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Macquarie Island Cloud and Radiation Experiment (MICRE) Science Plan

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Summary

Clouds over the Southern Ocean are poorly represented in present day reanalysis products and global climate model simulations. Errors in top-of-atmosphere (TOA) broadband radiative fluxes in this region are among the largest globally, with large implications for modeling both regional and global scale climate responses. Model TOA radiative errors are due largely to errors in the model representation of clouds and aerosols. However, our knowledge of cloud and aerosol properties over the Southern Ocean relies heavily on satellite data sets. Uncertainty in satellite retrievals of cloud and aerosol properties, as well as estimates of surface shortwave and longwave fluxes based on these properties, are especially large for the Southern Ocean.

In response to the need for additional measurements of surface radiative fluxes, as well as cloud and aerosol properties over the Southern Ocean, the Atmospheric Radiation Measurement (ARM) Climate Research Facility will deploy a variety of ground-instrumentation to Macquarie Island to conduct the Macquarie Island Cloud and Radiation Experiment (MICRE). The island is ideally situated at 54° S, 159° E and has a small permanently manned research station. The research station is operated by the Australian Antarctic Division (AAD) and manned year-round, in part by the Australian Bureau of Meteorology (BOM). This experiment will be conducted in coordination with AAD and BOM activities planned at this site, specifically, deployment of the Centre for Australian Weather and Climate Research (CAWCR) millimeter-wavelength cloud radar and the CAWCR Cloud and Aerosol Backscatter lidar.

ARM instrumentation is expected to include the following:

- a set of surface broadband radiometers (sky and ground radiation),
- a microwave radiometer (preferably a three-channel system),
- a multifilter rotating shadowband radiometer,
- a laser disdrometer or other precipitation disdrometer, and
- a sun photometer or other instrument capable of making narrow-band (visible and shortwave-infrared) narrow-field of view measurements.

These measurements and associated retrievals will be used to address a number of scientific issues that include evaluating the seasonal cycle of satellite-derived and climate-model-simulated surface radiative fluxes, along with cloud and aerosol properties over the Southern Ocean, as well as isolating factors that contribute to errors (e.g., errors in assumed or simulated boundary layer structure/moisture, presences of supercooled water, etc.). The deployment will be for a 2-year period in order to characterize the full seasonal cycle and its variability.

Acronyms and Abbreviations

AAD	Australian Antarctic Division
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
CAWCR	Centre for Australian Weather and Climate Research
CESD	Climate and Environmental Sciences Division
DOE	U.S. Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
MICRE	Macquarie Island Cloud and Radiation Experiment
MFRSR	multifilter rotating shadow band radiometer
MWR	microwave radiometer
NFOV	narrow field of view
NASA	National Aeronautics and Space Administration
TOA	top-of-atmosphere

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1.0 Introduction

Clouds over the Southern Ocean are poorly represented in present day reanalysis products and global climate model simulations. Errors in top-of-atmosphere (TOA) broadband radiative fluxes in this region are among the largest globally, with large implications for modeling both regional and global scale climate responses (e.g., Trenberth and Fasullo 2010, Ceppi et al. 2012). Recent analyses of model simulations suggest that model radiative errors in the Southern Ocean are due to a lack of low-level postfrontal clouds (including clouds well behind the front) and perhaps a lack of supercooled liquid water that contribute most to the model biases (Bodas-Salcedo et al. 2013, Huang et al. 2014). These assessments of model performance, as well as our knowledge of cloud and aerosol properties over the Southern Ocean, rely heavily on satellite data sets. Satellite data sets are incomplete in that the observations are not continuous (i.e., they are acquired only when the satellite passes nearby), generally do not sample the diurnal cycle, and view primarily the tops of cloud systems (especially for the passive instruments). This is especially problematic for retrievals of aerosol, low-cloud properties, and layers of supercooled water embedded within (rather than at the top of) clouds, as well as estimates of surface shortwave and longwave fluxes based on these properties.

There is also significant concern on the accuracy of the satellite data sets that do exist. These concerns are due in part to the fact there has been little ground-based or in situ validation of satellite data sets over the Southern Ocean, coupled with the fact that both satellite and other data sets show that cloud properties in this region differ from those in other regions including over the Northern Hemisphere extratropical oceans. In particular, satellite retrievals indicate the Southern Ocean has a greater occurrence of multi-layer clouds (Heidinger and Pavolonis 2005, Marchand et al. 2010) and mixed-phase clouds with supercooled liquid water (Hu et al. 2010, Morrison et al. 2010) than the Northern Hemisphere extratropical oceans. Limited in situ observations likewise record extensive cloud layers composed of supercooled liquid water with cloud-top temperatures down to -22°C over the Southern Ocean (Chubb et al. 2013). Satellite cloud microphysical property retrievals, as well as estimates of radiative fluxes, for multi-layer and mixed-phased cloud-types are prone to large errors because of the difficulty in robustly identifying when these conditions occur, as well as the additional degrees of freedom (unknowns) that must be determine or specified. Even relatively advanced multi-instrument retrievals from the current A-Train generally treat mixed-phase clouds empirically (Mace 2010). The presence of mixed-phase conditions and frequent light precipitation likewise constitutes a major source of uncertainty in estimation of precipitation (Behrangi et al. 2012), with differences between estimates based on cloud radar (CloudSat) and microwave (AMSR-E) being especially large (factor of two) over the Southern Ocean (Haynes et al. 2009).

The data sets that do exists for the Southern Ocean show there is a large seasonal cycle in cloud and aerosol properties including cloud condensation nuclei (Ayers and Gras 1991), aerosol optical depth, aerosol composition (Sciare et al. 2009), and cloud droplet number concentration with extremely low cloud droplet number concentrations in the winter (below 40 per cm^3) and much larger values (factors of 2 to 3) during the summer (Boers et al. 1998). Ice nuclei values have also been observed to be very low and may well be an important factor in explaining the prevalence of supercooled water clouds over the Southern Ocean (Burrows et al. 2013). The large increase in summer time aerosol and cloud droplet numbers is likely due to biogenic sources. Processes that determine cloud-forming aerosol properties in pristine environments such as the Southern Ocean are poorly understood and need to be investigated, including the role of marine sources for the production of ice nuclei (Burrows et al. 2013). Recent papers have pointed toward uncertainties in natural aerosols as a major source of uncertainty in the effective radiative forcing by aerosols (Carslaw et al. 2013), and this hinders our ability to use historical observations to constrain estimates of the Earth's climate sensitivity (Kiehl 2007) or to test climate model simulations of anthropogenic aerosol impacts on climate change.

In response to the need for additional measurements of cloud, aerosol, and radiation properties over the Southern Ocean, the Atmospheric Radiation Measurement (ARM) Climate Research Facility will conduct 2-years of observations during the Macquarie Island Cloud and Radiation Experiment (MICRE) in order to fully characterize the full seasonal cycle and its variability. Section 3.0 discusses specific scientific goals and measurement requirements, and Section 5.0 addresses logistical issues.

2.0 Deployment Site

Macquarie Island is well situated for the study of Southern Ocean atmosphere. It is located at 54° S, 159° E. An analysis of satellite data sets on 1 and 0.5 degree grids shows no difference in observed cloud cover near the island with surrounding regions (which is not true of other potential sites located on Antarctica or South America). The aforementioned climate model radiation bias is likewise large and relatively spatially homogenous at this location.

The island has a small permanently manned research station. The research station is operated by the Australian Antarctic Division (AAD) and manned in part by the Australian Bureau of Meteorology (BOM). This manned presence includes technicians supported by BOM, and BOM has agreed to facilitate the installation and support of the ARM instruments at their meteorological enclosure on Macquarie Island. Standard surface meteorology and twice-daily balloon soundings are routinely collected at Macquarie Island.

Also of particular importance is that MICRE will be conducted in coordination with AAD and BOM activities planned at this site. Specifically, Simon Alexander (AAD) and Alain Protat (Centre for Australian Weather and Climate Research; [CAWCR]) are currently leading an effort to deploy the CAWCR millimeter-wavelength cloud radar and the CAWCR cloud and aerosol backscatter lidar to Macquarie Island.

3.0 Science Goals and Measurement Requirements

The overarching objective of this proposed field campaign is to make observations of the surface broadband radiative fluxes in combination with other measurements useful in characterizing cloud and aerosol properties. Specifically, we seek passive microwave observations, which can be used to retrieve cloud-water-path, as well as provide a critical constraint on cloud radar-based retrievals of cloud-microphysical properties (e.g, Frisch et al. 1998; Dong and Mace 2003). Similarly, narrow-band, narrow-field-of-view (NFOV) radiometer measurements have proven to be useful in the retrieving cloud microphysical properties (Chiu et al. 2006, 2010). While broadband shortwave and narrow-band multifilter rotating shadowband radiometer (MFRSR) observations can also be used as a constraint rather than NFOV measurements (Min and Harrison 1996), NFOV is preferred as there is less spatial mismatch between NFOV and the active sensors. Being able to contrast ground-based retrieval techniques is also valuable, in this regard, and it is desirable to have both instruments. MFRSR and sun photometer measurements will also provide valuable information on aerosol optical depth.

These measurements and retrievals will be used to address the following scientific issues:

- How accurate are satellite-derived and climate-model-simulated surface radiative fluxes at Macquarie Island?
- How do surface radiative errors vary with large-scale/synoptic conditions and cloud-type? Do observations at Macquarie Island support current studies that suggest the error in model clouds is due primarily to low-level postfrontal clouds, including clouds well behind the front? If so, what factors (e.g., errors in boundary layer structure/moisture, supercooled water, etc.) are involved?
- How do satellite retrievals of cloud water path, effective radius, and number concentration of low-level clouds compare with ground-based retrievals? Are satellites capturing the seasonal cycle of these properties correctly?
- Under what large-scale/synoptic conditions and under what cloud-types are retrieval differences largest? And why?
- How do satellite retrievals of aerosol optical properties (specifically aerosol optical depth) compare with ground-based results? What are the implications in terms of aerosol physical properties and seasonal variability?

We anticipate that addressing the above questions will help pinpoint conditions under which satellite observations and models are most in need of improvement; and the results will help guide the development of processed-based modeling studies. The twice-daily radiosondes launched from Macquarie will aid in understanding conditions that drive errors, as well as help constrain large-scale forcing needed in processed-based modeling studies.

4.0 Instruments

We stress that the ARM Facility observations are supplementing observations already being made by BOM at Macquarie Island, which include basic surface observations (winds, pressure, surface air temperature, relative humidity, cumulative surface precipitation, etc.), as well as twice-a-day radiosondes, in addition to the already mentioned cloud radar and lidar (end of section 2.0).

MICRE is part of a larger strategy—The Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study or SOCRATES—to obtain observations over the Southern Ocean that will investigate a variety of critical scientific issues. SOCRATES is an international and multi-agency activity that will nominally include measurements from aircraft and ship (including the Australian ship *R/V Investigator*) with Macquarie Island being one focus of these measurements. The SOCRATES white paper can be obtained at http://www.atmos.washington.edu/socrates/.

Our experience with the ARM Facility shows that the value of the Macquarie radar, lidar, and other data sets will be greatly improved when combined with observations from a variety of radiometers.

Specifically, the ARM Facility will deploy the following instruments to Macquarie Island as part of MICRE.

Table 1. ARM Facility instruments to be deployed at Macquarie Island.

Instrument Name	Key Quantities Measured (Notes)
SKYRAD, GRDRAD	Upwelling and dowelling surface broadband shortwave and longwave fluxes.
Microwave Radiometer (MWR)	Microwave brightness temperatures for the retrieval of column water vapor and liquid water path (3-channel system preferred, TBD).
Multifilter Rotating Shadowband Radiometer (MFRSR)	Direct and diffuse radiances at several visible and shortwave infrared frequencies for the retrieval of aerosol and cloud optical depth.
Sun Photometer or other instrument capable of making narrow-band (visible and shortwave infrared) narrow-field of view measurements	Nadir viewing radiances at several visible and shortwave infrared frequencies for the retrieval of cloud optical depth.
Disdrometer (laser, TBD)	Drop size distribution, precipitation rate and amount.

5.0 Logistics

As with most of the Southern Ocean, Macquarie Island is a remote location. The island is resupplied by ship once or twice a year, with the March 2016 visit being the time to deploy instruments. ARM instruments will need to be in Hobart, Tasmania, Australia, for loading onto the ship about 1 month before the ship sails and would be shipped back to the United States about 1 month after return.

Our nominal plan is for one or two ARM Facility personnel to travel to Macquarie, set up the instrumentation and train local BOM technicians. Details will be determined via consultations between the ARM Facility's technical division, BOM's technical support group, and AAD logistical capacity. BOM personnel stationed on Macquarie Island will be available to provide on-site support in the form of daily cleaning radiometer domes, checking that instruments are up and running, and other simple tasks. MICRE investigators Roger Marchand and Simon Alexander will facilitate communications between the ARM Facility and BOM personnel and will be directly involved in deployment planning. The set-up voyage will require approximately 3 weeks (a 1-week voyage out, up to 1 week spent at Macquarie, and a 1-week voyage back).

While satellite communications are available, the bandwidth is limited, and 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 BOM, but some bandwidth will be available for this purpose.

We note that the island has no dock facility capable of supporting sea containers. All equipment must be small and light enough that it can be transported by helicopter sling or lifted by (at most) a few people from a small boat. As such, this site is not well suited for a full ARM Mobile Facility deployment, and hence another reason for collaboration with Australian efforts.

Additional details on conditions at Macquarie can be found at http://www.antarctica.gov.au/living-and-working/stations/macquarie-island.

6.0 Relevance to DOE Mission

The U.S. Department of Energy (DOE) and DOE Office of Biological and Environmental Research, Climate and Environmental Sciences Division (CESD), in particular, has a long history in supporting basic research that addresses key uncertainties in the understanding of Earth’s complex climate. This is well represented in the CESD strategic plan, which sets as a priority “focused research on key earth system processes that represent significant uncertainties and currently limit predictive understanding,” and calls for a “comprehensive portfolio of research on cloud-aerosol-precipitation interactions” that includes collecting “observations made across a wide range of environmental conditions.” In particular the CESD strategic plans seeks to leverage DOE capabilities including the ARM Facility in order to provide “insight into understanding and describing cloud and aerosol influences on Earth’s radiative balance and climate” (page 4 of CESD strategic plan).

The scientific objective of this deployment supports this CESD priority. As described in the introduction, the Southern Ocean is recognized as a region where climate model simulations are believed to have large errors with profound implications for climate change projections, and for which knowledge of precipitation, cloud and aerosol properties, and surface radiation is highly uncertain. The proposed deployment will provide a much needed baseline data set from which to evaluate surface radiative fluxes from climate models, as well as those derived from satellite data sets. In addition, retrievals of cloud and aerosol properties will inform potential changes to climate model parameterizations, as well as be used in evaluating satellite property retrievals. As a global modeler at the recent Southern Ocean workshop put it, the question is not whether climate model clouds can be tuned to eliminate radiative biases in the Southern Ocean, but rather the question is can we eliminate biases in the Southern Ocean without simply generating new biases elsewhere? For that, we need to get the same model parameterizations to produce the correct cloud properties for clouds in all regions, and in particular, this means we need to know more about the properties of Southern Ocean clouds and aerosols and to have confidence in our knowledge of these properties. Given the paucity of ground-based measurements over the Southern Oceans, this deployment will produce a much-needed data set. Working in collaboration with Australian efforts provides a wonderful opportunity for the ARM Facility to make a big impact with a relatively modest deployment.

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