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Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) Science Plan

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Executive Summary

The Southern Ocean (SO) is the stormiest place on earth, buffeted by winds and waves that circle the ice of Antarctica, and sheathed in clouds that mantle a dynamic ocean with rich ecosystems. The remote and usually pristine environment, typically removed from anthropogenic and natural continental aerosol sources, makes the SO unique for examining cloud-aerosol interactions for liquid and ice clouds, and the role of primary and secondary marine biogenic aerosols and sea salt. There is strong seasonality in aerosol sources and sinks over the SO that are poorly understood. Weather and climate models are challenged by uncertainties and biases in the simulation of SO clouds, aerosols, and air-sea exchanges that trace to poor physical understanding of these processes, and by cloud feedbacks (e.g., phase changes) in response to warming. Models almost universally underestimate sunlight reflected by near surface cloud, particularly in the cold sector of cyclonic storm systems, and this may be due to difficulties in representing pervasive supercooled and mixed-phase boundary-layer (BL) clouds.

Motivated by these issues, a large international multi-agency effort called the Southern Ocean Clouds Radiation Aerosol Transport Experimental Study (SOCRATES) has been proposed to improve understanding of clouds, aerosols, air-sea exchanges and their interactions over the SO. Coincident with SOCRATES, the Measurements of Aerosols, Radiation and CloUds over the Southern Ocean (MARCUS) experiment will be conducted where the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility's second Mobile Facility (AMF2) will be installed on the Australian Antarctic supply vessel *Aurora Australis* (AA) as it makes routine transits between Hobart, Australia, and the Antarctic, visiting the Australian Antarctic stations Mawson, Davis, and Casey, as well as Macquarie Island. During MARCUS, the AMF2 will acquire comprehensive observations of aerosols (including cloud condensation nuclei [CCN] and ice nucleating particles [INP]) in the BL, vertical distributions of macrophysical and microphysical properties of liquid and mixed-phase clouds, and downwelling radiative fluxes over the SO during a 7-month period (September 2017 to April 2018) centered upon the Austral summer. The MARCUS observations will be self-standing and unique in that they will capture the variability in aerosol and cloud properties across the SO from spring to autumn, especially in cold waters at latitudes poleward of 55˚S, where supercooled and mixed-phase BL clouds in the cold sector of cyclones are frequent and where past and planned SO observations are most sparse.

The data to be obtained during MARCUS under a range of synoptic settings will document how temperature-dependent distributions of cloud properties and frequency of supercooled water vary with concentrations of CCN and INPs, synoptic regime, latitude and season (spring, summer, autumn). MARCUS data will also help understand the sources, sinks, and variability of CCN and INPs, the increased bias of absorbed shortwave radiation in summer in models, and conditions conducive to extensive supercooled water. Specific hypotheses will be tested under four themes to understand 1) the synoptically varying vertical structure of SO BL clouds and aerosols, 2) sources and sinks of SO CCN and INPs, including the role of local biogenic sources over spring, summer, and autumn, 3) mechanisms controlling supercooled liquid and mixed-phase clouds, and 4) advances in retrievals of clouds, precipitation, and aerosols over the SO. Parameterization development and testing needs are integrated in MARCUS' design and in the design of the entire multi-agency SOCRATES field study so that systematic confrontation and improvement of leading climate models with data will be possible.

Acronyms and Abbreviations

AA	Aurora Australis
AAD	Australian Antarctic Division
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACE	Aerosol Characterization Experiment
ACRE	Australian Cloud and Radiation Experiment
AMF2	second ARM Mobile Facility
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement Climate Research Facility
AWARE	ARM West Antarctic Radiation Experiment
BAF	bulk aerodynamic fluxes
BAS	British Antarctic Survey
BER	Biological and Environmental Research
C	celsius
CCN	cloud condensation nuclei
CESD	Climate and Environmental Sciences Division
CMIP	Coupled Model Intercomparison Project
CPC	condensation particle counter
CSPOT	Cimel sun photometer
DMS	dimethyl sulfide
DOE	U.S. Department of Energy
FTP	file transfer protocol
GCM	general circulation model
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water Cycle Experiment
GHz	gigahertz
GPCI	GCSS Pacific Cross-section Intercomparison
G-5	Gulfstream 6550
HTDMA	Hygroscopic Tandem Differential Mobility Analyzer
HIAPER	High Performance Instrumented Aircraft Platform for Environmental Research
HIPPO	HIAPER Pole-to-Pole Observations
HSRL	High Spectral Resolution Lidar
ICARTT	International Consortium for Atmospheric Research on Transport and Transformation file format standard
INP	ice nucleating particles
KAZR	Ka-band Zenith Radar
MAERI	Marine Atmospheric Emitted Radiance Interferometer
MAGIC	Marine ARM GCPI Investigation of Clouds
MARCUS	Measurements of Aerosol, Radiation and Clouds over the Southern Ocean
MICRE	Macquarie Island Cloud and Radiation Experiment

MPL	micropulse lidar
MWR	microwave radiometer
Nd	cloud droplet number concentration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NH	Northern Hemisphere
PRP2	portable radiation measurement package
PSAP	particle soot absorption photometer
R/V	research vessel
RWP	radar wind profiler
SEASCAPE	Southern Ocean Aerosol Clouds and Ice Processes Experiment
SH	Southern Hemisphere
SO	Southern Ocean
SOCEX	Southern Ocean Cloud Experiment
SOCRATES	Southern Ocean Cloud Radiation Aerosol Transport Experimental Study
SONDE	Balloon-Borne Sounding System
SPN	sun pyranometer
SWACR	Marine 95-GHz Cloud Radar
TSI	total sky imager
UAS	Uninhabited Aerospace Systems
VCEIL	Vaisala ceilometer
X-SACR	X-band Scanning Cloud Radar

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1.0 Introduction

Emerging from the DOE-sponsored 2014 workshop on Southern Ocean Clouds, Aerosols, Radiation, and the Air-Sea Interface, the SOCRATES white paper (Marchand et al. 2014)[1] describes the motivation, scientific themes, and testable hypotheses that have led to the need for a new multi-agency and international measurement campaign to study clouds, aerosols, and the air-sea interface over the Southern Ocean (SO). In this Section, the motivation for MARCUS is reviewed in the context of prior modeling and observational studies over the SO. The deployment site, namely the *Aurora Australis* (AA), is described in Section 2. Specific hypotheses to be tested using MARCUS data are listed in the discussion of science goals in Section 3. The measurement requirements are listed in Section 4, and the needed instruments are discussed in Section 5. Logistical aspects are described in Section 6, and the relevance to the DOE mission is elucidated in Section 7.

The SO influences the atmospheric and oceanic circulation of the entire Southern Hemisphere (SH) and beyond. Its unique importance as an object of scientific study derives from the remarkable differences between the Northern Hemisphere (NH) and SH in geography and human settlement patterns. The ice continent of Antarctica and the unbroken circumpolar expanse of the SO promote strong latitudinal gradients in atmospheric and ocean properties, affect ocean heat and carbon uptake, and generate extra-tropical cyclones that spawn extensive and diverse clouds, which affect both the local and global energy balance and climate.

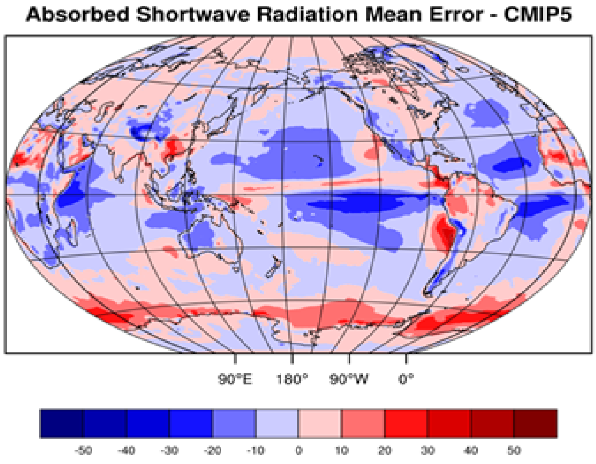

Figure 1. CMIP5 model clouds do not reflect enough sunlight. Ensemble mean error [W m-2] for CMIP5 models in shortwave radiation absorbed by the Earth System. Red values indicate too much shortwave radiation absorbed. There is also a larger intermodal spread over the SO than over other latitudes (not shown).

Clouds over the SO differ from those over the NH because of its remoteness from anthropogenic and natural continental aerosol sources. This makes the SO a unique venue to improve our understanding of cloud-precipitation-aerosol interactions, and the role of marine biogenic aerosols of primary and secondary origin and sea salt. Almost all model cloud parameterizations have been developed using NH data. It has been shown that clouds over the SO are poorly represented in global climate model (GCM)

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[1] The SOCRATES whitepaper is available at http://www.atmos.washington.edu/socrates/SOCRATES_white_paper_Final_Sep29_2014.pdf

simulations (Trenberth and Fasullo 2010) and even present-day reanalysis products (Naud et al. 2014). The CMIP5 ensemble has a mean error in annual mean absorbed shortwave radiation (Figure 1) between 55°S and the Antarctic coast, especially during Austral summer, inducing year-round warm SST biases. This bias is mainly due to too little cloud, though sea ice may also contribute (Ceppi et al. 2014). The large radiation biases interact with the location of the SH jet in climate models (Ceppi et al. 2012, 2014), influence the tropical circulation (Hwang and Frierson, 2013) and may correlate with climate sensitivity (Trenberth and Fasullo 2010). Biases may also impact Antarctic sea ice, and sea ice trends, which are opposite in models and observations (Flato et al. 2013).

Current understanding of SO cloud and aerosol processes is largely based upon data gathered from a limited number of data sets (Table 1) and model studies. A long record of surface aerosol measurements from Cape Grim (41° S, 145° E) led to an understanding of the strong seasonality in CCN concentrations with greater ocean biogeochemical activity during summer (Ayers and Gras 1991) being the likely cause. Seasonal cycles in aerosol optical depth and aerosol composition (Sciare et al. 2009) have also been observed, and the Southern Ocean Cloud Experiment (SOCEX) aircraft campaigns, with two phases, summer (July 1993, Boers et al. 1998) and winter (January-February 1995, Boers et al. 1996), measured N_d a factor of 2-3 higher in summer than winter. SOCEX was conducted at latitudes 40-43°S and did not include comprehensive aerosol composition measurements. While natural aerosols play a key role (McCoy et al. 2015a) and it has been hypothesized that the summertime peak is due to marine biogenic sources, the pathway remains uncertain (Quinn and Bates 2011). In addition, concentrations of INPs have been observed to be very low in this pristine region (Bigg 1973) remote from dust sources (DeMott et al. 2015), although data have not been collected in more than 40 years. This may explain the prevalence of supercooled water clouds over the SO (Kanitz et al. 2011) and it enhances the potential importance of marine aerosol as INPs (Burrows et al. 2013) and the role of secondary ice production processes. McCoy et al. (2015b) noted that GCMs simulate a distressingly broad range of sensitivities of liquid versus ice partitioning to temperature in SO clouds, and that this affects the SO cloud albedo response to a warmer climate. This underlines the need for in situ and remote-sensing observational constraints of this partitioning, which is challenging to infer from satellite and surface measurements alone.

Table 1. Past intensive observational studies focused on clouds and aerosols over the Southern Ocean.

Field Experiment	**Time**	**Range**	**Primary Science**
SOCEX I & II	Jul 1993; Jan 1995	40° -43° S	Cloud microphysics characterization and seasonal bounds
ACE 1	Nov/Dec 1995	40° -55° S	Atmospheric chemistry; limited cloud microphysics observations
HIPPO	5 flights 2009-11	43° -67° S	Global atmospheric chemistry; secondary cloud microphysics observations

The first Aerosol Characterization Experiment (ACE-1, Bates et al. 1998a) in 1995 involved two ground sites (Macquarie Island and Cape Grim), two research vessels, and the NSF/NCAR C-130 aircraft. It measured chemical and physical processes controlling atmospheric aerosol relevant to radiative forcing and climate. ACE-1 documented the role of dimethyl sulfide (DMS)-derived sulfate aerosols over the SO including the potential for new particle formation and growth (Bates et al. 1998b), vertical aerosol structure including subsidence of near-cloud-nucleated aerosols from the free troposphere (Clarke et al. 1998b, Weber et al. 1998), and the importance of sea-spray aerosol (Bates et al. 1998a). ACE-1 sampled north of 54°S and largely away from clouds. More recently, the HIAPER Pole-to-Pole Observations (HIPPO) using the NSF/NCAR G-V aircraft (Wofsy et al. 2011; Chubb et al. 2016) provided the only in situ data set on clouds and aerosols south of Macquarie Island (54°S), with 4 transects down to 67°S encountering some supercooled and BL clouds (Chubb et al. 2013). HIPPO sampled the full tropospheric depth and concentrated on atmospheric chemistry, but did not include airborne remote sensing and provided only limited profiles. Ground-based atmospheric chemistry observations are ongoing at Lauder and Baring Head (New Zealand) and Cape Grim (Australia). Although clouds are not the focus of the upcoming 2016 O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) study, some cloud data will be collected with the facility instruments on the NSF/NCAR G-V as it flies through BL clouds while sampling the air-sea exchange of O_2 and CO_2 over the SO from Punta Arenas, Chile.

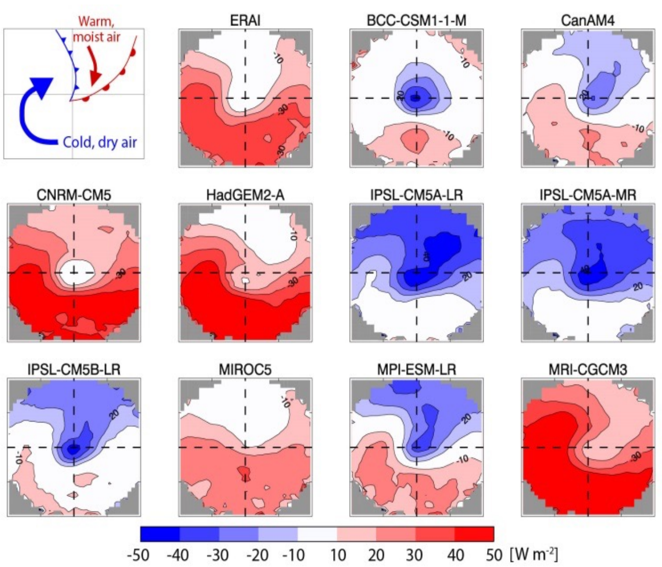

Figure 2. Cyclone compositing indicates consistent patterns of insufficient reflected shortwave (red) in the cold, dry regions of the cyclones. The figure demonstrates a bias in absorbed shortwave radiation for AMIP models from Bodas Salcedo et al. (2013).

Recent analysis of model simulations suggests several possible reasons for model radiative errors in the SO. A major contributor is a lack of clouds in the cold sectors of cyclones (Figure 2). Errors in the representation of mid-topped clouds in the warm conveyor belt of shallow cyclones near the Antarctic continent have also been documented (Mason et al. 2014). The minority of climate models with enough SO zonal-mean reflected shortwave radiation do so by compensating this error with overly bright high clouds in the warm sector of cyclones (Williams et al. 2013). Similar cold-sector cloud errors are found in climate model simulations of the NH oceanic storm tracks, but there they do not contribute to a substantial time-mean radiation bias, perhaps because the NH storm tracks are less active in the summer or because additional processes such as less availability of CCN and INPs exacerbate the biases in the SO.

Likely contributors to these errors include 1) model deficiencies in vertical turbulent transport due to both cumulus and PBL parameterization, 2) interaction between parameterized cumulus convection and stratiform cloud processes, e.g., through processes such as condensate detrainment, 3) microphysical deficiencies, (e.g., overly rapid glaciation of supercooled liquid cloud or excessive precipitation from cumulus), 4) errors in representing sub-grid condensate variability, 5) inadequate resolution of the circulation systems in which clouds evolve (Govekar et al. 2011, 2014), and 6) inaccurate representation of aerosols and their relationship to cloud properties.

Natural aerosols are a major source of uncertainty in the effective radiative forcing by aerosols (Ghan et al. 2013, Carslaw et al. 2013), complicating use of prior data to constrain estimates of Earth's climate sensitivity (Kiehl 2007) or to test GCM simulations of anthropogenic aerosol impacts on climate change. The SO is an important testbed for GCM simulations of aerosols and aerosol-cloud interaction. Model studies indicate that a significant fraction of global anthropogenic forcing is associated with aerosol-cloud interactions over the northern extratropical oceans (e.g., Kooperman et al. 2012; Zelinka et al. 2014), while the SO contributes negligibly (Korhonen et al. 2008), meaning present-day SO aerosol conditions may still be similar to those over oceans in the preindustrial era. CMIP5 climate models struggle to represent aerosol processes and to achieve accurate simulations of the annual mean and seasonal cycle of CCN and Nd over the SO. This could also contribute to the SO shortwave biases in some GCMs. In particular, it is not clear if the time variability (and especially the seasonal cycle) of the albedo of liquid clouds over the SO is strongly controlled by the corresponding time variability of CCN/INPs, or whether other physical controls on cloud cover dominate.

Despite the importance and the challenge of simulating cloud and aerosol effects over the SO, there have been only sparse and infrequent observations there. Observations are sorely needed to improve understanding of atmospheric and oceanic processes, their linkage, and representations in models. Strong synoptic variability, seasonality in aerosol sources and sinks, and latitudinal differences in BL air-sea properties create diverse cloud regimes. These considerations motivate MARCUS. The specific science goals of MARCUS are listed in Section 3.0.

2.0 Deployment Site

During MARCUS, the AMF2 will be deployed on board the Australian resupply vessel *Aurora Australis* (AA), depicted in Figure 3, for a 7-month period between September 2017 and April 2018. During this period, the ship will make three or four transits from Hobart (43˚S) to the Antarctic coast to resupply the Australian Antarctic stations Mawson (67.5˚S), Davis (69˚S) and Casey (66˚S). Transit times across the SO and through the sea ice from Hobart to Antarctica are approximately two weeks. The AA will spend approximately one week moored at each of the three stations (Mawson, Davis, and Casey) during the resupply; data will continue to be collected at these times. Standard surface meteorology and once- or twice-daily balloon soundings are routinely collected at these three stations.

Figure 3. The *Aurora Australis* docked in Hobart, Australia. Picture by Feral Arts –Aurora Australis (2) uploaded by russavia, License under CC BY 2.0 via Commons – https://commons.wikimedia.org/wiki/File:Aurora_Australis_(2).jpg# /media/File:Aurora_Australis_(2).jpg

Figure 4 shows the voyage tracks of the AA from the summer season 2012-2013. The voyages of the AA usually occur as follows: October-November: Davis; December: Casey; January: Marine Science (if occurring); February-March: Mawson and Davis (sometimes these are separate voyages); March or April: Macquarie Island. The exact schedule for the summer 2017/18 season will be determined in mid-2017 by the Australian Antarctic Division (AAD).

Such cruises will allow us to focus upon mapping cloud and aerosol properties over the SO and across the oceanic polar front over as wide of a range of times as the AA can be available. This strategy is important for mapping the strong gradients in oceanic, aerosol, and cloud properties, (and model biases), and frequent cyclones that exist between 45˚S and the Antarctic coast (~65ºS) that will be sampled as fully as possible. The data that will be collected while the AA is moored at the relative stations will be complementary to those collected near the McMurdo Station during the ARM West Antarctic Radiation Experiment (AWARE), and can provide more cloud information for the Antarctic continent.

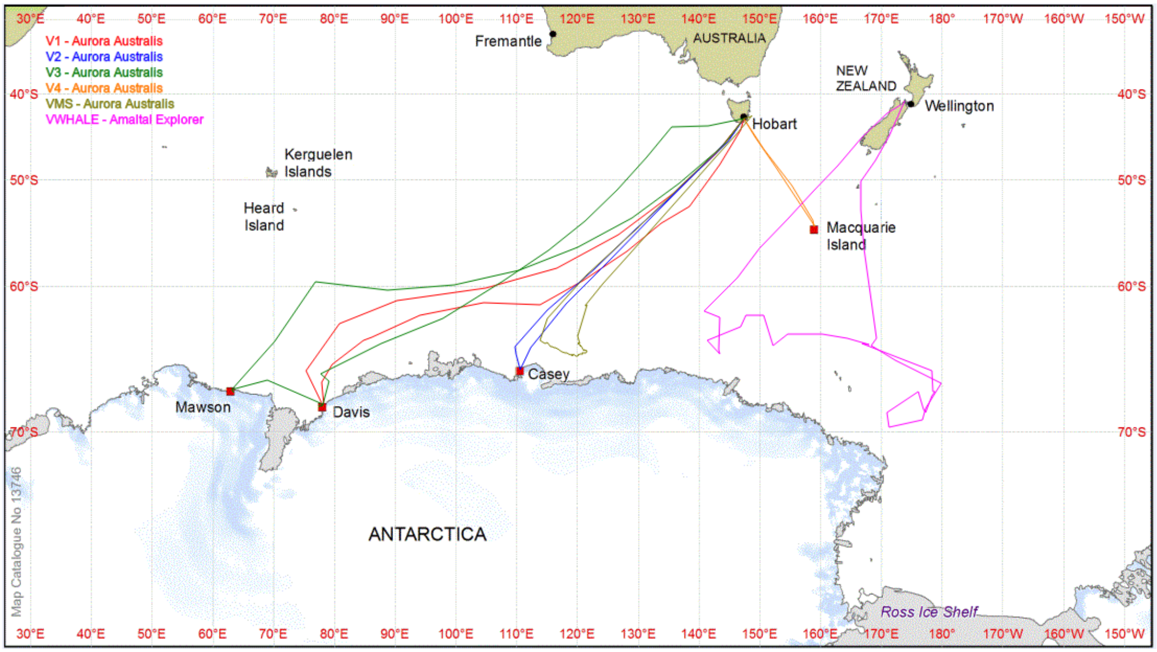

Figure 4. Voyage tracks of *Aurora Australis* (from Hobart) during summer season 2012-13.

3.0 Science Goals

The primary objectives of MARCUS are to understand 1) the synoptically varying vertical structure of SO BL clouds and aerosols, 2) sources and sinks of SO CCN and INPs, including the role of local biogenic sources over spring, summer, and autumn, 3) mechanisms controlling supercooled liquid and mixed-phase clouds, and 4) advances in retrievals of clouds, precipitation, and aerosols over the SO from ground-based and satellite remote sensing. Parameterization development and testing needs are integrated in MARCUS' design and in the design of the entire multi-agency SOCRATES program so that systematic confrontation and improvement of leading climate models with data will be possible. This will enable better understanding of reasons for the increased bias of absorbed shortwave radiation in summer in models and determination of processes responsible for the extensive supercooled water that has been remotely sensed in clouds over the SO. Specific hypotheses to be tested during MARCUS are as follows:

Synoptically varying vertical structure of SO BL clouds and aerosols

H1.1: A primary reason that climate models simulate too little cloud in the cold sector of mid-latitude cyclones is too much removal of liquid water in parameterized shallow convection schemes, due to biases in vertical transport and microphysics.

H1.2: Synoptic-scale aerosol variability is significantly correlated to SO liquid cloud droplet concentrations (N_d)**.**

Variability of sources and sinks of SO CCN and INPs and role of local biogenic sources over spring, summer, and autumn

H2.1: Entrainment of biogenically derived aerosols constitutes a major source of CCN for SO BL clouds during summer, with decreasing importance in spring and autumn and over colder ocean surfaces.

H2.2: Biogenic particles are the dominant source of INPs over the SO.

Supercooled liquid clouds over the SO

H3.1: Supercooled liquid clouds contribute substantially to observed cloud reflectance over the SO.

H3.2: At similar temperatures and latitudes, there are systematic differences between Northern and Southern Hemisphere clouds in terms of the prevalence of supercooled water, as well as in the mass contents of ice and supercooled water.

Advancing retrievals related to clouds, precipitation, and aerosols over the SO

H4.1: Current satellite-based estimates of SO liquid cloud droplet concentration and LWP have important biases due to the difficulty in separating the effects of cloud liquid, cloud ice, and precipitation. These biases can be reduced by more careful consideration of horizontal inhomogeneity and cloud phase screening.

H4.2: The satellite retrieval of the vertical distribution of cloud radiative effect is hampered by inaccurate cloud phase partitioning and cloud microphysical and aerosol properties over the SO.

4.0 Measurement Requirements

To address the scientific hypotheses set forth above, a focused set of observations over the SO coordinated with process and large-scale modeling is required. The MARCUS observations are part of a larger international multi-agency effort called the Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES). To address the MARCUS hypotheses, the MARCUS data can therefore be supplemented with data from the following platforms:

- Planned aerosol and cloud observations from National Science Foundation (NSF) Gulfstream (G-5);
- Planned aerosol and cloud remote sensing, biological sampling, microlayer, surface, and sub-surface seawater properties, aerosol (including CCN and INPs) and ocean eddy observations from the R/V I*nvestigator* and the *Ron Brown* in January 2018 over a north-south curtain extending from Australia/New Zealand to the Antarctic coast;
- Ground-based remote sensing and meteorological measurements from the DOE-funded Macquarie Island Cloud and Radiation Experiment (MICRE) and the Australian Cloud and Radiation Experiment (ACRE) from March 2016 to March 2018;
- Measurements from the AMF2 at McMurdo Station from January 2016 to January 2017 during the ARM Western Antarctic Radiation Experiment (AWARE);
- Cloud and aerosol measurements and possible deployment of uninhabited aerospace systems (UAS) from the R/V *Tangaro* in the sea ice edge region of the Ross Sea; and

- Proposed cloud, aerosol, and radiation measurements from a ship and the British Antarctic Survey (BAS) Twin Otter aircraft as part of the Southern Ocean Aerosol Clouds and Ice Processes Experiment (SEASCAPE).

Synergistic use of these data sets will be the most efficient way of addressing many of MARCUS' objectives. However, the MARCUS data by themselves are unique because they provide the only extensive data on lower-tropospheric (0-5 km) profiles and coordinated cloud/aerosol remote-sensing and radiative properties south of 60˚S, and in that they will be the only measurements across the full SO latitude range in the austral spring and autumn seasons. Thus, the MARCUS observations will be acquired in a region of great climatic importance, where supercooled and mixed-phase boundary-layer clouds in the cold sector of cyclones are frequent and where previous observations are few and far between, and hence can be used for hypotheses testing.

Table 2 presents key observational and modeling requirements for MARCUS. MARCUS has the following overarching observational objectives:

1. Characterize the physical properties of lower tropospheric cloud systems around mid-latitude cyclones over the full SO latitudinal range during spring, summer, and autumn;
2. Characterize microphysical and chemical properties of aerosols that play a role in regulating CCN and INPs over the SO and to investigate their significance for cloud and precipitation formation, and radiative properties;
3. Use satellite cloud, aerosol, and precipitation products to extend the temporal and spatial scale of the MARCUS observations to address the science questions;
4. As part of a SOCRATES-wide modeling strategy, the MARCUS data will be used to evaluate and improve the skill of models at different scales to reproduce the observed properties of SO cloud systems, aerosol physicochemical properties, and aerosol-cloud-precipitation interactions, and to use such models to develop a process-oriented understanding of mechanisms controlling the properties of cloud systems.

Table 2. Observational and modeling requirements for MARCUS (adapted from similar requirements for SOCRATES).

MARCUS observational requirement	To enhance our knowledge of SO aerosols, clouds, and their interactions in a variety of synoptic settings and to narrow the uncertainties in representing key processes in climate models, a comprehensive data set is needed that documents PBL structure, and associated vertical distributions of liquid and mixed-phase cloud and aerosol (including CCN and INP) properties over the SO under a range of synoptic settings.
MARCUS modeling requirement	For such a data set to have broad impact on climate modeling, the modeling community must be an integral part of the MARCUS design and be involved in a systematic confrontation of leading climate models with MARCUS data, e. g, using short-term hindcasts as in VOCALS model assessment (Wyant et al. 2014).

5.0 Instruments

Although the AA is not a dedicated research vessel, there is space for two AMF2 vans to be installed for the entire operational season. One of these containers will be located forward of the bridge on the port side of the ship, while the second can be located aft of the bridge on the bridge deck. Additionally, space is available on the monkey deck (directly above the bridge) to locate various instruments requiring as clear a view of the sky as available from the ship. This section discusses the technical layout of the AA along with the potential locations of the AMF2 containers.

Because of the limited space available on the AA, it is not possible to include the complete compliment of instruments available as part of the AMF2. The exact amount of space for instrumentation will be determined following detailed conversations between ARM, AAD, and the MARCUS team. We have categorized instruments according to whether their presence is critical for MARCUS hypothesis testing (category 1), important but not critical (category 2), or nice to have for use in investigations that extend beyond the original MARCUS hypotheses (category 3). We have reasonable confidence that the instruments identified as category 1 can be installed on the AA, but are not certain as to which of the category 2 instruments can be installed. The final assessment of instruments to install will be based on both identified importance and whether there is space available for a particular instrument. Table 3 lists the instruments on the AMF2 that will be installed on the AA together with their prioritization.

Table 3. Instruments to be installed on *Aurora Australis* for MARCUS. Shaded instruments are all part of the Aerosol Observing System (AOS) and all are expected to be deployed on AA.

Instrument	Measurement	Prioritization
Cloud condensation nuclei counter (CCN), part of AOS	Concentration of CCN as function of supersaturation	1
Ambient nephelometer, part of AOS)	Light-scattering coefficient of aerosols as function of ambient relative humidity	2
Wet nephelometer, part of AOS	Light-scattering coefficient of aerosols over range of relative humidities	1
Condensation particle counter (CPC), part of AOS	Concentration of aerosol particles for D > 10 nm	1
Hygroscopic Tandem Differential Mobility Analyzer (HTDMA), part of AOS	Aerosol (size, mass, number) distribution as function of relative humidity	2
Ultra-High-Sensitivity Aerosol Spectrometer (UHSAS), ordered as part of AOS	Aerosol size distributions from 0.06 to 1 μm at higher time resolutions than available from HTDMA (important given low aerosol concentrations expected)	1
3-wavelength particle soot absorption photometer (PSAP), part of AOS	Optical transmittance of particles at 3 wavelengths	2
Ozone, part of AOS	Measures ozone concentration by absorption	3

Instrument	**Measurement**	**Prioritization**
CO detector, ordered as part of AOS but not yet available	CO good indictor of anthropogenic influences (e.g., from ship plume, industrial sources)	1
Local meteorology, part of AOS	Wind speed and direction, temperature, relative humidity, pressure, and preciptiation	1
Cimel sunphotometer (CSPHOT)	Multi-channel radiometer measuring direct solar irradiance and sky radiance	1
Balloon-borne sounding system (SONDE)	Vertical profiles of temperature, relative humidity, and winds 4 times a day	1
Micropulse lidar (MPL)	Vertical profile of clouds and aerosols	1
Microwave radiometer (MWR) or 3-channel microwave radiometer (MWR)	Brightness temperature in 3 channels sensitive to water vapor and liquid water	1 (prefer 3-channel version)
High-Spectral-Resolution Lidar (HSRL)	Calibrated measurements of aerosol optical depth, volume backscatter coefficient, cross section, and depolarization	2 (anticipate insufficient space)
Total sky imager (TS)	Time series of hemispheric images	2
Marine 95-GHz Cloud Radar (SWACR) on stablized platform	Radar reflectivity, Doppler velocity, Spectral data	1
Dual-frequency (X-Ka) scanning cloud radar (KA-SACR; X-SACR)	Dual-frequency scanning cloud radar measuring reflectivity, Doppler velocity	3 (anticipate insufficient space)
Ka-band Zenith radar (KAZR)	Millimeter-wavelength cloud radar	2 (unless stabilized platform is available, then 1)
Vaisala ceilometer (VCEIL)	Detection of vertical cloud layers	1
Radar wind profiler (RWP)	Wind profiles and backscatter signal strength	2 (sufficient deck space uncertain)
Marine Atmospheric Emitted Radiance Interferometer (MAERI)	Thermal infrared spectral radiance, and measures of surface temperature and emissivity	2 or 3 (if space, secondary to most other category 2 instruments)
Inertial navigation system (SeaNav)	High-accuracy motion data in three rotational frames of reference	1 (lower priority if ship has such a system)
Stability platform	Corrects roll, pitch, and heave	1

Instrument	**Measurement**	**Prioritization**
Portable radiation measurement package (PRP2) and sun pyranometer (SPN)	Consists of PSP and PIR and fast-rotating shadowband radiometer (FRSR) and sun pyranometer	1 (for components giving downwelling radiation)
Bulk aerodynamic fluxes (BAF)	Measurement of aerodynamic fluxes	2
Ocean temperature	Measurement of ocean surface temperature	1
Video disdrometer (or Parsivel disdrometer if mounts more easily on monkey deck)	Raindrop size distributions	1 (reliable precipitation measurements on ship are difficult, so given lower priority

We assume that the first container will consist of instruments from the Aerosol Observing System (AOS), with a sun photometer and instruments for measuring downwelling radiation on the roof of the AOS container. Because many of the hypotheses involve understanding the sources and sinks of aerosols, CCN and INPs, or on their correlation with cloud parameters, most of the instruments are category 1. Further, as the AOS is essentially a standalone container that cannot be easily modified to replace any aerosol instrument deemed non-essential (i.e., those that are not category 1) with other instruments, we are requesting the complete suite of aerosol probes to be installed with the AOS to sample the BL aerosol characterisitics. Nevertheless, we have given a complete listing of the instruments by category in Table 2 in case the cost of deploying the complete suite becomes prohibitive. The category 1 instruments include the cloud condensation nuclei counter (CCN-100), the condensation particle counter (CPC), and the Cimel sun photometer (CSPHOT). We are also requesting two instruments that are projected to be part of the AMF2 but that have yet to be ordered: a CO detector that will provide a good indication of when anthropopenic influences (e.g., ship plume, source from a port, etc.) are encountered, and an Ultra-High-Sensitivity Aerosol Spectrometer (UHSAS) that should work better than the Hygroscopic Tandem Differential Mobility Analyzer (HTDMA) given the low aerosol concentrations that are anticipated. Both of these instruments should be available in time for MARCUS.

The second container will consist primarily of the marine W-band (95 GHz) ARM cloud radar (M-WACR) equipped with a stablized platform and the micropulse lidar (MPL). At a minimum, a ceilometer needs to be installed somewhere on the AA, but the MPL is also highly desired for better aerosol profiling and combined radar-lidar cloud retrievals. A ceilometer and 3-channel microwave radiometer (MWR) are category 1 instruments that will be installed somewhere on the monkey deck or elsewhere on the ship. The inertial navigation system is also required, together with measurements of ship motion, in order to help interpret these datastreams. We are requesting the use of the balloon-borne sounding system (SONDE) with 4 launches per day. Sufficient helium tanks for the launches will be installed on each voyage by AAD technicians. Although it is hard to get reliable measurements of precipitation from disdrometers on ships because the ship horizontal motion is probably about 50% of the terminal velocity of the raindrops, we still rank them as category 1 because they are relatively small in size and provide an important surface measurement for validation of remotely sensed precipitation amounts. It is also possible that a new-generation disdrometer specifically designed for ship operations that can also measure snow may be available for MARCUS (one has already been installed on the R/V *Investigator*). We will attempt to use it if such a probe is available and there is sufficient space.

The sampling equipment for the user-supplied filter samples will be mounted on the railing of the monkey deck. Interior space and modest power for a small pump and -25 °C freezer for sample storage, as accommodated on previous AMF deployments, is needed. Sample collection procedures will follow the examples of those used in the ARM MAGIC (*Horizon Spirit*) and ARM ACAPEX (National Oceanic and Atmospheric Administration [NOAA] *Ron Brown*) ship studies using sterile filter sample kits. Figure 5 shows the location of the filter sampler on a railing on the *Horizon Spirit* during MAGIC. AMF technicians will install the sampling head brace at an accessible external position, run vacuum lines to a supplied interior pump, and handle and store samples in a supplied freezer following provided protocol for daily filter collections. The typical schedule is a single 24-hour filter sample, timed as appropriate for technician schedules. Offline processing of particles washed from filters for immersion-freezing temperature spectra (0 to -27 °C) will be performed following the method outlined in Garcia et al. (2012) and Hill et al. (2014). Basics of the method involve re-suspension of filter collected particles in purified water and distribution into either 10-80-microliter wells or as a field of-1microliter droplets. Thermal processing of samples will be used to distinguish the contributions of biogenic versus inorganic INP, offering a window into specific marine sources versus transported continental aerosols. Frozen portions of samples can also be subjected to genomic analyses (pyrosequencing, via separate research funding) to look for associations of INP with biological aerosol communities, and to track air mass source influences. The filters will need to be stored and maintained frozen during the extent of each cruise, even when in port in Antarctic. The samples should also be stored frozen in Hobart over the extent of the cruises, with return shipping to the United States arranged by Colorado State University using "cyroport" shipping. The INP data archive will consist of 24-hour (daily), position- (latitude, longitude) and time-stamped start and end points of arrays of INP number concentrations (per liter of air), their 95% confidence intervals, immersion freezing processing temperatures, and heat treatment flag at 0.5 to 1°C intervals. Data will be reported in ICARTT format (FFI 2110). Data will be archived within 6 months of the end of the study.

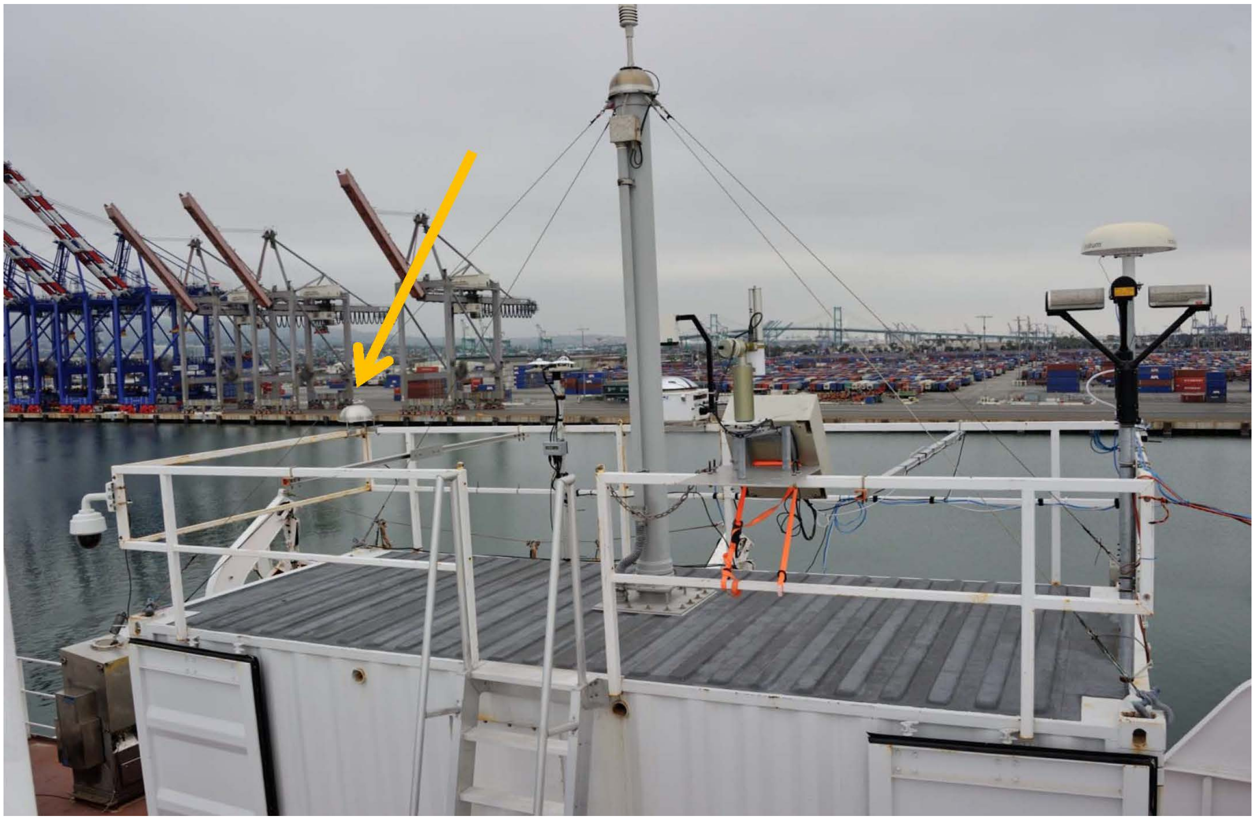

Figure 5. Location of filter sampler on *Horizon Spirit* indicated by arrow.

6.0 Logistics

We will work carefully with ARM infrastructure representatives to identify the optimum arrangement of instruments on the AA that will allow us to collect the data that are most critical for addressing our hypotheses. The technical layout of AA is illustrated in Figures 6, 7, and 8, along with the potential locations of the AMF2 containers. The final location of each instrument will be determined in coordination with the ARM infrastructure team and AAD technical support to ensure that our priority instruments are installed in appropriate positions on the ship.

Some additional considerations need to be accounted for in siting the instruments. First, it is critical that the aerosol instruments, radiometers, and sounding launches be in front of the stacks in order to avoid influences of the stacks. In addition, the exact placement of the instruments, especially the vertically pointing ones, in relation to the navigational system is important for ship motion corrections. Thus, it is critical that distances and angles of all probes, as well as digital photography, be used to document the location of all observing systems.

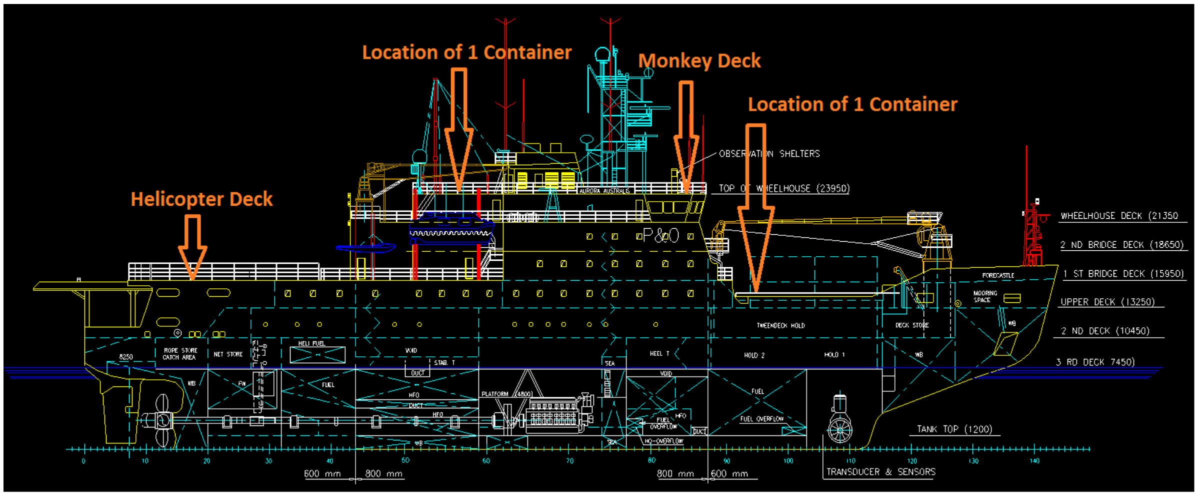

Figure 6. Cross section of the *Aurora Australis*.

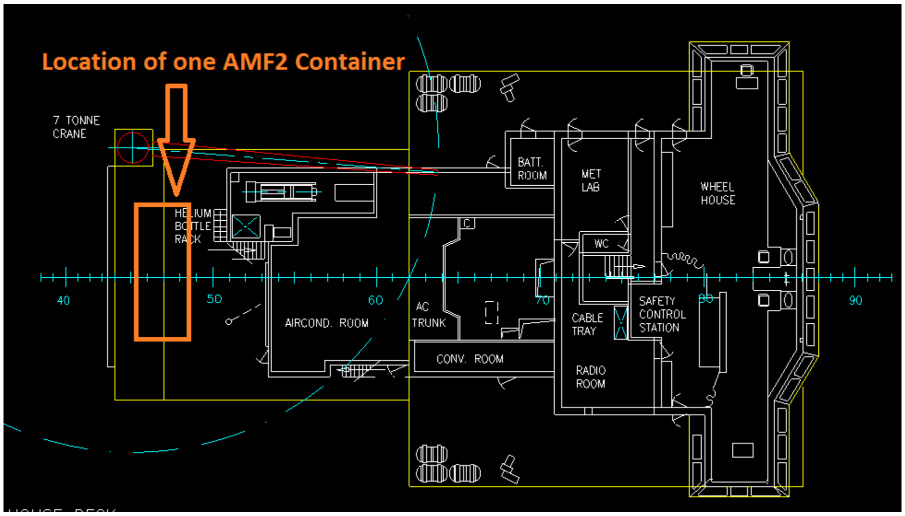

Figure 7. Top view of the location of one AMF2 container on the bridge deck. Forward is to the right.

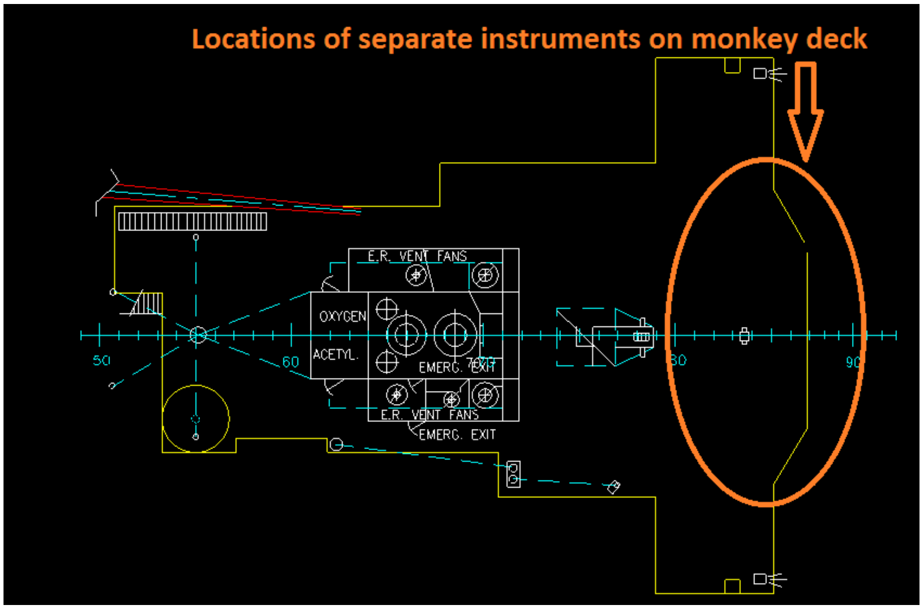

Figure 8. Approximate space 10m wide X 5m available at the fore of the monkey deck (directly above the bridge) for instruments requiring a clear view of the sky. Forward is to the right.

We envision that two technicians will be on board the ship to operate the AMF2 and to launch weather balloons with radiosondes. Four radiosondes will be launched each day, at 0:00, 06:00, 12:00, and 18:00 UTC. The technicians are also needed for handling and storing the filter samples in a supplied freezer following the provided protocol for the daily filter collections. ARM personnel are also required for installing all the equipment before the AA starts making its routine transits, and removing them after the end of the supply season.

While satellite communications are available to the ship, the bandwidth is very restricted, so deployment plans must include local storage and backup of all data. Details on how much data can be transmitted to monitor instrument performance will be negotiated with AAD, and could consist of, for instance, automatic status emails. Data will be removed each time the ship docks in Hobart, backed up locally, and then ftp'ed back to the ARM Climate Research Facility. The exact data-handling processes will be negotiated with ARM representatives. We are also requesting that the time, latitude, and longitude of all sonde launches and instrument status for each leg be recorded on a spreadsheet so that information on the quality control of the data is readily accessible.

MARCUS principal investigator Greg McFarquhar will be the principal point of contact with ARM personnel and technicians on board the AA, communicating with them when at Hobart, and working with them to ensure that the data collected are of sufficient quality to address the MARCUS objectives. Because the AA will follow tracks set by the AAD and is primarily on a resupply voyage rather than a science cruise, it is not anticipated that a scientific observer will be on board; the data collection tasks, filter samples, and sonde launches can be accomplished by the AMF technicians on board. On the AA, the designated AMF2 lead will be the point of contact between AMF2 and the captain. The MARCUS science team will quality-control the data as they are made available, and will perform enhanced cloud microphysical retrievals as soon as possible in order to ensure that data of sufficient quality are being obtained to address the goals proposed.

7.0 Relevancy to DOE/BER

The SO is the interface between the Antarctic ice sheet and the rest of the world; clouds (stratocumulus and deep frontal clouds) over the SO are thought to be very different than their NH counterparts because of the absence of continental sources of INPs and virtually all CCN are from the ocean, except for sources from the free troposphere. Model parameterizations are almost universally based on data collected in the NH. Data collected during MARCUS will provide insight into key processes controlling aerosols, clouds, and their interactions over the under-sampled SO. Biases in simulations of SO clouds, aerosols, radiation, and air-sea exchanges impact the SO surface energy balance and winds, and hence the atmospheric and oceanic circulation of the entire Southern Hemisphere and beyond (e.g., location of tropical rainfall belts, global cloud feedbacks, and carbon-cycle feedbacks). The new process-level understanding with data collected by the AMF2 will impact GCM development via improved parameterizations of cumulus, cloud microphysics, and aerosol-cloud interactions, in a region where models perform particularly poorly. Improved climate models will have broader impacts on our understanding of Antarctic climate change, cloud feedback processes, anthropogenic climate forcing from aerosol-cloud interactions, and ocean biogeochemical processes. Estimates of anthropogenic aerosol forcing in climate models will be improved from better estimates of a surrogate of the maritime pre-industrial state over the SO. Therefore, MARCUS data will lead to improved simulation of key climate processes that will impact our ability to estimate cloud feedbacks, carbon uptake and other biogeochemical processes, and Antarctic sea ice and ice shelves. Thus, MARCUS is relevant for reducing uncertainties in feedbacks and other processes from global models, and will ultimately help accomplish the long-term goal of predicting climate decades or centuries into the future—information needed to plan for future energy and resource needs.

The proposed deployment thus contributes to the mission of the Biological and Environmental Research program of DOE by collecting data with a scientific user facility that will support fundamental research and "advance understanding of the roles of Earth's biogeochemical systems (the atmosphere, land, oceans, sea ice, and subsurface) in determining climate so we can predict climate decades or centuries into the future." Further, it will contribute to one of the performance goals of BER, which is to "develop capabilities to improve understanding of critical sub-decadal processes and incorporate the results into Earth system models." MARCUS also contributes to the mission of the Climate and Environmental

Sciences Division (CESD) of BER by using "the unique capabilities and impacts of the ARM and EMSL scientific user facilities and other BER community resources to advance the frontier of climate and environmental science" by "advancing studies to enhance the understanding of atmospheric and terrestrial system processes." The MARCUS data, to be obtained in a region where few observations exist, will also contribute to the primary objective of the ARM Climate Research Facility of CESD by "providing a detailed and accurate description of the Earth's atmosphere in [a] diverse climate regime to resolve the uncertainties in climate and earth system models" by providing "the climate research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation in climate and earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface." Therefore Marcus contributes to strategic objective 3 of goal 1 of the DOE Strategic Plan 2014-2018 by delivering "scientific discoveries and major scientific tools that transform our understanding of nature" by "discovering the drivers and impacts of climate change."

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