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Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) Field Campaign Report

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Acronyms and Abbreviations

AERI	atmospheric emitted radiance interferometer
AMF	ARM Mobile Facility
AOS	aerosol observing system
ARM	Atmospheric Radiation Measurement
BL	boundary layer
CAPRICORN	Clouds, Aerosols, Precipitation, Radiation, and Atmospheric Composition over the Southern Ocean
CPC	condensation particle counter
DOE	U.S. Department of Energy
GCM	global climate model
HTDMA	humidified tandem differential mobility analyzer
LTS	lower tropospheric stability
LWP	liquid water path
MARCUS	Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean
MPL	micropulse lidar
MWACR	Marine W-Band (95 GHz) ARM Cloud Radar
MWR	microwave radiometer
OSE	observing system experiment
PSAP	particle soot absorption photometer
R/V	research vessel
RWP	radar wind profiler
SO	Southern Ocean
SOCRATES	Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study
SST	sea surface temperature
TSI	total sky imager
UHSAS	ultra-high-sensitivity aerosol spectrometer
WIBS4	Wideband Integrated Bioaerosol Sensor Mk.4

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1.0 Summary

The Southern Ocean (SO) is the stormiest place on earth, buffeted by winds and waves that circle the ice of Antarctica, 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, precipitation, and radiative transfer 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.

The Southern Ocean Clouds Radiation Transport Aerosol Transport Experimental Study (SOCRATES) white paper (Marchand et al. 2014) describes the motivation, scientific themes, and testable hypotheses that led to a multi-agency and international measurement campaign to study clouds, aerosols, and the air-sea interface over the SO. As a separate project within this international umbrella, the Measurement of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field program was conducted between 29 October 2017 and 25 March 2018. During MARCUS, instruments from the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's second Mobile Facility (AMF2) were installed on the Australian icebreaker *Aurora Australis* as it made resupply missions from Hobart, Tasmania to the Australian Antarctic stations of Casey, Mawson, and Davis, as well as Macquarie Island. Figure 1 shows the voyages conducted during MARCUS. The MARCUS data are unique in that they are the only set of data in the broader international effort that a) acquired comprehensive observations of clouds, aerosols, and radiation south of 60˚S, and b) acquired measurements across the full SO latitudinal range in the spring and fall seasons.

With instruments from the AMF2 and the ARM Aerosol Observing System (AOS), MARCUS obtained measurements of aerosols in the boundary layer, retrieved vertical distributions of macrophysical and microphysical properties of liquid and mixed-phase clouds, and measured downwelling radiative fluxes over the SO in order to address the following overarching campaign objectives:

- understand the synoptically varying vertical structure of SO BL clouds and aerosols;
- discover the sources and sinks of SO cloud condensation nuclei and ice nucleating particles, including the role of local biogenic sources over spring, summer, and fall;
- find the mechanisms controlling supercooled liquid and mixed-phase clouds; and
- advance retrievals of clouds, precipitation, and aerosols over the SO from ground-based and satellite remote sensing.

In order to acquire these observations, measurement capabilities included cutting-edge meteorological instrumentation, a broadband and spectral radiometer suite, in situ aerosol instrumentation, and remote-sensing instruments including the following: a cloud condensation nuclei counter; wet nephelometer; condensation particle counter (CPC); ultra-high-sensitivity aerosol spectrometer (USHAS); humidified

tandem differential mobility analyzer (HTDMA); particle soot absorption photometer (PSAP; CO detector; O_3 monitor; local meteorological measurements; Cimel sun photometer; atmospheric emitted radiance interferometer (AERI); balloon-borne sounding system; micropulse lidar; microwave radiometer (MWR); Marine W-band (95 GHz) ARM Cloud Radar (MWACR) on a stabilized platform; Vaisala ceilometer; radar wind profiler; inertial navigation system; portable radiation measurement package and sun pyranometer; total sky imager (TSI); ocean temperature; video disdrometer; and Parsivel disdrometer.

Because these instruments were deployed on board a moving vessel traversing rough seas, special preparation was required for all the instruments including routine cleaning to keep the instruments free of sea spray and efforts to correct for the pitch and roll of the ship. ARM technicians were on board each cruise, continually monitoring and maintaining the instruments as well as releasing radiosondes to collect the most complete and comprehensive set of data possible. Collaboration with Simon Alexander of the Australian Antarctic Division allowed the measurements of surface precipitation on the *Aurora Australis* and collaboration with Martin Schnaiter of Karlsruhe Institute of Technology allowed measurements of bioaerosol particles from the Wideband Integrated Bioaerosol Sensor Mk. 4 (WIBS4) based on fluorescence measurements in three excitation/emission wavebands on a single-particle basis. Finally, collaboration with Paul DeMott of Colorado State University allowed collections of aerosol filter samples at 24- and 48-hour duration on all voyages. The filters were returned frozen, and are being processed to determine how the ice nucleating particle concentrations vary with temperature for the immersion freezing mechanism, and will allow for further analysis to assess the chemical and biological composition of ice nucleating particles over the Southern Ocean.

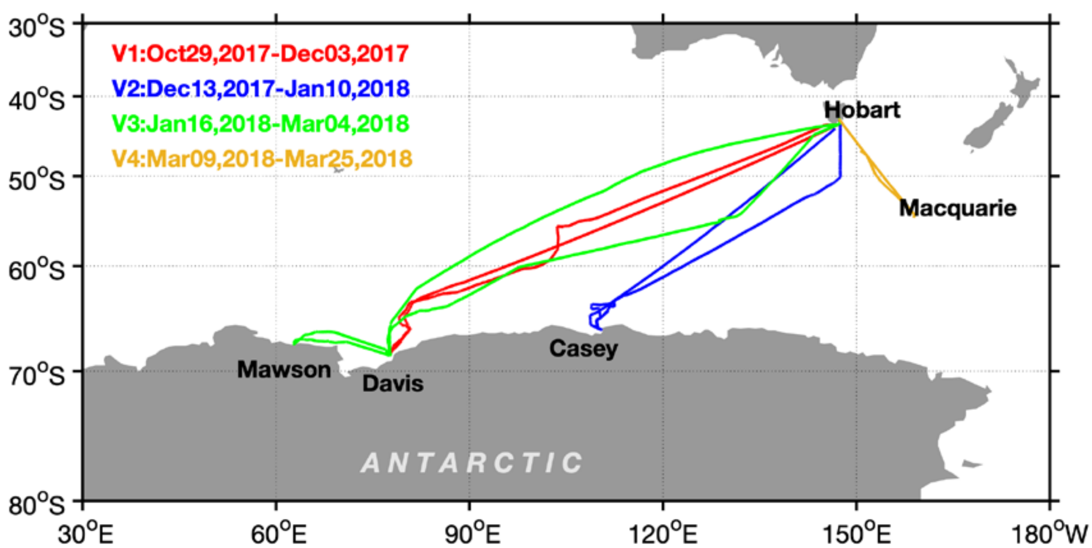

Figure 1. Tracks followed by the *Aurora Australis* on all four voyages of the MARCUS experiment.

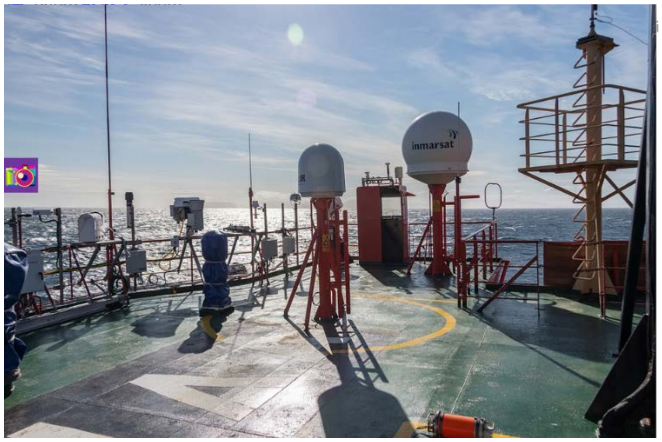

Figure 2. Some of the AMF2 instruments installed on the monkey deck of the *Aurora Australis* during MARCUS.

Figure 3. Balloon launch during SOCRATES (photo credit Doug Thost).

2.0 Results

Quality control and scientific investigations using the MARCUS data have started, yet are not yet complete. Overall, the quality of the MARCUS data is good, with the status of each instrument listed in Table 1 (green indicates good data, yellow use caution, and red data not available).

Table 1. Status of data quality from instruments on board the *Aurora Australis* during MARCUS (green: good data; yellow: use caution; red: data problematic).

Instrument	Measurement
Atmospheric emitted radiance interferometer	Longwave spectral radiance, spectral brightness temperature
Aerosol optical properties	Optical properties
Aerosol observing system (AOS)	Aerosol particle size (ship stack contamination)
Meteorological measurements associated with the aerosol observing system	Pressure (P), temperature (T), precipitation, dew point dew point temperature (T_d), wind speed, rain amount
Cloud condensation nuclei particle counter	Total concentration and binned counts
Ceilometer	Backscattered radiation, cloud base height, planetary boundary layer height
Carbon monoxide analyzer	CO, N_20 mixing ratios
Condensation particle counter	Aerosol concentration (fine particle concentration)
Humidified tandem differential mobility analyzer	Aerosol particle size distribution and concentration
Infrared thermometer	Surface skin temperature, longwave narrow band brightness temperature
Laser disdrometer	LWC, PSD, visibility
Marine precipitation instruments	Rain intensity and accumulated rain
Micropulse lidar (MPL)	Attenuated backscatter and polarization (polarization Problematic until 13 Jan. 2018)
Marine W-band (95 GHz) ARM Cloud Radar	Mean Doppler velocity, reflectivity and spectral width (caution due to periodic functioning of stable platform)
Microwave radiometer	Liquid water path, brightness temperature, and precipitable water
Microwave radiometer, 3-channel	Liquid water path, brightness temperature and Precipitable water
Navigational location and attitude	Ship motion coordinates
Nephelometer	Aerosol scattering and backscattered radiation
Ozone monitor	Ozone concentration
Particle soot absorption photometer	Aerosol absorption at 3 wavelengths
Radar wind profiler	Horizontal wind and vertical velocity
Balloon-borne sounding system	T, P, Td, wind speed and direction
Stabilized platform for W-band radar	Pitch, roll angles, heading stabilizes platform
Total sky imager	Cloud amount and fraction
Ultra-high-sensitivity aerosol spectrometer	Aerosol particle size distribution
Skyrad radiometers	A-level only (higher-level products being generated)
Rotating shadowband radiometer	A-level only (higher-level products being generated)
Cimel sun photometer	Raw data exists; cloud optical depth retrieval planned

It should be noted that even when data from an instrument are flagged as yellow, the data can still be used subject to some cautions. For example, the instruments on the AOS functioned well, but time periods where the data are contaminated by flow from the stack must be removed so that only background conditions over the Southern Ocean are being sampled. Two complementary efforts are proceeding to remove this contamination, one involving application of an algorithm developed to remove contamination from voyages of the *R/V Investigator* during the CAPRICORN field project (Humphries et al. 2018) and another using a machine-learning approach. Although the polarization channel from the MPL did not function for the first two voyages, the location of the clouds detected by the MPL are still usable. The stabilized platform malfunctioned periodically, meaning carefully quality control of the MWACR data are required and are proceeding. There will be a ShipCorr product generated that will attempt to correct for roll, pitch, and heave, but there will be periods with high wind speeds and ocean wave activity that cannot be corrected.

In addition to the direct measurements that are available from these instruments, several higher-level data products are also being generated for use in scientific investigations. For example, different algorithms are being used to retrieve cloud properties including the following techniques: (1) radar-lidar analysis to identify cloud boundaries and cloud phase; (2) a radar reflectivity-velocity light precipitation retrieval following Frisch et al. (1995) to provide precipitation rate, particle size, and precipitation water content; (3) a physical-iterative microwave radiometer (MWR) retrieval following Marchand et al. (2003) to give cloud liquid water path (LWP) and precipitable water vapor; and (4) a radar reflectivity-MWR LWP retrieval following Frisch et al. (2002) for cloud droplet number and effective radius for non-precipitating clouds. Several other retrievals are also under development, including most prominently a precipitation product that blends surface disdrometer, cloud radar, and depolarization lidar data to better identify precipitation phase (and type). A final retrieval will use vertically resolved MPL backscatter and depolarization ratio data to determine cloud boundaries and phase. This information will be merged with data from the millimeter radar to provide a complete profile of clouds through the troposphere. Cloud boundaries and ice virga will be determined by examining gradients in the lidar's return signal (Wang and Sassen 2001), while cloud phase is determined by quantifying the cloud layer depolarization ratio and backscatter (Hu et al. 2009). Algorithms recently developed combine these techniques (Alexander and Protat 2019) and will be applied to the MARCUS data.

Some preliminary analysis of the data collected during MARCUS has been conducted. First, an attempt has been made to determine how the cloud macrophysical and aerosol properties depend on the environmental conditions, and seasonal and latitudinal locations of the measurements. In particular, the dependence of the cloud base height, cloud top height, cloud base temperature, cloud top temperature, liquid water path, precipitable water vapor, cloud condensation nuclei concentration, and aerosol concentration on the following environmental conditions has been examined: latitude, season (spring, summer, fall), precipitating or non-precipitating cloud, sea surface temperature (SST), lower tropospheric stability, degree of coupling between the cloud and boundary layer, and relative location in cyclones and air mass origin. Figure 4 shows examples of this analysis where the variation of cloud properties on SST and lower tropospheric stability is displayed. Further analysis is being conducted and physical reasons for the resulting patterns is being hypothesized.

Another study showed that the MARCUS radiosonde observations could be used to reduce biases in upper tropospheric temperatures in ensemble forecast experiments (Sato et al. 2018). An observing system experiment (OSE) including the additional radiosondes showed that initial temperature biases of 7˚C present in the upper troposphere were reduced, with the spread in the upper level reduced by 15% in the OSE. Thus, the prediction of the mid-latitude cyclone tracks was improved because the upper-level troughs were better represented in the OSE forecast.

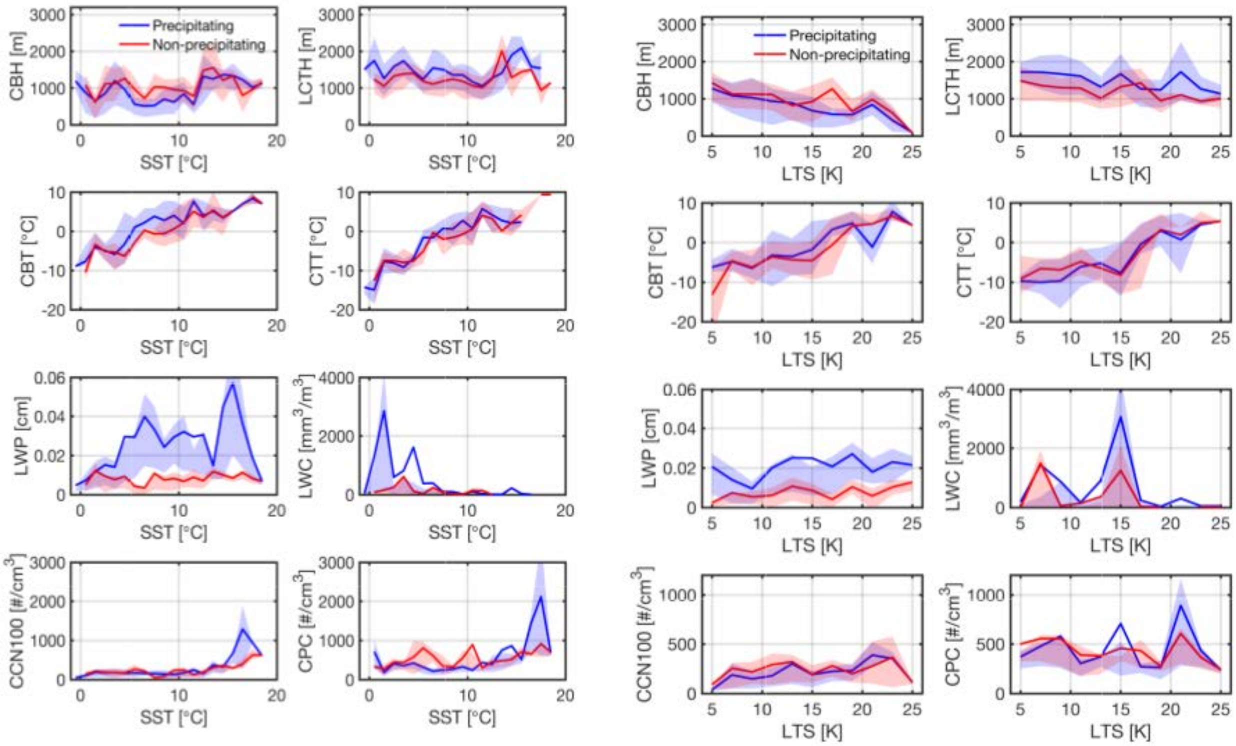

Figure 4. Variation of cloud and aerosol properties with sea surface temperature (SST) and lower tropospheric stability (LTS) for data obtained during all four voyages during MARCUS.

In summary, the data obtained during MARCUS provide the most comprehensive data on seasonal variation of the precipitation, radiation, and aerosol properties of Southern Ocean clouds, especially those clouds south of 55˚S where cold SSTs and supercooled water are believed to be prevalent, and biases in the shortwave radiative budget of climate and numerical weather prediction models largest. Thus, the MARCUS data are beginning to be used in several investigations to achieve critically needed evaluation of satellite retrievals and to advance our knowledge of SO cloud, precipitation, and aerosol properties beyond what can be determined from space. Further, they can provide a new process-level understanding that will impact GCM development via improved parameterizations of cumulus, cloud microphysics, and aerosol-cloud-precipitation interactions.

3.0 Publications and References

Although thus far few journal articles have been based on the MARCUS data, several are under preparation. Many presentations that have used the MARCUS data are listed here.

3.1 Journal Articles

Sato, K, J Inoue, S Alexander, G McFarquhar, and A Yamazaki. 2018. “Improved reanalysis and prediction of atmospheric fields over the Southern Ocean by campaign-based radiosonde observations.” *Geophysical Research Letters* 45(20): 11406–11413, doi:10.1029/2018GL079037

3.2 Conference Presentations

Alexander, SP, A Protat, RT Marchand, G McFarquhar, H Nguyen, AJ McDonald, and A Klekociuk. 2018. “Cloud properties over the Southern Ocean observed from the surface.” 15th American Meteorological Society Conference on Cloud Physics, Vancouver, British Columbia, 9–13 July.

Bretherton, CS, GM McFarquhar, R Marchand, A Protat, S Alexander, A Gettelman, Y Ming, and SOCS Team. 2018. “The Southern Ocean Climate Studies: Observations and modeling of Southern Ocean clouds and aerosols.” American Geophysical Union Fall Meeting, Washington, D.C.

DeMott, PJ, CS McCluskey, KA Moore, TCJ Hill, J Ezra, T Levin, CH Twohy, LM Russell, DW Toohey, B Rainwater, G McFarquhar, A Protat, R Humphries, J Mace, and SM Kreidenweis. 2018. “The concentrations, spatial distribution and compositions of ice nucleating particles in and around stratiform clouds over the Southern Ocean.” 10th International Aerosol Conference, American Association for Aerosol Research, St. Louis, Missouri, 2–7 September 2018.

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McFarquhar, GM, and the MARCUS Science Team. 2018. “Preliminary look at statistical distributions of cloud and aerosol properties over Southern Oceans during MARCUS.” 2018 Joint ARM user facility and Atmospheric Science Research Principal Investigator meeting, Tysons, Virginia, 19–23 March 2018.

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Schnaiter, M, PJ DeMott, TCJ Hill, and GM McFarquhar. 2019. “Fluorescent biological aerosol particles of the Southern Ocean boundary layer and their potential role for ice nucleation in clouds.” 11th American Meteorological Society Symposium on Cloud-Aerosol-Climate Interactions. American Meteorological Society Annual Meeting, Phoenix, Arizona.

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