
	rldpwvlwpliljclouM1.c1
Conner Flynn	rldmplpsM1.a0