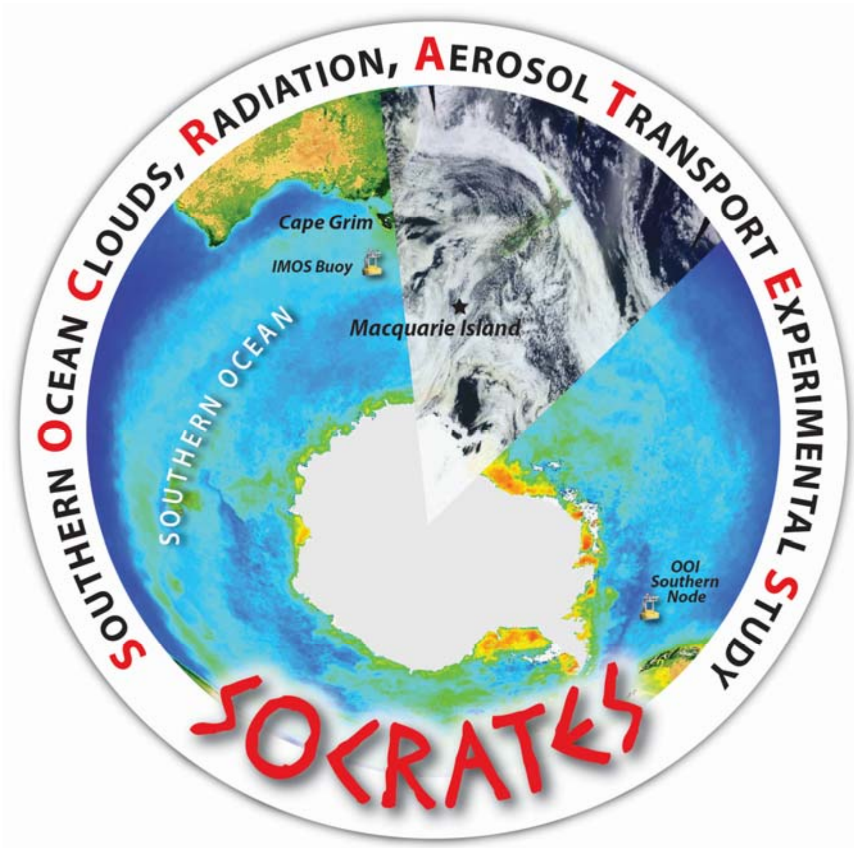
THE SOUTHERN OCEAN CLOUDS, RADIATION, AEROSOL TRANSPORT EXPERIMENTAL STUDY



THE SOCRATES PLANNING TEAM

Roj Marchand, Robert Wood, Chris Bretherton, University of Washington, Seattle, Washington
Greg McFarquhar, University of Illinois, Urbana, Illinois
Alain Protat, Bureau of Meteorology, Melbourne, Australia
Patricia Quinn, NOAA PMEL, Seattle
Steven Siems and Christian Jakob, Monash University, Melbourne, Australia
Simon Alexander, Australian Antarctic Division, Kingston, Tasmania, Australia
Bob Weller, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts

SOCRATES WORKSHOP PARTICIPANTS AND CONTRIBUTORS

Steve Ghan, Chris Hostetler, Gijs de Boer, Jay Mace, Pavlos Kollias, Richard Moore, Theodore Wilson, Dennis Hartmann, Jorgen Jensen, Jennifer Kay, Lynn Russell, Jacob Scheff, Elizabeth Maroon, Susannah Burrows, Sara Tucker, Jeff Stith, James Hudson, Joellen Russell, Yan Feng, Paul DeMott, Tom Lachlan-Cope, Paulo Ceppi, Daniel Grosvenor, Daniel McCoy, Nicholas Meskhidze, Chris Fairall, Sarah Gille, Tim Bates, Cassandra Gaston, Erica Dolinar, Ryan Stanfield, Keith Williams, Alejandro Bodas-Salcedo, Bob Rauber, Mike Harvey, Antony Clarke, Monica Orellana, Andreas Muhlbauer, Lorenzo Polvani, Yongxiang Hu, Scott Collis, Anna Gannet Hallar, Ying Li, Adrian James McDonald, Kalli Furtado, Gregory Roberts, Ann Fridlind, Andrew Ackerman, Carol Clayson, Benjamin Hillman

Preamble

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, and remote from most human influences. It influences the atmospheric and oceanic circulation of the entire southern hemisphere and beyond.

The remoteness from anthropogenic and natural continental aerosol sources makes the SO a unique testbed for our understanding of cloud-aerosol interaction, both for liquid and ice clouds, and the role of marine biogenic aerosols and their precursors. Weather forecast and climate models almost universally underpredict the amount of low-lying cloud in the cold sector of mid-latitude cyclonic storm systems, and this is particularly prominent over the SO, where such systems are ubiquitous year-round.

Climate models are challenged by uncertainties and biases in the simulation of SO clouds, aerosols, and air-sea exchanges which trace to poor physical understanding of these processes in this unique component of the climate system. These biases affect the simulated global energy budget (Fig. 1), the location of tropical rainfall belts, and simulation of anthropogenic indirect aerosol effects on climate, and may impact simulated global cloud feedbacks and carbon-cycle feedbacks on climate change. These biases further limit our understanding of the vast uptake of carbon dioxide into the SO. The SO surrounds Antarctica and therefore interacts closely with massive ice shelves whose stability to climate change is uncertain but could be catastrophic.

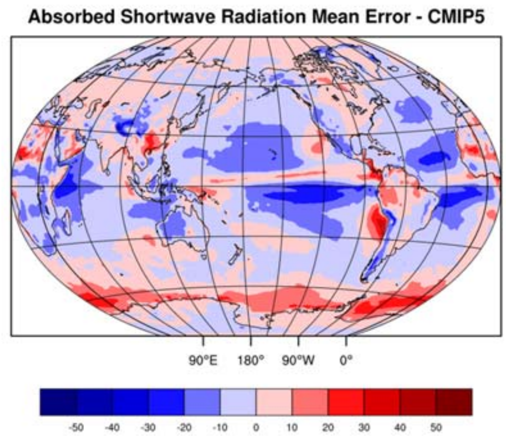


Figure 1: CMIP5 model clouds do not reflect enough sunlight. Ensemble mean error for CMIP5 models in shortwave radiation absorbed by the Earth System. Positive values indicate too much shortwave radiation absorbed.

There have been sparse and infrequent observations of clouds, aerosols, precipitation, radiation and the air-sea interface in this region (see section 1). Consequently, much is unknown about atmospheric and oceanographic processes and their linkage in this region. We believe that the time is ripe for a major new in-situ measurement campaign to study clouds, aerosols and the air-sea interface in the SO. This white paper provides a more detailed motivation, including scientific themes and testable hypotheses, leading to a proposed implementation plan for the **SO C**louds, **R**adiation, **A**erosol **T**ransport **E**xperimental **S**tudy (SOCRATES).

The scientific and modeling challenges addressed by SOCRATES are nationally and internationally acknowledged to be high priorities for climate science. The World Climate Research Program (WCRP) recently formulated six grand challenge problems, one of which is Clouds, Circulation and Climate Sensitivity[1]. WCRP note that '*limited understanding of clouds is the major source of uncertainty in climate sensitivity, and also contributes substantially to persistent biases in modelled circulation systems*'. A recent draft report of the Geosciences Division of the U.S. National Science Foundation has called out the Southern Ocean as one of five research frontiers, noting many of the themes central to SOCRATES. SOCRATES complements NSF's Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM), running from 2014-2020, which will focus on SO biochemistry, circulation, and carbon uptake. In particular, SOCRATES aims to stimulate atmospheric model improvements that will lead to a better representation of the entire earth system by reducing errors in SO surface energy balance and winds. This could improve not just the simulation of physical climate, but also of carbon uptake and other biogeochemical processes, as well as Antarctic sea ice and ice shelves.

---

[1] See *http://www.wcrp-climate.org/index.php/gc-clouds*

Prior observations

Table 1: Past intensive observational studies focused on the study of clouds and aerosols over the Southern Ocean

Field Experiment	Time	Range	Primary Science
Southern Ocean Cloud Experiments (SOCEX I & II) Boers et al. 1998	Jul 1993; Jan 1995	40°-43°S	Cloud Microphysics Characterization and seasonal bounds
Aerosol Characterization Experiment (ACE 1) Bates et al. 1998	Nov/Dec 1995	40°-55°S	Atmospheric Chemistry Secondary cloud microphysics obs.
HIAPER Pole to Pole Observations (HIPPO) Wofsy et al. 2011	5 flights 2009-11	43°-67°S	Global Atmospheric Chemistry; secondary cloud microphysics obs.

Our current level of understanding of cloud and aerosol processes over the SO is based upon data gathered from previous observations and associated model studies (Table 1 shows influential intensive observations). The SOCEX aircraft campaigns, with two phases: summer (Jul 1993, Boers et al. 1998) and winter (Jan-Feb 1995, Boers et al. 1996), measured cloud droplet concentrations that were a factor of 2-3 higher in summer than winter, suggestive of an important seasonal cycle in SO aerosol budgets and cloud-aerosol interaction. The SOCEX measurements were conducted at latitudes 40-43°S and did not have comprehensive aerosol composition measurements.

The first Aerosol Characterization Experiment (ACE-1, Bates et al. 1998a) was a comprehensive field experiment in 1995 involving two ground sites (Macquarie Island and Cape Grim), two research vessels, and the NSF/NCAR C-130 aircraft aimed at improved quantification of chemical and physical processes controlling atmospheric aerosol relevant to radiative forcing and climate. ACE-1 documented the role of dimethylsulfide (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. 1998, Weber et al. 1998), and the importance of sea-spray aerosol (Bates et al. 1998). However, sampling in ACE-1 stayed north of 54°S and largely away from clouds. More recently, the HIPPO campaigns using the NSF/NCAR G-V aircraft (Wofsy et al. 2011) have provided the only in-situ dataset on clouds and aerosols south of Macquarie Island (54°S), with four transects extending down to latitudes of 67°S.

Ground based atmospheric chemistry observations are ongoing at Lauder and Baring Head (New Zealand) and Cape Grim (Australia). 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 a likely cause being greater ocean biogeochemical activity during summer (Ayers and Gras 1991).

2. Climate model biases and observational knowledge gaps

A central motivation for SOCRATES is to provide measurements to support the improvement of climate model simulations of planetary boundary layer (PBL) processes, shallow convection, clouds, and aerosols over the SO. Satellite observations identify systematic SO cloud and aerosol biases in climate models, and global modelling studies demonstrate the importance of these biases. A comprehensive suite of in-situ measurements across the seasonal cycle is critical for supporting and testing improved process representations in the models, as well as for making better use of the satellite observations available to constrain models.

Clouds over the SO are poorly represented in global climate model simulations (Trenberth and Fasullo 2010) and even present-day reanalysis products (Naud et al. 2014). The CMIP5 ensemble mean error in annual mean absorbed shortwave radiation (Fig. 1) between 55°S and the Antarctic coast indicates systematically too much absorbed shortwave radiation, especially during Austral summer, inducing warm SST biases year-round over the SO. This bias is mainly due to too little cloud, though sea-ice may also contribute.

The large radiation biases interact with the location of the Southern Hemisphere 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). Recent analyses of model simulations suggest several possible reasons for the model radiative errors in the SO. A major contributor is a lack of clouds in the cold sectors of cyclones (Fig. 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 zonal-mean reflected shortwave radiation do so by compensating this error with overly bright high clouds in the warm sector of cyclones.

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., excessively rapid glaciation of supercooled liquid cloud or excessive precipitation from cumulus, (4) errors in representing sub-grid condensate variability, and (5) inadequate resolution of the circulation systems in which the clouds evolve (Govekar et al. 2014).

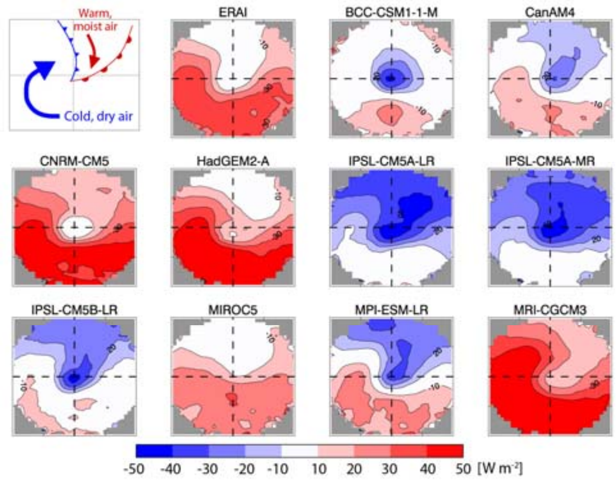


Figure 2: Cyclone compositing indicates consistent patterns of insufficient reflected shortwave in the cold, dry regions of the cyclones. Figure shows bias in absorbed shortwave radiation for AMIP models from Bodas-Salcedo et al. (2013).

Natural aerosols are a major source of uncertainty in the effective radiative forcing by aerosols (Ghan et al. 2013, Carslaw et al. 2013). This hinders our ability to use historical observations to constrain estimates of Earth's climate sensitivity (Kiehl 2007) or to test climate model simulations of anthropogenic aerosol impacts on climate change. The SO is an important testbed for climate model simulations of aerosols and aerosol-cloud interaction. It is far from most continental aerosol sources, and climate models suggest only weak anthropogenic aerosol impacts.

The datasets that do exist for the SO show there is a large seasonal cycle in cloud and aerosol properties including cloud condensation nuclei concentration (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 (<40 cm^{-3}) and much larger values during summer (Boers et al. 1998). The summertime peak is likely due to marine biogenic sources, but the pathway remains uncertain (Quinn and Bates 2011). Concentrations of efficient ice nuclei have been observed to be very low and may be an important factor in explaining the prevalence of supercooled water clouds over the SO; the importance of marine IN sources is an important modelling uncertainty (Burrows et al. 2013) as is the role of secondary ice production processes that may play an important role in these pristine environments.

CMIP5 climate models struggle to represent aerosol processes and to achieve accurate simulations of the annual mean and seasonal cycle of CCN and cloud droplet concentration over the SO. This may also contribute to the SO shortwave biases in some climate models. 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/IN, or whether other physical controls on cloud cover dominate.

Table 2 presents the key observational and modelling requirements to guide the development of SOCRATES measurements and associated modelling.

Table 2: Observational and modelling requirements for SOCRATES

SOCRATES observational requirement	To narrow the manifold uncertainties in representing key processes in climate models, a comprehensive dataset is needed to document PBL structure, and associated vertical distributions of liquid and mixed-phase cloud and aerosol (including CCN and IN) over the Southern Ocean, across the year under a range of synoptic settings. These observations will also be used to evaluate active and passive satellite observations.
SOCRATES modeling requirement	For such a dataset to have broad impact on climate modelling, the modelling community must be an integral part of the SOCRATES design and be involved in a systematic confrontation of leading climate models with SOCRATES datasets, e. g. using short-term hindcasts as in the VOCALS model assessment (Wyant et al. 2014).

3. Science themes

There is already great value in gathering an *in situ* dataset for constraining and improving process representations in climate models. Parameterization uncertainties also trace to a fundamental lack of understanding about many aspects of the SO cloud-aerosol-ocean system, which we categorize into four overlapping science themes underpinning SOCRATES. By design, these themes also encompass much of the aforementioned climate modelling uncertainty, but they are organized at a process level that flows into falsifiable hypotheses that SOCRATES is designed to test.

Theme 1: Documenting the synoptically-varying vertical structure of Southern Ocean boundary layers and clouds

In this theme, we consider issues that principally involve planetary boundary layer (PBL) vertical structure and turbulent transport, as well as their synoptic-scale context. SO PBLs and clouds are creatures of constantly evolving synoptic environments associated with the frequent passage of mid-latitude cyclones along the SO storm track. The SO includes an oceanic front (a zone of strong meridional SST gradients and complex ocean eddy and biogeological productivity structure) at 55-60^{o}S in the Australia/New Zealand sector, across which air-sea temperature differences and the PBL structure of advecting air masses change quickly. Modern global atmospheric models can resolve, assimilate and forecast this synoptic variability, which is a strong control on the relative humidity and hence the cloud distribution, even without a representation of aerosol variability (Naud et al. 2012). This shows the primacy of synoptic forcing in determining cloud macrophysical properties.

However, global models still suffer significant regime-dependent errors in their simulated cloud microphysical and radiative properties, including cloud cover. Deficiencies in turbulent and cumulus parameterizations may contribute. At Macquarie Island, well-mixed stratocumulus-topped PBLs less than 1 km deep are frequent (Huang et al. 2012a). In such PBLs, much can be inferred from surface measurements, e.g. the cloud base is tied to the near-surface lifted condensation level, and cloud-base aerosol concentrations are tied to near-surface aerosol concentrations. Despite their simple vertical structure, well-mixed cloud-topped PBLs have proved challenging for climate models to parameterize and simulate in other parts of the world such as the subtropics, due to insufficient vertical resolution, uncertainties about entrainment, and strong cloud-radiation feedbacks.

Over the SO, the lower troposphere often has more complex thermodynamic and aerosol structure, with multiple layers interacting with strong wind shear (e.g. Russell et al 1998; Jensen et al 2000) that are not well represented in reanalyses (Hande et al. 2012). Decoupled and cumuliform PBLs are also evident in satellite imagery of the SO. During ACE-1, 'buffer layers' were often seen above the lowest cloud layer (Russell et al. 1997), with thermodynamic and aerosol properties intermediate between the PBL and the overlying free troposphere. Buffer layers are poorly understood and inadequately documented; they might form due to synoptic lifting and differential advection, or due to shallow cumulus convection that detrains above the PBL.

Shallow convective microphysics/detrainment: Because shallow cumulus convection is common in the cold sector of mid-latitude cyclones, it is an important determinant of simulated SO cloud properties in climate models. Park et al. (2014) shows that in the CAM5 climate model, most of the simulated ice water path over the SO is within the updrafts of shallow cumulus clouds, even though most of the liquid water is in stratus clouds. This suggests that CAM5's cloud climatology might be sensitive to the phase partitioning of cumulus updraft condensate, which is a specified function of temperature. Indeed, Kay et al. (2014) found that if all cumulus updraft condensate in CAM5 is forced to remain liquid down to -20^{o}C, the simulated cloud cover and albedo increase substantially over the SO and approximately match satellite observations.

Presumably, shallow convection is equally important in reality in determining the vertical structure and phase of SO clouds, as well as in vertical aerosol transport and processing. In particular, the above discussion suggests that:

Hypothesis 1.1: A primary reason that most climate models simulate too little cloud in the cold sector of mid-latitude cyclones is inadequate liquid water reaching the tops of parameterized shallow convective clouds, due to vertical transport and microphysical biases.

The interaction of cumulus convection and mixed-phase microphysics is not well observed, aside from a few observations during SOCEX (Table 1). SOCRATES will naturally sample and document this important process with modern *in situ* and airborne remote sensing instrumentation.

Aerosol transport: A plausible consequence of the dynamic synoptic environment of the SO, and of regional variability in ocean productivity across the strong SST gradients characterizing this region, is:

Hypothesis 1.2: Over the SO, there is substantial free-tropospheric aerosol variability that is mainly tied to synoptically-varying long-range transport from remote oceanic and continental sources. Within the boundary layer, local processes such as surface sources and precipitation scavenging are also important contributors to aerosol variability.

So far, free-tropospheric aerosol measurements over the SO are too sparse to test this hypothesis, but SOCRATES can bring to the table a powerful combination of more aerosol measurements in and above the boundary layer, modelling and back-trajectory analysis, and satellite remote sensing. Within the PBL, we anticipate that climate models will be particularly challenged to simulate observed aerosol concentrations, due to aerosol interactions with parameterization challenges such as cumulus convection or turbulence-microphysics interaction.

A logical and testable follow-on to Hypothesis 1.2 is that the aerosol variability is not just substantial, but significant for cloud properties:

Hypothesis 1.3: Synoptic-scale aerosol variability has measurable effects on the cloud microphysical and radiative characteristics through its influence on cloud droplet and ice crystal concentrations.

This hypothesis can be tested by relating the measured cloud particle concentrations to relevant measures of aerosol, assuming there is sufficient space-time variability of both within clouds forming in a given broad meteorological regime.

Comparison with models: It is a challenge to compare models with a necessarily limited dataset in such a complex and variable environment, in which model errors in dynamics, clouds, aerosols, and surface properties quickly become intertwined. One strategy that holds promise for SOCRATES is running global climate models in a nudged-meteorology mode in which the three-dimensional wind field is constantly nudged toward a global reanalysis over the observation period (allowing the model to freely predict the associated temperature, humidity, cloud and aerosol fields), and the model is sampled at the time and location of the observations (Fig. 3).

To achieve a representative comparison, it is important to sample across synoptic regimes and latitudes, not just cold-sector or warm-sector clouds in one area. To average across synoptic variability requires a longer dataset than an airborne field campaign can collect; in this environment, extended-time observations are a critical complement to intensive *in situ* measurements.

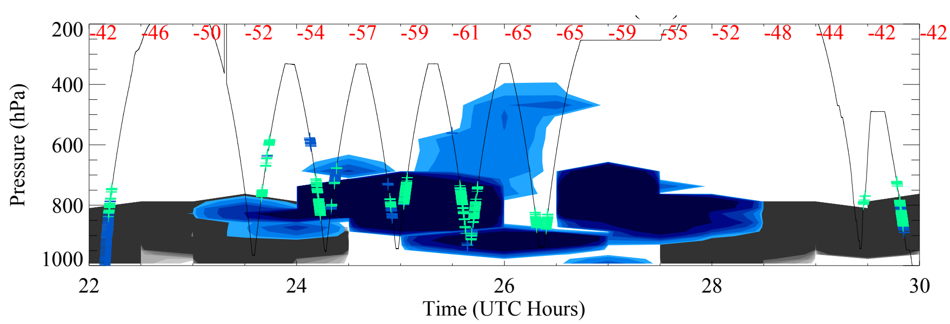


Figure 3: Comparison of measurements of cloud phase from a HIPPO flight (black flight track and colored symbols, green for supercooled water and blue for ice) with simulations from the CAM5 climate model, nudged to maintain observed meteorological conditions (shading in upper panel, blue for ice, black for liquid cloud). Latitude is shown in red along the top. Courtesy Andrew Gettelman (NCAR).

Theme 2: Understanding seasonal and synoptic variability in Southern Ocean cloud condensation and ice nucleus concentration and the role of local biogenic sources.

Processes that determine cloud-forming aerosol properties in pristine marine environments such as the SO remain poorly understood (Carslaw et al. 2010, Quinn and Bates 2011). Uncertainties in our understanding of aerosols in the preindustrial environment impede our ability to quantify the radiative forcing from anthropogenic aerosols over the industrial era (Carslaw et al. 2013, Ghan et al. 2013). Model studies indicate that a significant fraction of global anthropogenic aerosol 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). As a result, the SO has the potential to serve as a modern surrogate for aerosol conditions in the preindustrial era.

Lower tropospheric source and sink terms in the CCN and IN budgets over the SO are not well understood. Major unresolved issues are (a) the relative importance of local surface sources compared with long-range transport of primary aerosol and gas phase precursors; (b) the relative contributions of different surface-generated species to the surface source; and (c) the importance of spatiotemporally-varying sinks, most notably precipitation. Surface sources contributing to the CCN budget include primary sea-spray emissions composed of both sea salt and biogenic organic components (Quinn et al. 2014). In addition, there are surface sources of biogenic gas phase aerosol precursors, including dimethylsulfide (DMS) and organic species. Model studies (e.g., Korhonen et al. 2008) indicate that the impact of DMS on CCN concentrations over the SO primarily occurs via nucleation of new particles in the upper free troposphere (FT) with subsequent transport and subsidence back to the PBL. Observations are limited, but support the FT being an important aerosol transport pathway over the SO. Mean profiles of both total particle number (Clarke et al., 1998a) and CCN concentrations (Hudson et al. 1998) from ACE-1 indicate higher concentrations in the FT than in the PBL, consistent with an FT source of aerosols impacting the PBL CCN budget.

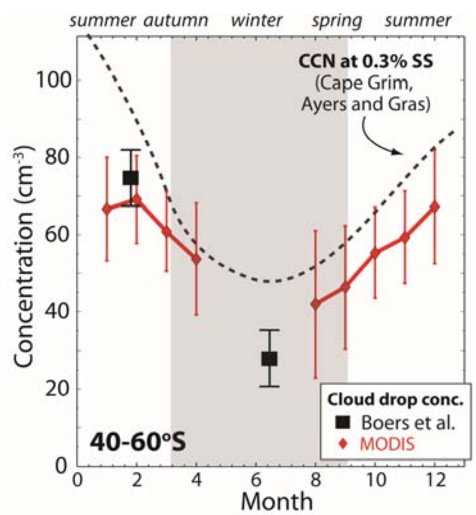


Figure 4: Seasonal cycles of cloud drop concentration (N_d) and CCN concentration over the Southern Ocean. N_d data are derived from passive visible/near-IR data from MODIS (red) and from limited aircraft flights during winter and summer (black squares). The seasonal cycle of CCN at 0.3% supersaturation from measurements at Cape Grim (Ayers and Gras 1991) is also shown, as are cloud droplet concentration measurements from SOCEX campaigns (Table 1).

Observations from Cape Grim, Tasmania (Fig. 4) show striking seasonality, with a clear summertime peak in CCN concentration that corresponds to the peak in methane sulphonic acid (MSA), an atmospheric oxidation product of DMS. The correspondence in the seasonal cycles of CCN and MSA has led to the hypothesis that increasing biological emissions of DMS from the ocean during warmer months when ocean productivity increases leads to an increase in CCN concentration (Ayers and Gras 1991). Satellite data imply a corresponding summertime maximum in cloud droplet concentration (N_d) over the entire SO (from 40-60^{o}S, Fig. 4). This motivates:

> Hypothesis 2.1: Entrainment of biogenically-derived aerosols from the free troposphere constitutes a major source of CCN for Southern Ocean PBL clouds during summer, but sea-salt aerosols are the dominant CCN source in winter.

To test this hypothesis, *in situ* measurements of aerosol physicochemical properties, their vertical structure and their CCN activity are needed, especially over the unexplored southern latitudes of the SO. The striking seasonal contrast (Fig. 4) motivates the need to make measurements during both summer and winter. Figure 5 provides a summary of the primary sources and production mechanisms for CCN and IN.

Major progress has been made in the development of new techniques for the characterization of aerosol composition and sources since ACE-1. Aerosol mass spectrometers are now available that are able to quantify size and chemical mass concentrations of aerosol species. In addition, new techniques for determining organic composition, isotopic composition, and genetic markers have made it possible to search for similarities between surface seawater and atmospheric aerosol properties. Methods are now available for generating freshly emitted sea spray aerosol before it is altered by interactions with existing atmospheric gases and particles (Keene et al., 2007; Bates et al., 2012). These techniques make it possible to isolate nascent sea spray aerosol and determine its cloud-forming properties.

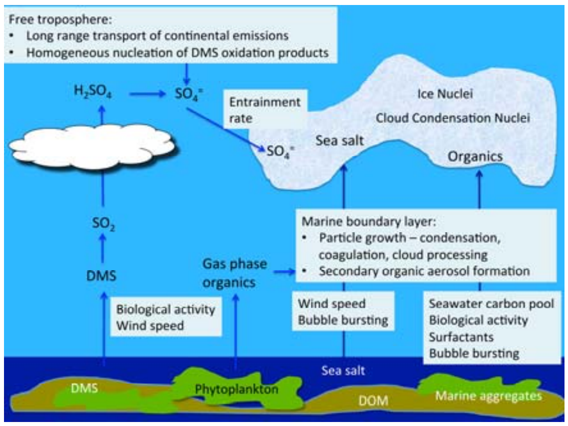


Figure 5. Major sources and production mechanisms for CCN and IN in the remote marine boundary layer. DMS contributes to the MBL CCN population primarily via particle nucleation in the FT in cloud outflow regions with subsequent subsidence. Sea salt and organics are emitted as a result of wind-driven bubble bursting.

Ice nuclei: The lack of extensive landmasses in the Southern Hemisphere extratropics limits the amount of dust able to serve as IN (Choi et al. 2010). Surface and satellite lidar observations indicate a higher frequency of supercooled liquid water clouds over the SO compared with other ocean regions, a finding that may indicate a lack of IN over the SO (Kanitz et al. 2011, Hu et al. 2010).

Given the lower dust and anthropogenic aerosol loadings than at comparable northern latitudes, there remain important questions regarding what aerosols nucleate ice over the SO, their number concentrations and seasonal variations (Burrows et al., 2013). Recent laboratory studies have confirmed a source of IN directly from sea spray particles (Prather et al., 2013), and have isolated some marine phytoplankton as active IN (Knopf et al., 2011), but little has been done to systematically characterize ocean-derived particles for their IN ability. Existing measurements of IN concentrations over the SO are limited to a single set of observations from 1969-1972 (Bigg, 1973). These measurements are an order of magnitude lower than concentrations measured over land regions by equivalent methods at that time (Pruppacher and Klett, 1997). Reported IN concentrations from other oceanic regions are broadly consistent with these results, but with some reports of patchy regions of very high IN concentrations occurring in regions of high biological productivity (Rosinski et al., 1987). An association of IN abundance with plankton was suggested by Schnell and Vali (1976). Additional measurements indicate that marine IN range in size from 50 to 300 nm (Bigg and Leck, 2001; Rosinski et al., 1987). Specific ice nucleating bacteria or viruses from oceans have not been clearly identified, suggesting the possibility that unidentified organic species are the primary source of marine IN. This suggests:

Hypothesis 2.2: Biogenic particles are the dominant source of ice nuclei over the Southern Ocean

There is a great need for new spatiotemporally-resolved measurements of IN over the SO. The current measurement community appears poised to take up this challenge with a suite of real-time and offline measurement methods that have shown good agreement in recent intercomparisons (e.g., DeMott et al., 2011; Garcia et al., 2012). Previously mentioned single particle analytical instruments, and new biological probes to specifically identify the action of marine organisms versus other organic aerosol types should add greatly to our understanding of sources and properties of IN over the SO (Hill et al., 2014).

Theme 3: Supercooled liquid and mixed-phase clouds

Supercooled liquid water clouds are common over high latitudes (Hu et al. 2010), especially over the SO. Satellite observations suggest that low-level clouds (with tops below 3 km) are dominant over the SO. These clouds are rarely glaciated at cloud-top, even at temperatures down to -25°C (Morrison et al. 2011, Huang et al 2012b). Beneath cloud-top there is a high degree of uncertainty in assigning the thermodynamic phase, especially in the common situation of multiple cloud layers (Mace 2010). These observations and their uncertainties motivate:

> Hypothesis 3.1: Supercooled liquid clouds contribute substantially to observed cloud reflectance over the Southern Ocean.

Although the remote sensing of supercooled clouds is challenging (see theme 4), satellite retrievals suggest that the SO features a greater occurrence of mixed-phase clouds with supercooled water (Hu et al. 2010, Morrison et al. 2011, Chubb et al. 2013) compared with similar latitudes in the Northern Hemisphere (Fig. 6). Because the partitioning of condensate into ice and liquid impacts cloud albedo (Sun and Shine 1994), the high frequency of supercooled water over the SO may play a role in the shortwave radiation bias discussed in section 2. Indeed, changes in supercooled water from warming and stability changes may control SO climate feedbacks (Kay et al. 2014).

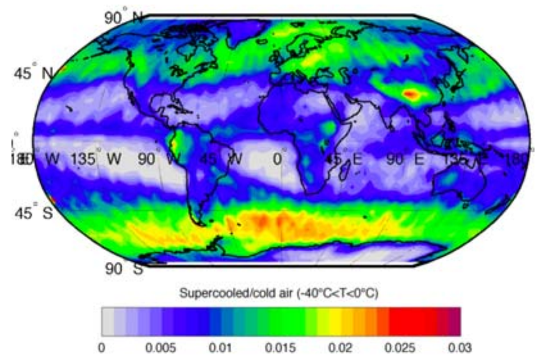


Figure 6: Probability of cloud containing supercooled liquid water between -40 and 0 °C, retrieved using CALIPSO depolarization measurements from DARDAR algorithm of Delanoë and Hogan (2008)

A key to understanding and modeling microphysical processes in mixed-phase and supercooled clouds lies in characterizing their physical properties. Much is unknown about the frequency of occurrence of supercooled water, the sizes and concentrations of cloud droplets, their vertical distribution, their formation mechanisms and the meteorological conditions supporting them. Mechanisms responsible for the production and evolution of ice in mixed-phase systems are not understood. A primary objective of SOCRATES is to collect a data set suitable to study interactions between microphysics, dynamics and radiation in mixed-phase and supercooled clouds. The resulting dataset will be used to develop and evaluate parameterizations in models with a variety of spatial and temporal scales, as well as for ground- and space-based remote sensing retrievals that can provide information on properties of such clouds. SOCRATES data will reach far beyond that available from the HIPPO project (Table 1), which effectively sampled cold clouds over the SO on only two flights, finding large amounts of supercooled water up to 0.5 g m^{-3}, widespread drizzle, and infrequent ice at temperatures as low as -22˚C (Chubb et al. 2013).

Ground-based remote sensing studies over the Arctic (e.g., Shupe et al. 2001, 2005; Intrieri et al. 2002) have shown that supercooled water and mixed-phase clouds occur frequently and are radiatively significant (Dong et al. 2001; Dong and Mace 2003; Zuidema et al. 2005). Compared to the properties of supercooled and mixed-phase clouds measured *in situ* over the Arctic (e.g., Lawson et al. 2001; Rangno and Hobbs 2001; Korolev et al. 2003; Preni et al. 2009; Earle et al. 2011; Lance et al. 2011), the limited data over the SO (Chubb et al. 2013) suggest there is more frequent drizzle, less frequent ice, smaller liquid droplet concentrations and larger liquid particles over the SO. However, there are insufficient *in situ* and remote sensing data to validate this conclusion over a wide range of meteorological conditions, leading to:

Hypothesis 3.2: At similar temperatures and latitudes, there are systematic differences in the sizes and concentrations of supercooled drops, as well as in the mass contents and concentrations of ice crystals between Northern and Southern Hemisphere clouds.

In addition to obtaining observations in the Southern Hemisphere to compare against previous observations in the Northern Hemisphere, it is vital to identify the large-scale forcing and surface processes responsible for the formation and maintenance of supercooled water in SO clouds, and understand how these processes are modulated by aerosols. For instance, Fig. 7 shows that in the more polluted Arctic spring clouds compared to cleaner fall clouds (McFarquhar et al. 2007), larger liquid droplet concentrations, smaller liquid effective radii and lower ice crystal concentrations were measured *in situ*. Thus, it is plausible that the lower aerosol concentrations over the SO and the scarcity of efficient ice nuclei, such as dust particles, could explain the pervasiveness of supercooled water there:

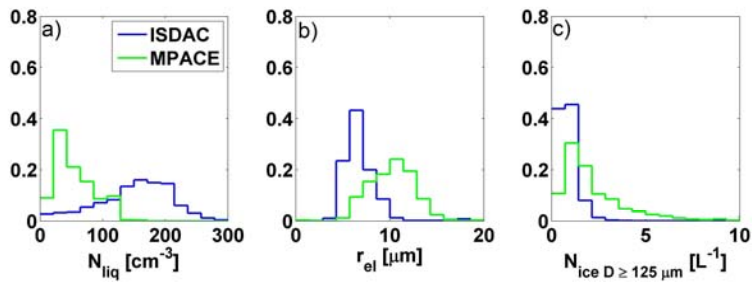


Figure 7: Normalized histograms of (a) (supercooled droplet concentration N_{liq}, (b) liquid cloud effective radius r_{el}, and (c) ice crystal concentration N_{ice} (D>125 μm) from single-layer stratus and stratocumulus measured in Arctic during more polluted spring (ISDAC) and cleaner fall (MPACE); decrease in r_{el} and N_{ice} and increase in N_{liq} with more polluted conditions shows evidence of indirect effect (adapted from Jackson et al. 2012).

Hypothesis 3.3: The activity of IN is the main modulator of the range of temperatures at which supercooled stratus clouds are observed.

Data collected over the SO offer an opportunity to evaluate this hypothesis and various indirect aerosol effects on clouds and radiation because of the unique pristine environment that will be sampled. Although the primary processes by which aerosols indirectly affect liquid clouds (Twomey 1974; Albrecht 1989; Hansen et al. 1997) and the associated dynamical responses (Pincus and Baker 1994; Boers and Mitchell 1994) are well established, the dominant indirect effects in ice and mixed-phase clouds (e.g., Lohmann 2002; Borys et al. 2003; Rangno and Hobbs 2001) are not as well known. Further, since aerosol effects cannot be studied in isolation of meteorological and surface forcing, understanding from Arctic cloud studies may not apply to the SO. From the Arctic, it is known that the commonly observed structure of a liquid cloud top with precipitating ice below (Hobbs and Rangno 1998; Curry et al. 2000) can persist for a long time only when an appropriate balance between cloud top radiative cooling, microphysical heating, ice sedimentation and large-scale forcing exists (e.g., Pinto 1998; Harrington et al. 1999, Morrison et al. 2008; Luo et al. 2008a, 2008b). This balance critically depends on ice crystal fall speeds, ice nucleation mechanisms and large-scale forcing (e.g., Jiang et al. 2000; Harrington and Olsson 2001; Lohmann 2002; Morrison et al. 2003; Fridlind et al. 2007; Xie et al. 2008; Avramov and Harrington 2010). Given expected differences in IN, surface forcing and meteorology between the Arctic and SO, additional data over the SO should help better understand the balance and physical processes the can lead to the persistence of mixed-phase and supercooled clouds.

Over the SO, ocean-produced aerosols dominate because of the scarcity of land. As discussed in theme 2, there remains an important question of what aerosols nucleate ice over this region with lower dust and anthropogenic loadings than comparable latitudes in the Northern Hemisphere. The scarcity of aerosols and ice nuclei might also enhance the importance of secondary ice crystal production processes (Hallett and Mossop 1974), about which much is also unknown (Cantrell and Heymsfield 2005).

Because of the prevalence of frontal systems over the SO (e.g., Mace 2010), it is vital to understand how the structure, frequency and characteristics of supercooled water depend on the synoptic meteorology and frontal dynamics. Studies in mid-latitude wintertime cyclones have shown that generating cells 1-2 km deep with horizontal scales of 0.5-2 km and vertical velocities of 1-2 m s^{-1} are ubiquitous near cloud tops with supercooled water present at temperatures as low as -31˚C (e.g., Rosenow et al. 2014; Plummer et al. 2014; Rauber et al. 2014; Kumjian et al. 2014), with these cells subsequently generating ice that continues to grow by diffusion, riming and aggregation in fall streaks. The extent to which similar processes occur in SO frontal systems, and the relative importance of such systems, as opposed to shallow convection in the boundary layer, for generating supercooled water is unknown. SOCRATES observations will determine the role of supercooled water during the lifecycle of PBL and frontal clouds, and thus address hypothesis 3.1 as well as 3.2.

SOCRATES data will be critical in the development of parameterizations for, and evaluation of simulations from models. Comparison of the limited HIPPO observations with a simulation from CAM5 nudged to observed meteorology, showed the model positioned the ice and water cloud well, but simulated liquid water droplet and ice crystal concentrations were far too high (Andrew Gettelman, personal communication). Clearly a more extensive dataset is needed for such evaluations. Model simulations, combined with sensitivity studies can predict the importance of different mechanisms (e.g., liquid activation and riming, primary ice nucleation, secondary ice nucleation) for producing ice and liquid over the SO. In addition, ground-based remote sensing observations, in combination with models and *in situ* data, can be used to examine the role of albedo and precipitation susceptibility in the summer and winter. A-train retrievals (Mace et al. 2014) suggest that albedo susceptibility is significant in summer and winter, but that precipitation susceptibility diminishes in winter consistent with modelling studies of Feingold et al. (2013).

Theme 4: Advancing satellite retrievals related to clouds, precipitation, and aerosols, over the Southern Ocean

Satellite-derived products are crucial for our understanding of SO cloud, precipitation, aerosol and surface fluxes, and for the evaluation and improvement of global models. However, the accuracy of many satellite datasets over the SO is questionable, due to a lack of *in situ* reference measurements, the use of empirical relationships in retrievals derived almost entirely on Northern Hemisphere datasets, themselves often limited, and specific challenges presented by the SO region. We organize these issues around three hypotheses to be addressed by SOCRATES, involving (1) satellite remote sensing of difficult SO cloud types and precipitation, (2) SO aerosol-liquid cloud interaction, and (3) boundary-layer aerosol over the windy, cloudy SO.

Before introducing these hypotheses, we stress that there are other SO satellite remote sensing issues that SOCRATES datasets may help address. One important example is satellite estimates of surface energy and water flux components (broadband radiation, as well as sensible and latent heat fluxes), which are important observational benchmarks for climate models. These can be compared with ship and Macquarie Island observations. One example of the need for such comparison is the spread of over 20% in current satellite-based estimates for the seasonal cycle of SO latent heat fluxes (Bourassa et al. 2013, Yu et al. 2011). This spread is due in part to high winds (Fig. 9) that create large waves and have a strong impact on bulk aerodynamic flux formulations, as well as increase white capping which brightens the surface at visible wavelengths and can affect aerosol retrievals. As noted by the U.S. CLIVAR Working Group on High Latitude Surface Fluxes, SO satellite surface flux estimates must be also validated against careful multiyear region-specific measurements, such as the NSF OOI SO flux reference buoy west of southern Chile.

Hypothesis 4.1: Large errors in current remote-sensing estimates of SO mixed-phase and multilayer cloud properties, and precipitation can be reduced by using detailed in-situ observations to constrain the retrieval assumptions

The SO features a greater occurrence of multi-layer and mid-level clouds (Heidinger and Pavolonis 2005, Mace et al. 2009, Marchand et al. 2010, Huang et al. 2014) and mixed-phase clouds with supercooled liquid water (Hu et al. 2010, Morrison et al. 2011, Chubb et al. 2013, Huang et al. 2014) than comparable latitudes in the Northern Hemisphere (Fig. 6). Property estimation for multi-layer, mixed-phase and precipitating clouds is prone to large errors because of the difficulty in robustly identifying when these conditions occur, as well as the additional unknowns that must be determined or specified as part of the retrieval. Even advanced multi-instrument retrievals from the A-Train generally treat mixed-phase clouds empirically (Mace 2010), and there are inconsistencies in the retrieved distribution of cloud-top thermodynamic phase between various instruments and methods (Fig. 8). Mixed-phase conditions and frequent light precipitation of the SO storm track are challenges for satellite estimation of precipitation, with factor-of-two differences between cloud radar (CloudSat) and microwave (e.g., AMSR-E) estimates (Haynes et al. 2009, Behrangi et al. 2012, 2014). Ground-based and airborne observations in these complex vertical cloud structures collocated with satellite overpasses (or high-altitude aircraft carrying equivalent remote sensing instrumentation) are critical for developing and testing better algorithms, as well as for more fully documenting the successes and limitations of those currently in use over the broad range of SO synoptic conditions.

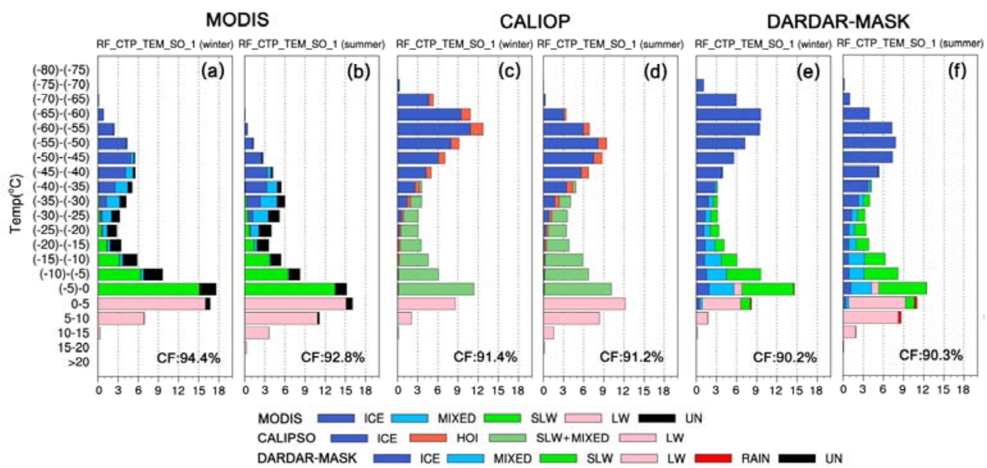


Figure 8: Vertical distribution of cloud top phase retrieved from MODIS operations product (Platnick et al. 2003), CALIOP (Hu et al. 2010) and DARDAR algorithm (Delanoë and Hogan 2010). The operational MODIS retrieval shows less high cloud and a warm bias (expected) with much less SLW below -20°C and a lot of "uncertain". CALIPSO does not distinguish between SLW and Mixed Phase, while DARDAR records considerable glaciation (ice-only) at cloud-top between 0 and -30°C, which is not reported by either CALIPSO or MODIS. From Huang et al (2014b).

Hypothesis 4.2: Current satellite VIS based estimates of SO liquid cloud droplet concentration and LWP have important biases, particularly in winter, due to the persistently low sun angle and 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.

Liquid cloud droplet number concentration and liquid water path (LWP) are key indicators of aerosol-cloud interaction. They are often inferred from MODIS and other satellite datasets using a combination of visible (VIS) radiances and other measurements, such as shortwave-infrared radiances, radar-reflectivity and lidar backscatter. These retrievals assume a locally plane-parallel cloud layer. In a real horizontally inhomogeneous cloud layer, such a retrieval is sensitive to zenith angle, with the largest uncertainties at the high zenith angles typical of the SO at higher latitudes and in winter (Várnai and Marshak 2007, Grosvenor and Wood 2014). In addition, if the upper part of the cloud layer includes either ice crystals or a substantial density of precipitation, the retrieved droplet effective radius will no longer correspond to the typical cloud droplet size, and negatively impact the retrieval estimate of number concentration and LWP.

Satellite VIS based retrievals suggest that that the SO features a strong seasonal and latitudinal dependence in cloud droplet number concentration (Fig. 4 above, Hu et al. 2007, Bréon and Tanré 2002), broadly consistent with very limited *in situ* observations. However, this may not be accurately characterized by current satellite products. In general, satellite retrievals of cloud microphysics have seen little to no detailed *in situ* validation at large zenith angles. SOCRATES can address this through airborne sampling of SO liquid cloud layers at large solar zenith angles, ideally collocated with satellite overpasses (or high-altitude aircraft carrying equivalent remote sensing instrumentation), as well as using surface-based remote sensing.

Satellite VIS based retrievals of low cloud cannot be performed under mid and high-altitude clouds, which are frequent over the SO. Hence, they represent highly-conditionally-sampled datasets whose climatological representativeness must be assessed. LWP can be also obtained from passive microwave retrievals valid over a broader range of conditions. However, microwave retrievals have other important issues. Lebsock and Su (2014) found large and seasonally dependent differences between MODIS and passive microwave (AMSR-E) LWP retrievals over the SO, which they attributed primarily to microwave retrieval errors related to wind speed and partitioning between cloud and rain water that can be better understood using, SOCRATES measurements.

Hypothesis 4.3: Better satellite estimates of accumulation-mode aerosol within the SO boundary layer can be developed with the help of SO surface and airborne observations.

Satellites could be a powerful tool to generalize SOCRATES observations of SO boundary-layer accumulation-mode aerosol number concentration and mass and their dependence on synoptic regime and season. MODIS and MISR provide widely used datasets characterizing aerosol optical depth (AOD) at visible through shortwave IR wavelengths, along with the fine-mode fraction and other measures of aerosol particle size and aerosol type (e.g., Kahn et al. 2010). Over the SO, where most of the large aerosol is in the boundary layer and sea-spray produces copious large salt particles, AOD is thought to mainly measure coarse-mode aerosol, but the fine-mode fraction may also give useful information about boundary-layer accumulation mode aerosol concentration.

However, these satellite products have serious shortcomings over the windy, cloudy SO. Both MODIS and MISR show a band of increased AOD over the SO that is inconsistent with Maritime Aerosol Network (MAN) observations from ship-borne Microtop sun-photometers that suggest small aerosol optical depths of 0.04-0.1 (Smirnov et al. 2011). Contamination of the satellite estimates by clouds or cloud-adjacency effects are thought to contribute (Zhang and Reid 2006, Witek et al. 2013), but a recent study (Toth et al. 2013) suggests they cannot fully explain the discrepancy. Kleidman et al. (2012) noted the AOD discrepancy also increases with observed wind speed, perhaps due to increased surface albedo at higher wind speed due to whitecapping, an effect neglected in MODIS Collection 5 but which is being considered in MODIS Collection 6. High surface winds speeds are a frequent occurrence over both the Northern and Southern Hemisphere oceans at latitudes poleward of 40^o (Fig. 9). Even neglecting AOD biases, aerosol size and type retrievals become uncertain when AODs are low, even, suggesting caution in interpreting studies such as Remer et al (2008), who found a seasonally varying SO fine mode fraction in MODIS retrievals consistent with biomass burning aerosols.

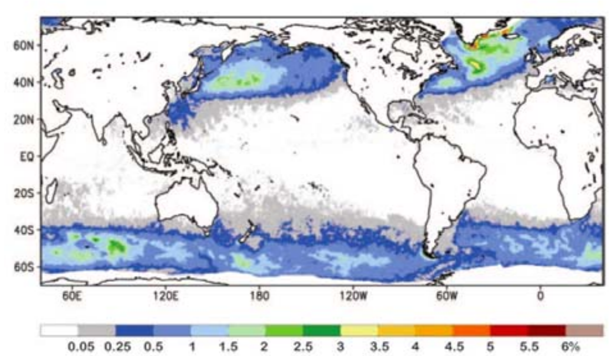


Figure 9: Frequency of winds exceeding 25 m s^{-1} from QuikSCAT (1999-2009). Taken from Bourassa et al. (2013).

CALIPSO (lidar) retrievals show small aerosol optical depth over the SO similar to the MAN datasets (Winker et al. 2013, Redemann et al. 2012), and in principle can be used to separate boundary layer and free tropospheric contributions to the total aerosol optical depth. However, CALIPSO has difficulty detecting aerosols in low concentration, which is the usual case for the SO free-troposphere (Winker et al. 2013). We are not aware of any studies examining the accuracy of free-tropospheric aerosols over the Southern Ocean.

The validity of MISR, MODIS and even CALIPSO aerosol optical depth and aerosol size characterization remains unclear over the Southern Oceans with a strong need for high-quality *in situ* and surface observations that SOCRATES will provide. SOCRATES also presents an opportunity to examine the relationships between these satellite products, SO boundary layer accumulation-mode aerosol and cloud droplet concentration, a central link in studying SO cloud-aerosol interaction.

4. Implementation Strategy

To address the scientific issues and questions raised in the previous section, we propose a set of focused observations over the SO, that will be coordinated with process and large scale modelling spanning a variety of temporal and spatial scales. This coordinated observational and modelling program will also make extensive use of existing and future planned satellite datasets that include retrievals of cloud and aerosol properties, surface ocean state, and other meteorological variables. To focus the observational requirements, the following overarching objectives are proposed:

(i) To characterize the physical properties of lower-tropospheric cloud systems around mid-latitude cyclones over the Southern Ocean during summer and winter;

(ii) To characterize microphysical and chemical properties of aerosols and aerosol precursor compounds, including DMS, that may play a role in regulating cloud condensation nuclei (CCN) and ice nuclei (IN) over the Southern Ocean and to investigate their relative significance for cloud and precipitation formation, and radiative properties;

(iii) To characterize surface seawater properties, including organic matter concentration and composition and biological activity, that may impact the composition and cloud-nucleating ability of ocean-derived CCN and IN;

(iv) To assess the quality of satellite cloud, aerosol, precipitation, and upper ocean products, to develop new ones, and to use these products to address the science questions;

(v) To evaluate and improve the skill of models at different scales to reproduce the observed properties of Southern Ocean 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 the cloud systems.

A Southern Ocean measurement program is needed to address the challenges in understanding the vertical distribution of aerosols, the seasonal cycle of aerosols, the conditions favouring supercooled liquid cloud, the generation and atmospheric evolution of marine CCN and IN and precursors, and the lower-tropospheric dynamics and PBL context for these processes. There are strong gradients in aerosol and cloud properties (and model biases) across the latitudes of the Southern Ocean between 40˚S and the Antarctic coast (~65ºS), and ideally this entire gradient should be sampled. The observations required to address the objectives include both fine-resolution, intensive observations from airborne and shipboard platforms (e.g., measurements of cloud and aerosol concentrations and physical characteristics), and longer timescale observations that capture the seasonal cycle. No single measurement campaign can fully address the program objectives, and so a combination of the following activities is proposed:

- Continuous ground-based observations from island sites that span the seasonal cycle;
- Intensive but short duration (1-2 month) airborne observations during both summer and winter, including *in situ* and remote sensing observations made by low- and high-level aircraft platforms;
- Intensive, short duration (1-2 month) shipboard observations during summer and winter, including atmospheric *in situ* and remote observations and microlayer, surface, and sub-surface seawater observations;

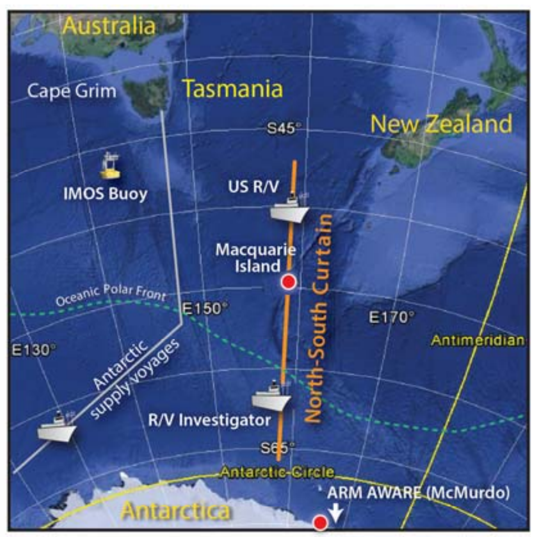
- ARM Mobile Facility measurements on an Antarctic supply vessel to capture broader seasonal variability (spring through autumn) in aerosol and cloud properties at different latitudes across the SO, especially at latitudes south of 60°S.
- Routine profiling of lower atmospheric properties from Macquarie Island and deployed research vessels, including operation of unmanned aerial systems (UAS) for enhanced space-time sampling and for aerosol profiling.
- Analysis of cloud, aerosol and meteorological parameters retrieved from satellites;
- Construction and analysis of model simulations over a variety of temporal and spatial scales (e.g., using large eddy simulations, cloud resolving models, regional climate models and global climate and chemical/aerosol transport models).

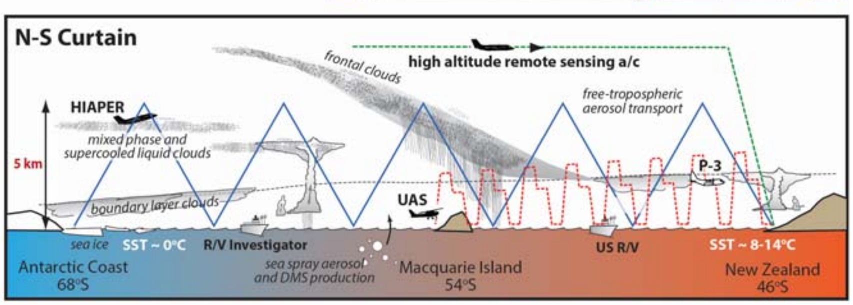
We present a strategy for each of these components in this section that includes ground-based, shipborne and aircraft measurements that together form SOCRATES. It is anticipated that multi-agency support and international cooperation will be required to accomplish SOCRATES objectives given the scope of the program and the challenge of working in the remote SO region.

4.1 SOCRATES Curtain Concept

The following sections describe the planned SOCRATES activities organized by platform type, including ground-based observations, ship observations, aircraft observations and satellites. Figure 10 shows a map of the proposed platform sampling during SOCRATES, which focuses upon mapping cloud and aerosol properties along a north-south meridian we are terming the **SOCRATES Curtain.** The curtain encapsulates our need for sampling at a range of latitudes across the Southern Ocean. The Australasian sector of the Southern Ocean is selected because it is representative of the SO as a whole (e.g. Figs 1, 6 and 9), because Macquarie Island is among the few island sites in the Southern Ocean without major orography and is an active scientific station, and because of the availability of the Australian-supported R/V Investigator (see section 4.3).

Figure 10: Schematic showing SOCRATES sampling locations and platforms (top), and a detailed sampling schematic for the north-south SOCRATES Curtain of sampling from 45°S to the Antarctic circle (bottom).





4.2 Ground-Based and Buoy Observations

Macquarie Island and Davis: Australia operates stations at Macquarie Island (54°S 159°E) and Davis, Antarctica (69°S, 78°E) where meteorological measurements and daily balloon soundings are made. Continuous cloud radar and lidar observations are planned for a full year at Macquarie (2016) and Davis (2019) as part of the Australian Antarctic Division (AAD) proposed Antarctic Clouds and Radiation Experiment (ACRE). An ARM Intensive Observation Period proposal has also been submitted to supplement the ACRE Macquarie instrumentation with a variety of surface radiometers, including microwave radiometers, surface broadband radiometers and either a sun photometer or a Multi-filter Rotating Shadowband Radiometer in 2016 and 2017. The continuous data collected at these ground-based sites will complement short-duration, intensive ship-borne and aircraft campaigns over the SO. The ACRE data will quantify the seasonal cycle of various cloud and radiation properties and enable satellite validation and model evaluation in the Southern Ocean and coastal east Antarctic. In addition, a proposal currently under consideration at the AAD involves the deployment of "polarsondes" on the routine rawinsondes launched at Macquarie Island. The polarsonde is an inexpensive instrument designed to detect the phase of cloud particles by analysis of the changes in polarisation of backscattered light**.** Polarsondes have been tested in Greenland and Belgium and have successfully picked out the layer of supercooled liquid at the top of Arctic stratus.

Other ground based measurements: Several months of aerosol measurements were taken at Palmer Station (65°S, 64°W) on the Antarctic Peninsula during 10/2013-3/2014 by researchers at Scripps, and continued and enhanced measurements from this site are planned. The DOE supported ARM West Antarctic Radiation Experiment (AWARE) will make extensive cloud and aerosol measurements at McMurdo base on Antarctica (78°S, 167°E) from October 2015 until March 2016. The CAPE Grim station on Tasmania (41°S, 145°E) continues to provide long-term baseline DMS and aerosol measurements.

NSF Ocean Observatories Initiative (OOI) buoy: A long-term NSF OOI climate reference buoy making meteorological and upper ocean measurements, including surface downwelling radiative fluxes, is planned for installation in Jan 2015 at 55°S, 90°W west of Punta Arenas (Chile). There is significant power provision on the OOI buoy to house novel instrumentation beyond that typically deployed on ocean moorings, and it would be useful to explore the potential for cloud and aerosol measurements to enhance the proposed SOCRATES sampling.

Australian IMOS buoy: An Australian buoy was deployed to (47°S, 142°E), southwest of Tasmania, from March 2010 to October 2013 and collected a range of observations at the sea surface including meteorological parameters and downwelling radiation. The buoy was operated and maintained by the Integrated Marine Observing System (IMOS) and the Australian Bureau of Meteorology. The buoy will be reinstalled once the Australian Marine National Facility ship R/V Investigator is operational. Additional instruments could be deployed on the buoy for field campaigns. The existing data are freely available and IMOS would welcome any collaboration for SO campaigns which might use the buoy's data and strengthen the case for its redeployment in years to come.

4.3 Shipborne Observations

SOCRATES requires shipborne observations to characterize SO seawater properties and near-surface conditions that determine the amount and composition of biogenic aerosol fluxed from the ocean into the PBL. Ships can also be invaluable platforms for the remote sensing of cloud macro- and microphysical properties, precipitation, and aerosol properties required to improve our understanding of cloud and aerosol processes over the SO and their parameterizations in models. Ships sample around the clock for many days, complementing episodic aircraft sampling while still being mobile. SOCRATES will use ships for (i) characterizing seawater properties, near-surface aerosol size distribution and composition across the polar front and more broadly, the SOCRATES curtain, (ii) collecting remote sensing observations of cloud, precipitation, and aerosol properties, (iii) evaluating satellite derived cloud and aerosol products, rainfall, and surface ocean properties;, and (iv) providing data to evaluate and improve earth system modelling of the SO region. We stress, that coordinating aircraft in situ measurements with ship collections is a critical element in addressing SOCRATES hypothesis.

R/V Investigator: Accurately predicting the structure and evolution of fronts and associated cloud systems in weather prediction and climate models is of great practical importance for Australia. As a result the Australian-funded CAPRICORN project (Clouds, Aerosols, Precipitation, Radiation, and atmospherIc Composition Over the southeRn oceaN), will involve two one-month cruises into the Southern Ocean during austral summer 2015-2016 and austral winter 2017, and a two-month cruise in austral summer 2017-2018 during the time period of the extensive SOCRATES aircraft observations (section 4.4), with a new research vessel (R/V), the Investigator, equipped with extensive cloud, precipitation, aerosol, atmospheric composition, oceanographic, and air-sea flux instrumentation (see Table 3). The main objectives of CAPRICORN are to: (i) characterize the cloud macrophysical and microphysical properties, atmospheric composition, and precipitation properties of atmospheric frontal cloud systems and associated interactions; (ii) evaluate CloudSat-CALIPSO cloud microphysics, CloudSat and GPM rainfall properties, CALIPSO lidar-derived ocean products, and CALIPSO aerosol/cloud discrimination, and (iii) evaluate the current skills of the Australian Community Climate and Earth System Simulator (ACCESS) model at different scales (from high-resolution models resolving convection explicitly to weather forecast and climate models with coarser resolution) to reproduce the properties of SO frontal cloud systems.

U.S. Research Vessel: A U.S. ship is proposed for austral summer 2017–2018. The global class vessel should have a large foredeck located high on the ship that accommodates the placement of up to five 20' instrumented containers. This location on the ship allows for the sampling of aerosols and gases with minimal flow distortion issues and contamination from the ship's stack. The aft main deck should accommodate several more 20' containers for housing measurements of surface seawater properties from the ship's uncontaminated seawater line or remote sensing instrumentation. The complement of remote and in situ observations will allow for a full characterization of cloud, precipitation, aerosol, atmospheric composition, surface and sub-surface seawater, and air-sea fluxes across the polar front. A nascent sea spray aerosol generator (Sea Sweep; Bates et al., 2012) could be deployed to characterize the chemical, physical, and cloud-nucleating properties of freshly emitted sea spray aerosol. Information acquired from Sea Sweep will be coupled with measurements of microlayer and surface seawater properties to assess the impact of ocean biogeochemistry on sea spray aerosol.

These two ships will sample different latitudes along the SOCRATES curtain (Fig. 10) between 45^{o}S and the Antarctic Circle to complement the aircraft and Macquarie ground-based measurements by providing comprehensive sampling on both sides of the polar front. The two ships will also collect samples across oceanic (north-south) gradients collocate at some point for a direct measurement comparison (nominally near Macquarie Island).

ARM Mobile Facility: Addressing SOCRATES hypothesis requires both intensive shipborne measurements and longer term measurements to document the seasonal aerosol and cloud microphysical evolution. The longer term measurements at Macquarie Island (section 4.2) is well situated to document seasonal variability in the center of the SO storm track, but there is also a need for seasonal sampling south of 60^{o}S in the subantarctic waters. The installation of the DOE ARM Mobile Facility (AMF) on a ship or icebreaker supplying stations in the Antarctic is proposed to address this measurement need. Given the supply ships cover a much wider area than will the R/V Investigator or U.S. research vessel, the aerosol and chemical properties will be measured and the cloud will be retrieved over a much wider geographic area and hence will provide a context for interpreting the data obtained over the more limited SOCRATES domain. Although observations may not be possible in the deep winter, such a strategy could provide multiple cruises, including measurements of aerosols and chemistry, to document the evolution of the seasonal cycle from spring (October) to autumn (April) in a previously undersampled region. Following the success of the Marine ARM GPCI (GCSS Pacific Cross-section Intercomparison) Investigation of Clouds (MAGIC) field campaign, a ship sailing a predefined route will be the platform for the AMF. Possible platforms include the French ship L'Astrolabe that transits between Hobart, Tasmania and the French Station Dumont d'Urville, the Australian icebreaker Aurora Australis that transits between Hobart and four

Australian stations (three on coastal East Antarctica plus Macquarie Island), and American ships (R/V Laurence M. Gould) that transit between Argentina and US bases in Antarctic.

4.4 Airborne Observations

Airborne in-situ and remote sensing observations play a critical role in detailed, vertically-resolved sampling of the coupling of SO cloud microphysics, aerosol processes, turbulence and radiation. The biggest challenge is the requirement for observations south of 60°S where model shortwave cloud biases are most acute (Figs 1 and 2 above), a problem exacerbated by the scarcity of suitable air bases over the region as well as potential icing conditions. Because of the lack of surface sites and the limitations of satellite observations, airborne remote sensing forms a critical context for interpreting the *in situ* observations. Recent analysis from the Profiling of Winter Storms Project (PLOWS, Plummer et al. 2014a, 2014b; Rosenow et al. 2014) showed airborne radar and lidar observations that can provide the context to interpret the microphysical processes acting in generating cells and accompanying fall streaks.

Figure 10 shows a schematic of the aircraft sampling envisioned, using a mid-level profiling aircraft such as the NCAR/NSF G-V, a high altitude remote sensing aircraft such as the NASA ER-2, and a low-level boundary aircraft such as the NOAA P-3. Although the data from each aircraft can be used alone to address specific hypotheses, great synergy is gained from coincident *in situ* and remote sensing data sets. Our preferred aircraft strategy relies on the coordinated use of multiple aircraft so that the cloud and aerosol vertical structure can be remotely sensed at the same time the relevant cloud and aerosol parameters are sampled *in situ*, but one vertically-profiling aircraft could be used with some compromise in data collocation. Cloud radar and lidar from the remote sensing aircraft could measure the vertical structure of cloud macrophysical properties of virtually all clouds. Cloud radar–lidar algorithms (e.g., Mace 2010; Delanoe and Hogan, 2008; Deng et al. 2010) can also be used to characterize the vertical structure of the microphysical properties and thermodynamic phase of clouds. However, these algorithms hold assumptions that will need to be thoroughly evaluated using the detailed microphysical measurements from the *in situ* aircraft. The characterization of aerosol-cloud-precipitation interactions can also be achieved using the characterization of aerosols from the combined lidar/*in situ* measurements from two aircraft. Because sampling at a variety of heights in the PBL is required and because such low-level flying with altitude changes limits the range of the lower altitude aircraft, the use of multiple aircraft would also allow the G-V aircraft to transit south of 60°S, thus allowing better sampling of the pristine air masses that would otherwise not be possible. The use of two aircraft also ensures that the remote sensing observations are always useful: retrievals are typically only useful for straight and level legs, which will not be flown when one aircraft is profiling the clouds.

NSF/NCAR G-V: The G-V would be the primary measurement platform characterizing microphysical properties of mid-level (z>2 km) and high-level (z>4 km) clouds with a complete set of microphysical probes. The primary flight pattern of the G-V will be sawtooth ascents and descents along the SO Curtain from 5 km to as close to the ocean surface as possible. The longer range of the G-V compared to the P-3 will allow it to fly to 63°S or beyond, almost as far south as the Antarctic coast. Similar, but much deeper patterns were flown during HIPPO; the shallower SOCRATES sawtooths will provide many more cloud and aerosol profiles, and will include enhanced *in situ* and remote sensing capabilities for measuring clouds and aerosols, including a new Doppler cloud radar and lidar. The G-V will also fly level remote sensing legs between the ramped ascents and descents and release dropsondes. We are also planning for the installation of a multi-wavelength radiometer, such as the MAS or MASTER, which would provide cross-track scanning for retrieval of cloud, aerosol and surface properties. The G-V is the only aircraft with the range to fly south of 60°S where climate model biases are largest (Fig. 1). We envision both a summer and a winter G-V campaign to provide critical information on the seasonal cycle needed to address SOCRATES hypotheses.

High-altitude remote sensing aircraft: A high-altitude remote sensing aircraft would provide comprehensive context for the *in situ* data from the mid-level and boundary-layer aircraft and for evaluating and improving satellite retrieval schemes, including the problematic case of high zenith angles. We propose to use the NASA ER-2 with active and passive remote sensing instruments for profiling clouds and aerosols (e.g., MASTER for passive retrieval of cloud, aerosol and surface properties, Doppler radar and lidar for active cloud, aerosol and precipitation measurements, HAMSR for retrieving vertical temperature, water vapour and liquid water profiles, the High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP); the Conical Scanning Millimeter-wave Imaging Radiometer, CoSMIR; the Advanced Microwave Precipitation Radiometer, AMPR; and Air-MSPI for multi-directional multi-wavelength retrievals of clouds and aerosols with a high accuracy polarization imager. The ER-2 remote sensing data provide comprehensive data (at higher resolution than from satellite remote sensors and throughout the flight) with spatial coverage not possible from ground-based remote sensors; its combination with *in situ* data from the P-3 and G-V would allow validation of the retrievals of supercooled cloud microphysical properties in a region where no other data are currently available. Planned underflights of satellites (see Section 4.5) will also aid in satellite validation objectives, e.g., SOCRATES data obtained from the G-V and ER-2 could be used to test GPM algorithms in the climatologically important but poorly sampled high-latitude oceanic storm track regime.

NOAA P-3: The P-3 will be equipped with a complete range of cloud and aerosol probes, measuring both solid and liquid hydrometeors, and the concentration and compositions of aerosols, including CCN and IN counters. A CVI inlet and measurements of aerosol chemistry are needed to understand seasonal and synoptic variability in SO cloud CCN and IN concentration, and the role of local biogenic sources. The P-3 would fly a combination of straight and level legs together with profiles through the boundary layer clouds to characterize both cloud microphysical properties and aerosol concentrations and composition above and below cloud. Level legs as close to the ocean surface as safety allows would sample aerosols originating from the ocean surface, and would hence determine how concentrations of sea salt and biogenic aerosols vary with wind speed. Higher altitude level legs from the P-3 would characterize aerosols in the free troposphere to address whether entrainment of biogenically-derived aerosols from the lower free troposphere constitutes a major source of CCN during the summer, as well as examining the long range transport of continental emissions. The P-3 level legs within cloud would characterize cloud microphysical properties, and together with observations of aerosols above and below cloud would permit investigations of the relationship between cloud properties, CCN and aerosols. Depending on cloud depth, ramped ascents and descents could be executed to sample cloud vertical structure.

Unmanned aircraft: Because of operational limitations associated with the endurance and altitude range of the P-3 and G-V manned aircraft, and cost limitations on the number of flights which can be performed by these aircraft, there is potential for unmanned aircraft systems (UAS) in SOCRATES. The SO is a challenging operating environment for a UAS, particular for shipboard deployment. Nevertheless, a variety of different platforms and sensors are under consideration to provide information on PBL thermodynamic and dynamic structure, aerosol properties and variability, for which UAS would have great advantages. They can be operated routinely over extended time periods to accumulate statistics within different synoptic regimes and provide high-frequency profiling of PBL temperature, humidity, and winds. UAS can operate down to 5-10 m above the ocean surface.

Routine UAS flights from Macquarie Island could help document vertical profiles of aerosol properties at Macquarie Island and document situations in which ground-based aerosol measurements may not be representative of the particles entrained into cloud. UAS could be used to investigate the transition between land and ocean surface around Macquarie Island, as context for the long-term, land-based instrumentation there.

Small UAS could operate from the deck of research vessels involved with SOCRATES to supplement the vertical profiling available from ship-launched radiosondes by measuring meteorological parameters (e.g., temperature, humidity, pressure, winds) and aerosol properties (e.g., number concentration and size distribution, light scattering and absorption, chemical composition). Ship-borne UAS launch and recovery can be challenging, though several techniques have historically been used in such operations. Examples include UAS with vertical take-off and landing (VTOL) capabilities, as well catapult launch and wire-capture recovery devices.

Currently, a proposal complementary to ACRE involving UAS is under review with the AAD. This proposal calls for the operation of the DataHawk UAS (Lawrence and Balsley, 2013) for the summer of 2016/2017 with an extension into 2017/2018 to support SOCRATES. The small, low-cost DataHawk will be used to estimate surface fluxes and measure the thermodynamic structure of the PBL over and around Macquarie Island.

4.5 Satellite observations

Validation and characterization of satellite retrievals is an important objective for SOCRATES. This is important not only for satellite studies, model evaluation, and long term monitoring but will also play an important role in addressing SO hypotheses. For example, hypothesis 1.1 (which looks at boundary layer cloud properties and thermodynamic vertical structure) or hypothesis 3.1 (which looks at the relationship between supercooled liquid water and cloud reflectivity) will benefit from coordinated data acquisition with satellite overpasses. The unique role of validated satellite observations and products in the investigation of the complex SO processes will be to provide invaluable insights into the regional, intraseasonal, and inter-annual variability of the cloud, aerosol, and boundary layer processes and their interactions. While aircraft can provide *in situ* measurements of cloud and IN properties that are useful in addressing these hypotheses, these measurements will sample only a small volume of the atmosphere and satellite data are needed to put them in context by providing information on differences between those particular areas sampled and the larger region, as well as, providing information on larger scale variability and increasing statistical certainty. SOCRATES will include coordinating acquisition of field data with satellite overpasses, to the extent possible. However, the intent is to include a high-altitude remote sensing aircraft that can reproduce many satellite observations (see previous section). Coordination with wide-swath satellite instruments such as MODIS, CERES, a various microwave instrument (e.g. AMSR-E, GPM) should not be difficult to achieve. Although more challenging to achieve, coordinated flights along CloudSat radar and CALIPSO lidar measurements (if we are fortunate enough for these systems to continue operations sufficiently long), as well as radar and lidar that will be part of GPM and the upcoming EarthCare missions will also be given a high priority as part of experiment planning including flight and ship positioning.

As detailed in science theme 4, there is a wide variety of satellite products in need of evaluation, and addressing hypotheses 4.1 and 4.3 will require a wide variety of field observations including cloud microphysical properties (especially liquid and ice water contents and water paths, as well as cloud, drizzle and precipitation drop size distributions and particle habits), aerosol microphysical properties (particle size distributions, hygroscopicity, CCN, composition, and ice-nucleating properties at various activation thresholds), optical and radiative properties (cloud and aerosol optical depth/extinction, as well as surface downward and upward shortwave and longwave broadband fluxes with some supporting narrow-band data), as well as surface sensible and latent heat fluxes. Not all of these quantities need be (or are likely to be) made from a single platform or even strictly from aircraft. While it is desirable to have this complete set of observations, subsets of these measurements can advance particular satellite retrievals and evaluations using multi-month observations from islands or ships will help establishing statistical certainty and help in the evaluation of diurnal and seasonal variability.

4.6 Measurement requirements

The Science Traceability Matrix (STM, Table 3) includes measurement requirements that are subjective estimates based on three main considerations.

The first is basic science, as laid out in the SOCRATES hypotheses. For aerosol properties, especially potential ice nuclei, and for mixed and ice phase cloud processes, and for aerosol sources and sinks across the seasonal cycle, the existing level of understanding and SO observational context is weak, so SOCRATES should aim for the best feasible accuracy. Requirements estimated in this way are labelled ‘S’ (science) in the NEED column of the STM

The second consideration is importance for SO shortwave radiative fluxes, whose errors in CMIP climate models are tens of W m^{-2} in the mean, and larger in cold-sector cloud regimes (e. g. Figs. 1-2). To provide a useful observational constraint for reducing these biases, and for improving remote-sensing retrievals with the same goal, we insist that measured cloud (e.g., liquid water path and ice water path), radiation or aerosol data should be accurate enough to constrain instantaneous shortwave radiative forcing within 10 W m^{-2} if they could be achieved over the entire atmospheric column. Measurement requirements estimated in this way are labelled ‘R’ (radiation-constrained) in the STM.

The third consideration is model comparison. Because of the complex and rapidly varying synoptic environment we plan to compare our observations with nudged global model simulations as in Fig. 3. To evaluate the model in this way, we need to test whether the model is adequately simulating the observed regional atmospheric conditions in addition to the observed cloud and boundary layer structures; both types of observations must be sufficiently accurate (e. g. within 10% of characteristic synoptic variability) and representative to usefully constrain the models. Measurement requirements estimated in this way are labelled ‘M’ (model comparison) in the STM. There is considerable uncertainty and controversy in estimating the best achievable accuracies in many of the quantities included in Table 3. At the time of SOCRATES, we will use the best possible uncertainty estimates available, and determine how those uncertainties cascade to uncertainties in radiation and model comparisons.

Multiple instruments and platforms are listed in the STM when they provide estimates of a particular quantity (e. g. cloud particle size and phase) with complementary sampling properties. Indeed, obtaining collocated samples with different platforms is a key part of the SOCRATES design; tying together the spatial context provided by satellites, with the temporal and seasonal sampling provided by ground-based site and ships, with the detailed vertical profiles obtained by aircraft. Individual experiment proposals will document more thoroughly how the specific measurements can be used to test specific scientific hypotheses.

4.7 Proposed timeline

Timeline of proposed SOCRATES activities. *already funded* *requested*

Platform (campaign)	2016				2017				2018				2019			
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Macquarie Ground (ACRE)	requested	requested	requested	requested												
Macquarie Island (ARM part of ACRE)	requested	requested	requested	requested	requested	requested	requested	requested	requested							
UAS deployments from Macquarie				requested	requested			requested	requested							
Davis station (ACRE)													requested	requested	requested	requested
NSF OOI Climate Reference buoy	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded
Australian IMOS buoy	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded
R/V Investigator cruises (CAPRICORN)	already funded						already funded		already funded							
US Research Vessel cruises									requested							
ARM Mobile Facility at McMurdo (AWARE)	already funded															
ARM Mobile Facility marine deployment								requested	requested	requested						
NSF/NCAR GV deployments							requested		requested							
NOAA P3 deployment									requested							
NASA ER2 deployment									requested							
Satellite observations	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded	already funded

Table 3: Science traceability matrix (STM) linking observations with scientific themes and hypotheses

Science Objective	Scientific Parameter	Required Accuracy	Instrument type [platform(s)]	Scientific Hypotheses	Field Measurement Requirements
Theme 1: Synoptically varying vertical structure of SO	Profiles of temperature	±1 K (M)	Dropsondes, radiosondes, *in situ* probes, and satellite retrievals will all contribute [a/c, ships, ground, sat, uas]	1.1, 3.2, 3.3	• Intensive field measurements with adequate sampling of synoptic regimes, seasonal cycle, and vertical structure • Measurements along a routine flight track across the SO from ~40ºS to at least 65ºS • Airborne and surface remote sensing to provide context for *in situ* measurements • Sampling that permits assessment of variability in clouds and aerosols from surface to 6 km altitude. • Airborne, ship and ground based sampling during both summer and winter • Aircraft observations of cloud and aerosol microphysics taken in context of remote sensing data • Boundary layer observations from aircraft, UAS, ship and ground sites.
	Profiles of moisture	±5% (M)		1.1	
	Profiles of wind	±1 m s^{-1} (M)		1.1, 1.3	
	Cloud cover	±0.05 (R)	Various: radar, lidar, radiometers [a/c, ships ground, satellite]	1.2, 3.1, 4.1	
	Cloud base, top	±100 m (R)		1.2, 3.1, 4.1	
	Vertical velocity	±0.5 m s^{-1} (M)	Radar [a/c, ships and ground], *In situ* turbulence probe [a/c]	1.1, 1.2, 1.3	
	Turbulent fluxes	20% (S)	Turbulence probe, high freq. temp and moisture [a/c]	1.1, 2.1	
Theme 2: Seasonal & synoptic variability of CCN and IN	Aerosol concentration and size dist.	±20% conc. (S) ±.07 μm size (S)	Aerosol spectrometers [a/c, ships, ground, uas]	1.3, 2.1, 2.2, 3.2, 4.3	
	CCN conc.	±20% (S)	CCN counters [a/c, ships, ground]	2.1, 2.2,	
	IN conc.	±50% (S)	Various methods [a/c, ships]	2.2, 3.1, 3.2	
	Aerosol composition		Aerosol mass spectrometers, filter samples [a/c, ships]	1.3, 2.1, 2.2, 3.2	
	Aerosol optical properties & AOD		Nephelom. [a/c, ships] Lidar and/or NB radiances [ground, ships, satell.]	1.3, 2.1	
	Gas chemistry: CO, O_3		*In situ* probes [a/c, ships], NB radiances [satellite]	1.3, 2.1	
	Ocean surface biogeochem. (DMS, organics, Chl-a, bubble surface tension)		Sea-sweep and ship seawater inlet [ships]	1.2, 2.1, 2.2	
Themes 3 and 4: Remotely Sensed and *in situ* supercooled & mixed-phase clouds	Reflectivity profiles	±1 dBZ (S)	mm and cm radars [a/c, ships, ground, satellite]	1.2, 3.1, 4.1, 4.2	
	Hydrometeor fall speeds	±0.2 ms^{-1} (S)			
	Polarization Ratio and Lidar Scattering Cross-section		Lidars, including HSRL [a/c, ships, ground, satellite]		
	Cloud liquid water path	10 g m^{-2} (R)	Passive microwave radiom. [ships, ground, satellite]	1.1, 3.1, 4.1, 4.2	
	Broadband LW/SW	±3% or 10 W m^{-2} (R)	Radiometer, SW spectrometer [ships, ground, a/c, satellite]	3.1, 4.1-4.3	
	Multi–λ Passive Radiation	±2% refl.; ±1 K TIR (S)	Spectroradiometers [a/c, satellite], SW spectrometer [ground, ships]	3.1-3.4, 3.5, 4.1, 4.2, 4.3	
	Cloud optical properties	±20% (R)	various retrievals: Radar/Lidar/Radiometers, sunphotometer [ships, ground, satellite]	3.1-3.4, 4.1, 4.2	
	Cloud/drizzle particle size dist.	±3 μm, ±20% (S)	Particle spectrometer probes and particle imagers [a/c]	1.3, 2.8, 3.1-3.4, 4.1, 4.2	
	Ice particle size dist., shapes, habits	±10 μm, ±20% (S)		2.2, 3.2-3.4, 4.1, 4.2	
	Bulk liquid & ice water content	±.05 g m^{-3} (S)	Liquid water and ice particle probes [a/c]	1.3, 3.1-3.4, 4.1, 4.2	
	Surface precip.	10% (S)	Disdrometer [ships, ground], radar [a/c, ships, ground, sat]	1.2, 4.1, 4.2	

5. Modelling program

SOCRATES is in large part motivated by challenges in simulating Southern Ocean cloud and aerosol in the current climate that also may affect their responses to future anthropogenic climate change. Recalling section 2, these challenges include representing cold-sector lower-tropospheric cloud, the background aerosol distribution in the region, and their interaction with each other within a constantly changing atmosphere above a dynamic, biologically active ocean.

A first important step toward improving models will be to better understand aspects of their cloud and aerosol simulations using analyses of existing model intercomparison datasets such as the CMIP5 archive. Basic features such as simulated frequency of occurrence, microphysical properties, and vertical structure of SO mixed phase cloud have not yet been documented across a suite of climate models; similarly for effective radius or measures of the vertical distribution of aerosols.

Some known biases and uncertainties are already being addressed through ongoing international efforts. The Global Atmospheric System Study (GASS) has been conducting model intercomparison projects related to Arctic mixed-phase boundary-layer clouds, based on observations from the Mixed-Phase Arctic Cloud Experiment (MPACE, Klein et al. 2009) and the Indirect and Semi-Direct Aerosol Campaign (ISDAC, Ovchinnikov et al. 2014). These have compared single-column version of climate models (SCMs) with very high-resolution large-eddy simulations (LES). The LES process-modeling component has helped to identify fundamental modelling uncertainties (e. g. ice nucleation processes) as well as providing a comparison for the SCMs. A current GASS case is to simulate an aircraft-sampled North Atlantic winter cold-air outbreak (Field et al. 2013) in which the cloud structure is more cumuliform. In this case, another focus is large-scale model performance across a range of horizontal resolutions from 1-20 km in which shallow cumulus convection is partly, but not well, resolved; mixed phase processes are also important. This latter case may be a good Northern Hemisphere analogue for addressing Southern Ocean cold-sector boundary-layer cloud biases, although the observations are limited.

By the time of SOCRATES, these studies will have laid a foundation for confronting climate and detailed process models with a large and complex new dataset on SO cloud-aerosol-surface interaction. We will formulate further model intercomparison cases that draw both on SOCRATES observations and on associated improvements in remote sensing datasets. The SOCRATES model intercomparison would blend process modelling with global model simulations nudged toward observed wind fields (as in Fig. 3) so that they can be directly compared with *in situ* observations, and would be coordinated with GASS. SOCRATES datasets (particularly the curtain sampling across the SO) would also be used to constrain models as part of the AEROCOM project. Improved remote sensing datasets could feed into the Cloud Feedbacks Model Intercomparison Project (CFMIP), which has popularized and systematized cutting-edge methodologies such as instrument simulators (Klein and Jakob 1999; Bodas-Salcedo et al. 2011; Klein et al. 2013) for evaluating climate model output using new remote-sensing approaches.

6. Educational outreach program

As with recent NSF deployments such as RICO (Rauber et al. 2007) and IDEAS (see *www.eol.ucar.edu/raf/Projects/IDEAS*) a strong educational component is planned as part of SOCRATES. Opportunities will be provided for participation in activities for students at all educational background, including K-12, undergraduate and graduate students. The following activities will be planned:

1) Funded proposals of SOCRATES science team members will support graduate student travel to the field to participate in data collection, and provide funding for subsequent analysis of data and attendance at SOCRATES science team meetings and professional conferences. It is expected that these students will write peer-reviewed articles using SOCRATES data.
2) A grant will be written to the NSF Research Experience for Undergraduate (REU) program to fund travel for undergraduates to the field, and provide summer internships for processing

and analysis of SOCRATES data. It is anticipated students will participate in a variety of activities, including at the flight center and on the research vessels.

3) During SOCRATES, in-field educational activities will be provided for all undergraduate and graduate students, as well as any postdoctoral associates. We anticipate participation from students from the United States, Australia and New Zealand in these activities. Scientists working on SOCRATES will provide in-field seminars in their area of expertise, and instrument scientists will provide the students with hands-on experience with all of the major instrumentation platforms.
4) The final mission of SOCRATES will be completely planned and executed by the students, two of whom will be selected to serve as mission and co-mission scientist. The students will decide in the manner the field assets should be deployed (e.g., aircraft, UAS, R/V, etc.). The only non-students participating will be those regarded as essential (e.g., pilots, technical instrument operators, etc.)
5) A team of students from various universities will be selected to manage the project forecast operations for SOCRATES, with assistance from relevant science team members and forecasters in Australia and New Zealand.
6) Educational outreach will be provided to schools in the local deployment sites (anticipated to be New Zealand or Tasmania). Members of the SOCRATES science team, and students, will volunteer to give presentations at local elementary and high schools, as well as to universities.
7) Following the model set by the DOE project MAGIC, a regular newsletter for non-scientists and scientists interested in SOCRATES will be published and made available by email on the web, where SOCRATES activities will be described in layman terms.
8) Because the remoteness of the planned field activities will necessarily limit the numbers of students who can travel to the field site, other activities are planned to maximize the educational impact of the project. The lead scientists for SOCRATES will write an on-line blog to document their experiences in the field, the science questions being addressed on a daily basis, and strategies for addressing them. In addition, we will set up a web site following the lead from PREDICT and other projects (e.g., https://www.eol.ucar.edu/content/predict-educational-resources) we will make educational resources aimed at K-12 students available, referring to activities underway within SOCRATES. An on-line question and answer site, "Ask Socrates" will be set up, where students or other members of the public will pose questions related to the role of clouds and aerosols on climate change, which will be answered by SOCRATES scientists.

7. Broader Impacts

SOCRATES is a program of research that will shed important light into key processes controlling aerosols, clouds and their interactions over the Southern Ocean, which is an under-sampled and remote region. The new process level understanding gained from SOCRATES will directly impact climate model development in a region where models perform particularly poorly. Improved 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.

8. References

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

Ayers, G. P. and Gras, J. L., 1991: Seasonal relationship between cloud condensation nuclei and aerosol methanesulfonate in marine air, Nature, 353, 834–835.

Bates, T. S., B. J. Huebert, J. L. Gras, F. B. Griffiths, *and* P. A. Durkee (1998), International Global Atmospheric Chemistry (IGAC) Project's First Aerosol Characterization Experiment (ACE 1): Overview, J. Geophys. Res., 103(D13), 16297–16318, *doi:10.1029/97JD03741.*

Bates, T. S., et al. (2012), Measurements of ocean derived aerosol off the coast of California, J. Geophys. Res., 117, D00V15, doi:10.1029/2012JD017588.

Behrangi, A., M. Lebsock, S. Wong, and B. Lambrigtsen, 2012: On the quantification of oceanic rainfall using spaceborne sensors. J. Geophys. Res., 117, D20105.

Behrangi, A., G. Stephens, R. Adler, G. Huffman, B. Lambrigtsen, and M. Lebsock, 2014: An update on oceanic precipitation rate and its zonal distribution in light of advanced observations from space. J. Climate., 27, 3957-65. doi:10.1175/JCLI-D-13- 00679.1

Bigg, E. K., 1973: Ice nucleus concentrations in remote areas. *J. Atmos. Sci.,* **30**, 1153-1157.

Bigg, E. K., and C. Leck, 2001: Cloud-active particles over the central Arctic Ocean, 2001: *J. Geophys. Res.,* **106**, 32,155-32,166.

Bodas-Salcedo, A., K. Williams, M. Ringer, I. Beau, J. Cole, J. Dufresne, T. Koshiro, B. Stevens, Z. Wang, and T. Yokohata, 2013: Origins of the solar radiation biases over the Southern Ocean in CFMIP2 models. J. Climate. doi:10.1175/JCLI-D-13-00169.1.

Bodas-Salcedo, A., M. J. Webb, S. Bony, H. Chepfer, J.-L. DuFresne, S. A. Klein, Y. Zhang, R. Marchand, J. M . Haynes, R. Pincus, and V. O. John, 2011: COSP: Satellite simulation software for model assessment. *Bull. Amer. Meteor. Soc.*, **92**, 1023-1043.

Boers, R., and R. M. Mitchell, 1994: Absorption feedback in stratocumulus clouds - Influence on cloud-top albedo. *Tellus*, **46,** 229-241.

Boers, R., J. B. Jensen, P. B. Krummel, and H. Gerber, 1996: Microphysical and short-wave radiative structure of wintertime stratocumulus clouds over the Southern Ocean. Quart. J. Roy. Meteor. Soc., 122, 1307–1339, doi: 10.1002/qj.49712253405

Boers, R., J. B. Jensen, and P. B. Krummel, 1998: Microphysical and short-wave radiative structure of stratocumulus clouds over the Southern Ocean: Summer results and seasonal differences, *Q. J. R. Meteorol. Soc*., 124, 151–168, doi:10.1002/qj.49712454507.

Borys, R. D., D. H. Lowenthal, S. A. Cohn, and W. O. J. Brown, 2003: Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.*, **30(10),** 1538, 1510.1029/2002gl016855.

Bourassa, Mark A., and Coauthors, 2013: High-Latitude Ocean and Sea Ice Surface Fluxes: Challenges for Climate Research. *Bull. Amer. Meteor. Soc.*, **94**, 403–423. doi: 10.1175/BAMS-D-11-00244.1.

Bréon, F.-M., Tanré, D., and Generoso, S., 2002: Aerosol effect on cloud droplet size monitored from satellite, *Science*, **295**, 834–838, DOI: 10.1126/science.1066434.

Burrows, S. M., Hoose, C., Pöschl, U., and Lawrence, M. G.: Ice nuclei in marine air: biogenic particles or dust?, *Atmos. Chem. Phys*., **13**, 245-267, doi:10.5194/acp-13-245-2013, 2013.

Carslaw, K. S., Boucher, O., Spracklen, D. V., Mann, G. W., Rae, J. G. L., Woodward, S., and Kulmala, M.: A review of natural aerosol interactions and feedbacks within the Earth system, Atmos. Chem. Phys., 10, 1701-1737, doi:10.5194/acp-10-1701-2010, 2010.

Carslaw et al. (2013) Large contribution of natural aerosols to uncertainty in indirect forcing. Nature. DOI: 10.1038/nature12674

Ceppi, P., Y.-T. Hwang, D. M. W. Frierson and D.L. Hartmann, 2012: Southern Hemisphere jet latitude biases in CMIP5 models linked to shortwave cloud forcing. Geophys. Res. Lett., doi:10.1029/2012GL053115.

Ceppi, P., M. D. Zelinka, and D. L. Hartmann (2014), The response of the Southern Hemispheric eddy-driven jet to future changes in shortwave radiation in CMIP5, Geophys. Res. Lett., 41, 3244–3250, doi:10.1002/2014GL060043.

Choi, Y. S., Ho, C. H., Kim, S. W., & Lindzen, R. S. (2010). Observational Diagnosis of Cloud Phase in the Winter Antarctic Atmosphere for Parameterizations in Climate Models. Advances in Atmospheric Sciences, 27(6), 1233-1245. doi: 10.1007/s00376-010-9175-3

Chubb, T. H., J. B. Jensen, S. T. Siems, and M. J. Manton (2013), In situ observations of supercooled liquid clouds over the Southern Ocean during the HIAPER Pole-to-Pole Observation (HIPPO) campaigns, Geophys. Res. Lett., 40, 5280–5285, doi:10.1002/grl.50986.

Clarke, A.D., J. L. Varner, F. Eisele, R. Tanner, L. Mauldin and M. Litchy, 1998a: Particle production in the remote marine atmsophere: Cloud outflow and subsidence during ACE-1, *J. Geophys, Res.*, **103**, 16397-16409.

Clarke, A. D., et al., 1998b: Particle Nucleation in the Tropical Boundary Layer and Its Coupling to Marine Sulfur Sources. Science, 282, 89, DOI: 10.1126/science.282.5386.89.

Delanoë J and Hogan R., 2008: A variational scheme for retrieving ice cloud properties from combined radar, lidar and infrared radiometer. *J. Geophys. Res.,* 113, D07204, doi:10.1029/2007JD009000.

DeMott, P. J., O. Möhler, O. Stetzer, G. Vali, Z. Levin, M. D. Petters, M. Murakami, T. Leisner, U. Bundke, H. Klein, Z. Kanji, R. Cotton, H. Jones, M. Petters, A. Prenni, S. Benz, M. Brinkmann, D. Rzesanke, H. Saathoff, M. Nicolet, S. Gallavardin, A. Saito, B. Nillius, H. Bingemer, J. Abbatt, K. Ardon, E. Ganor, D. G. Georgakopoulos, and C. Saunders, 2011: Resurgence in ice nucleation research. *Bull. Amer. Meteor. Soc.,* **92**, 1623-1635.

Deng, M., G. G. Mace, Z. Wang, and H. Okamoto, 2010: Tropical Composition, Cloud and Climate Coupling Experiment validation for cirrus cloud profiling retrieval using CloudSat radar and CALIPSO lidar. *J. Geophys. Res.*, **115**, D00J15, doi:10.1029/2009JD013104.

Dong, X. Q., and G. G. Mace, 2003: Arctic stratus cloud properties and radiative forcing derived from ground-based data collected at Barrow, Alaska. *J. Climate*, **16,** 445-461.

Dong, X. Q., G. G. Mace, P. Minnis, and D. F. Young, 2001: Arctic stratus cloud properties and their effect on the surface radiation budget: Selected cases from FIRE ACE. *J. Geophys. Res.*, **106,** 15297-15312, doi:15210.11029/12000JD900404.

Earle, M. E., and Coauthors, 2011: Factors influencing the microphysics and radiative properties of liquid-dominated Arctic clouds: Insight from observations of aerosol and clouds during ISDAC. *J. Geophys. Res.*, **116,** D00T09, doi:10.1029/2011jd015887.

Field, P. R., R. J. Cotton, K. McBeath, A. P. Lock, S. Webster, and R. P. Allan, 2013: Improving a convection-permitting model simulation of a cold air outbreak. *Q. J. R. Meteorol. Soc*. DOI:10.1002/qj.2116.

Feingold, G., A. McComiskey, D. Rosenfeld, and A. Sorooshian (2013), On the relationship between cloud contact time and precipitation susceptibility to aerosol, J. Geophys. Res. Atmos., 118, 10,544–10,554, doi:10.1002/jgrd.50819.

Garcia, E., T. C. J. Hill, A. J. Prenni, P. J. DeMott, G. D. Franc and S. M. Kreidenweis, 2012: Biogenic ice nuclei in boundary layer air over two U.S. High Plains agricultural regions, J. Geophys. Res.117, D18209, doi:10.1029/2012JD018343.

Ghan, S. J., S. J. Smith, M. Wang, K. Zhang, K. Pringle, K. Carslaw, J. Pierce, S. Bauer, and P. Adams (2013), A simple model of global aerosol indirect effects, *J. Geophys. Res.*, **118**, 6688–6707, doi:10.1002/jgrd.50567.

Grosvenor, D. P. and Wood, R.: The effect of solar zenith angle on MODIS cloud optical and microphysical retrievals within marine liquid water clouds*, Atmos. Chem. Phys*., **14**, 7291-7321, doi:10.5194/acp-14-7291-2014, 2014.

Govekar, P. D., C. Jakob, M. J. Reeder, and J. Haynes (2011), The three-dimensional distribution of clouds around Southern Hemisphere extratropical cyclones, Geophys. Res. Lett., 38, L21805, doi:10.1029/2011GL049091.

Hande, L. B, S. T. Siems, M. J. Manton, and D. Belusic (2012), Observations of wind shear over the Southern Ocean. *J. Geophys. Res.*, **117**, D12206, doi:10.1029/2012JD017488.

Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, **102,** 6831-6864.

Hallett, J., and S. C. Mossop (1974), Production of secondary ice crystals during the riming process, Nature, 249, 26–28, doi:10.1038/249026a0.

Haynes, J. M., T. S. L'Ecuyer, G. L. Stephens, S. D. Miller, C. Mitrescu, N. B. Wood, and S. Tanelli (2009), Rainfall retrieval over the ocean with spaceborne W-band radar, J. Geophys. Res., 114, D00A22, doi:10.1029/2008JD009973.

Hill, T. C. J., D. G. Georgakopoulos, P. J. DeMott, W. L. Stump, and G. D. Franc, 2014: Quantification of the ina gene in ice nucleation active bacteria. Appl. Environ. Microbiol. 80(4):1256-1267, DOI: 10.1128/AEM.02967-13.

Heidinger, A. K., and M. J. Pavolonis (2005), Global daytime distribution of overlapping cirrus cloud from NOAA's Advanced Very High Resolution Radiometer, J. Clim., 18, 4772–4784, doi:10.1175/JCLI3535.1.

Hu, Y., Vaughan, M., McClain, C., Behrenfeld, M., Maring, H., Anderson, D., Sun-Mack, S., Flittner, D., Huang, J., Wielicki, B., Minnis, P., Weimer, C., Trepte, C., and Kuehn, R.: Global statistics of liquid water content and effective number concentration of water clouds over ocean derived from combined CALIPSO and MODIS measurements, Atmos. Chem. Phys., 7, 3353-3359, doi:10.5194/acp-7-3353-2007, 2007.

Hu, Y., S. Rodier, K. Xu, W. Sun, J. Huang, B. Lin, P. Zhai, and D. Josset (2010), Occurrence, liquid water content, and fraction of supercooled water clouds from combined CALIOP/IIR/MODIS measurements. J. Geophys. Res., 115, D00H34, doi:10.1029/2009JD012384.

Hudson, J.G., Y. Xie, and S.S. Yum, Vertical distributions of cloud condensation nuclei spectra over the summertime Southern Ocean, J. Geophys. Res., 103, 16,609-16,624, 1998.

Huang. Y., S. T. Siems, M. J. Manton, L. B. Hande and J. M. Haynes, 2012a: The structure of low-altitude clouds over the Southern Ocean as seen by CloudSat. *J. Climate*, **25**, 2535-2546, DOI: 10.1175/JCLI-D-11-00131.1.

Huang, Y., S. T. Siems, M. J. Manton, A. Protat, and J. Delanoë, 2012b: A study on the low-altitude clouds over the Southern Ocean using the DARDAR-MASK. *J. Geophys. Res*., **117**, D18204, doi:10.1029/2012JD017800.

Huang, Yi, Steven T. Siems, Michael J. Manton, Gregory Thompson, 2014: An Evaluation of WRF Simulations of Clouds over the Southern Ocean with A-Train Observations. *Mon. Wea. Rev.*, **142**, 647–667. doi: 10.1175/MWR-D-13-00128.1

Cantrell, Will and Andrew Heymsfield, 2005: Production of Ice in Tropospheric Clouds: A Review. Bull. Amer. Meteor. Soc., 86, 795–807. doi: 10.1175/BAMS-86-6-795

Intrieri, J. M., C. W. Fairall, M. D. Shupe, P. O. G. Persson, E. L. Andreas, P. S. Guest, and R. E. Moritz, 2002: An annual cycle of Arctic surface cloud forcing at SHEBA. *J. Geophys. Res.*, **107,** 8039, doi:8010.1029/2000jc000439.

Jackson, R.C., G.M. McFarquhar, A.V. Korolev, M.E. Earle, P.S.K. Liu, R.P. Lawson, S. Brooks, M. Wolde, A. Laskin, and M. Freer, 2012: The dependence of ice microphysics on aerosol concentration in arctic mixed-phase stratus clouds during ISDAC and M-PACE. *J. Geophys. Res.*, **117**, D15, doi:10.1029/2012JD017668.

Jensen, J. B., S. Lee, P. B. Krummel, J. Katzfey, and D. Gogoasa, 2000: Precipitation in marine cumulus and stratocumulus. Part I: Thermodynamic and dynamic observations of closed cell circulations and cumulus bands. Atmos. Res., 54, 117–155

Kahn, R. A., B. J. Gaitley, M. J. Garay, D. J. Diner, T. F. Eck, A. Smirnov, and B. N. Holben (2010), Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network, J. Geophys. Res., 115, D23209, doi:10.1029/2010JD014601.

Kanitz, T., Seifert, P., Ansmann, A., Engelmann, R., Althausen, D., Casiccia, C., & Rohwer, E. G. (2011). Contrasting the impact of aerosols at northern and southern midlatitudes on heterogeneous ice formation. Geophysical Research Letters, 38, 5. doi: L17802.

Kay, J. E., B. Medeiros, Y.-T. Hwang, A. Gettelman, J. Perket, and M. G. Flanner, 2014: Processes controlling Southern Ocean shortwave climate feedbacks in CESM, *Geophys. Res. Lett*., **41**, doi:10.1002/2013GL058315.

Keene, W.C., H. Maring, J.R. Maben et al., 2007, Chemical and physical characteristics of nascent aerosols produced by bursting bubbles at a model air-sea interface, *J. Geophys. Res.,* **112**, D21202, doi:10.1029/2007JD008464.

Kiehl, J. T. (2007), Twentieth century climate model response and climate sensitivity, Geophys. Res. Lett., 34, L22710, doi:10.1029/2007GL031383.

Kleidman, R. G., Smirnov, A., Levy, R. C., Mattoo, S., and Tanre, D.: Evaluation and wind speed dependence of MODIS aerosol retrievals over open ocean, IEEE T. Geosci. Remote, 50, 429– 435, 2012. doi: 10.1109/TGRS.2011.2162073

Klein, S. A., and C. Jakob, 1999: Validation and sensitivities of frontal clouds simulated by the ECMWF model. *Mon. Wea. Rev*., **127**, 2514-2531.

Klein, S. A., and coauthors, 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single layer cloud. *Quart. J. Roy. Meteor. Soc.*, **135**, 979–1002.

Klein, S. A., Y. Zhang, M. D. Zelinka, R. Pincus, J. Boyle, and P. J. Gleckler, 2013: Are climate model simulations of clouds improving? An evaluation using the ISCCP simulatior. *J. Geophys. Res*., **188**, 1329-1342, doi:10.1002/jgrd.50141

Knopf, D. A., P. A. Alpert, B. Wang, and J. Y. Aller, 2011: Stimulation of ice nucleation by marine diatoms. *Nature Geosci.,* **4**, 88-90.

Kooperman, G. J., M. S. Pritchard, S. J. Ghan, M. Wang, R. C. J. Somerville, and L. M. Russell (2012), Constraining the influence of natural variability to improve estimates of global aerosol indirect effects in a nudged version of the Community Atmosphere Model 5, J. Geophys. Res., 117, D23204, doi:10.1029/2012JD018588.

Korhonen, H., K.S. Carslaw, D.V. Spracklen, G.W. Mann, and M.T. Woodhouse, 2008: Influence of oceanic dimethyl sulphide emissions on cloud condensation nuclei concentrations and seasonality over the remote Southern Hemisphere oceans: A global model study, *J. Geophys. Res.,* **113**, D15204, doi:10.1029/2007JD009718.

Korolev, A. V., Isaac, G. A., Cober, S. G., Strapp, J. W. and Hallett, J. (2003), Microphysical characterization of mixed-phase clouds. Q.J.R. Meteorol. Soc., 129: 39–65. doi: 10.1256/qj.01.204

Kumjian, Matthew R., Steven A. Rutledge, Roy M. Rasmussen, Patrick C. Kennedy, and Mike Dixon, 2014: High-Resolution Polarimetric Radar Observations of Snow-Generating Cells. J. Appl. Meteor. Climatol., 53, 1636–1658. doi: 10.1175/JAMC-D-13-0312.1

Lance, S., C. A. Brock, D. Rogers, and J. A. Gordon, 2010: Water droplet calibration of the Cloud Droplet Probe (CDP) and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC. *Atmos. Meas. Tech.*, **3,** 1683-1706.

Lawrence, D.A. and B.B. Balsley, 2013: High-resolution atmospheric sensing of multiple atmospheric variables using the DataHawk small airborne measurement system, J. Atmos. Ocean. Tech., 30, 2352-2366.

Lawson, R. P., B. A. Baker, C. G. Schmitt, and T. L. Jensen (2001), An overview of microphysical properties of Arctic clouds observed in May and July 1998 during FIRE ACE, J. Geophys. Res., 106(D14), 14989–15014, doi:10.1029/2000JD900789.

Lebsock, M., and H. Su (2014), Application of active spaceborne remote sensing for understanding biases between passive cloud water path retrievals, J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD021568.

Lohmann, U., 2002: A glaciation indirect aerosol effect caused by soot aerosols. *Geophys. Res. Lett.*, **29,** 1052, doi:1010.1029/2001gl014357.

Mace, G.G., et al., 2009: A description of hydrometeor layer occurrence statistics derived from the first year of merged CloudSat and CALIPSO data. *J. Geophys. Res.*, *114*, doi:10.1029/2009JD009755.

Mace, G. G., 2010: Cloud properties and radiative forcing over the maritime storm tracks of the storm tracks of the Southern Ocean and North Atlantic derived from A-Train, J. Geophys. Res., 115, D10201, doi:10.1029/2009JD012517.

Marchand, R., T. Ackerman, M. Smyth, and W. B. Rossow, 2010: A review of cloud top height and optical depth histograms from MISR, ISCCP, and MODIS, J. Geophys. Res., 115, D16206, doi:10.1029/2009JD013422.

Mason, shannon Christian Jakob, Alain Protat, and Julien Delanoë, 2014: Characterizing Observed Midtopped Cloud Regimes Associated with Southern Ocean Shortwave Radiation Biases. J. Climate, 27, 6189–6203. doi: 10.1175/JCLI-D-14-00139.1

McFarquhar, G. M., and Coauthors, 2007: Ice properties of single-layer stratocumulus during the Mixed-Phase Arctic Cloud Experiment: 1. Observations. *J. Geophys. Res.*, **112,** D24201, doi:24210.21029/22007JD008633.

Morrison, A. E., S. T. Siems, M. J. Manton, 2011: A Three-Year Climatology of Cloud-Top Phase over the Southern Ocean and North Pacific. *J. Climate*, **24**, 2405–2418. doi: 10.1175/2010JCLI3842.1.

Catherine M. Naud, Derek J. Posselt, and Susan C. van den Heever, 2012: Observational Analysis of Cloud and Precipitation in Midlatitude Cyclones: Northern versus Southern Hemisphere Warm Fronts. J. Climate, 25, 5135–5151. doi: 10.1175/JCLI-D-11-00569.1

Naud, C., J. F. Booth, and A. D. Del Genio, 2014: Evaluation of ERA-Interim and MERRA Cloudiness in the Southern Oceans. *J. Climate*, **27**, 2109-2124, doi:10.1175/JCLI-D-13-00432.1.

Ovchinnikov M, A Ackerman, A Avramov, A Cheng, J Fan, A Fridlind, SJ Ghan, JY Harrington, C Hoose, A Korolev, G McFarquhar, H Morrison, M Paukert, J Savre, B Shipway, MD Shupe, A Solomon, and K Sulia. 2014. Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions. *Journal of Advances in Modeling Earth Systems*, **6**, 223-248. doi:10.1002/2013MS000282

Park, S., C. S. Bretherton, and P. J. Rasch, 2014: Integrating Cloud Processes in the Community Atmosphere Model, Version 5. *J. Climate*, in press.

Pincus, R., and M. B. Baker, 1994: Effect of precipitation on the albedo susceptibility of clouds in the marine boundary layer. *Nature*, **372,** 250-252.

Plummer, D., G. McFarquhar, R. Rauber, B. Jewett, and D. Leon, 2014: Structure and statistical analysis of the microphysical properties of generating cells in the comma-head region of continental winter cyclones. J. Atmos. Sci. doi:10.1175/JAS-D-14-0100.1, in press.

Prather KA, Bertram TH, Grassian VH, Deane GB, Stokes MD, DeMott PJ, Aluwihare LI, Palenik BP, Azam F, Seinfeld JH, Moffet RC, Molina MJ, Cappa CD, Geiger FM, Roberts GC, Russell LM, Ault AP, Baltrusaitis J, Collins DB, Corrigan CE, Cuadra-Rodriguez LA, Ebben CJ, Forestieri SD, Guasco TL, Hersey SP, Kim MJ, Lambert WF, Modini RL, Mui W, Pedler BE, Ruppel MJ, Ryder OS, Schoepp NG, Sullivan RC, Zhao D., 2013: Bringing the ocean into the laboratory to probe the chemical complexity of sea spray aerosol. *Proc. Nat. Acad. Sci. USA*, **110**, 7550-7555. doi: 10.1073/pnas.130026211

Prenni, A. J., P. J. Demott, D. C. Rogers, S. M. Kreidenweis, G. M. McFarquhar, G. Zhang, and M. R. Poellot, 2009: Ice nuclei characteristics from M-PACE and their relation to ice formation in clouds. *Tellus*, **61,** 436-448.

Pruppacher, H. R. and J. D. Klett, *Microphysics of Clouds and Precipitation*, Kluwer Academic Publishers, Netherlands, 1997.

Quinn, P.K. and T.S. Bates, 2011: The case against climate regulation via oceanic phytoplankton sulfur emissions, *Nature*, **480**, 51 – 56.

Quinn, P.K., T.S. Bates, K. Schulz, D. Coffman, A. Frossard, L. Russell, W. Keene, and D. Kieber, 2014: Contribution of sea surface carbon to organic carbon enrichment in seaspray aerosol, *Nat. Geo.,* **7**, 228 – 232.

Rangno, A. L., and P. V. Hobbs, 2001: Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations. *J. Geophys. Res.*, **106,** 15065-15075.

Redemann, J., Vaughan, M. A., Zhang, Q., Shinozuka, Y., Russell, P. B., Livingston, J. M., Kacenelenbogen, M., and Remer, L. A.: The comparison of MODIS-Aqua (C5) and CALIOP (V2 & V3) aerosol optical depth, Atmos. Chem. Phys., 12, 3025-3043, doi:10.5194/acp-12-3025-2012, 2012.

Remer, L. A., et al. (2008), Global aerosol climatology from the MODIS satellite sensors, J. Geophys. Res., 113, D14S07, doi:10.1029/2007JD009661.

Rauber, Robert M., Harry T. Ochs III, Marilé Colón-Robles, Anne Marie Hertel, Erin Riepe, Sarah Scalia, Eric Snodgrass, Bjorn Stevens, Jennifer Davison, Simona Bordoni, Brian Medeiros, Panu Trivej, Sabine Göke, Olga L. Mayol-Bracero, Humberto Caro-Gautier, Maylissa Deliz, Yarilis Méndez-Lopez, Flavia Morales-García, Diana L. Ortiz-Montalvo, David Rogers, Charles Knight, Jorgen Jensen, Paquita Zuidema, Shaunna Donaher, Virendra Ghate, Ieng Jo, Kristen Rasmussen, Efthymios Serpetzoglou, Sarah Bereznicki, Colleen Henry, Ela Grzeszczak, Michael Kruk, Jason Lowenstein, Judith Malley, Subhashree Mishra, Louise A. Nuijens, Dennis O'Donnell, Haiwei Shen, Michael Siedsma, Jennifer Small, and Jonathan Zawislak, 2007: In the Driver's Seat: Rico and Education. Bull. Amer. Meteor. Soc., 88, 1929–1937. doi: 10.1175/BAMS-88-12-1929

Rauber, Robert M., Joseph Wegman, David M. Plummer, Andrew A. Rosenow, Melissa Peterson, Greg M. McFarquhar, Brian F. Jewett, David Leon, Patrick S. Market, Kevin R. Knupp, Jason M. Keeler, and Steven M. Battaglia, 2014: Stability and Charging Characteristics of the Comma Head Region of Continental Winter Cyclones. J. Atmos. Sci., 71, 1559–1582. doi: 10.1175/JAS-D-13-0253.1

Rosenow, Andrew A. David M. Plummer, Robert M. Rauber, Greg M. McFarquhar, Brian F. Jewett, and David Leon, 2014: Vertical Velocity and Physical Structure of Generating Cells and Convection in the Comma Head Region of Continental Winter Cyclones. J. Atmos. Sci., 71, 1538–1558. doi: 10.1175/JAS-D-13-0249.1

Rosinski, J., Haagenson, P. L., Nagamoto, C. T., and Parungo, F., 1987: Nature of ice-forming nuclei in marine air masses, *J. Aerosol Sci*., **18**, 291–309, doi:10.1016/0021-8502(87)90024-3.

Russell, L. M., D.H. Lenschow, K.K. Laursen, P.B. Krummel, S.T. Siems, A.R. Bandy, D.C. Thornton, and T.S. Bates, 1998: Bidirectional mixing in an ACE-1 marine boundary layer overlain by a second turbulent layer. J. Geophys. Res., **103**, 16411-16432.

Schnell, R. C. and Vali, G., 1976: Biogenic ice nuclei: Part I. Terrestrial and marine sources, *J. Atmos. Sci.*, **33**, 1554–1564, doi:10.1175/1520-0469(1976)033<1554:BINPIT>2.0.CO;2, 1976.

Sciare, J., O. Favez, R. Sarda-Este`ve, K. Oikonomou, H. Cachier, and V. Kazan (2009), Long-term observations of carbonaceous aerosols in the Austral Ocean atmosphere: Evidence of a biogenic marine organic source, J. Geophys. Res., 114, D15302, doi:10.1029/2009JD011998.

Shupe, M. D., T. Uttal, S. Y. Matrosov, and A. S. Frisch, 2001: Cloud water contents and hydrometeor sizes during the FIRE Arctic Clouds Experiment. *J. Geophys. Res.*, **106,** 15015-15028.

Shupe, M. D., T. Uttal, and S. Y. Matrosov, 2005: Arctic cloud microphysics retrievals from surface-based remote sensors at SHEBA. *J. Appl. Meteor.*, **44,** 1544-1562.Sun, Z., and K.P. Shine, 1994: Studies of the radiative properties of ice and mixed-phase clouds. *Quart. J. Roy. Meteor. Soc.*, **120**, 111-137.

Smirnov, A., Holben, B. N., Giles, D. M., Slutsker, I., O'Neill, N. T., Eck, T. F., Macke, A., Croot, P., Courcoux, Y., Sakerin, S. M., Smyth, T. J., Zielinski, T., Zibordi, G., Goes, J. I., Harvey, M. J., Quinn, P. K., Nelson, N. B., Radionov, V. F., Duarte, C. M., Losno, R., Sciare, J., Voss, K. J., Kinne, S., Nalli, N. R., Joseph, E., Krishna Moorthy, K., Covert, D. S., Gulev, S. K., Milinevsky, G., Larouche, P., Belanger, S., Horne, E., Chin, M., Remer, L. A., Kahn, R. A., Reid, J. S., Schulz, M., Heald, C. L., Zhang, J., Lapina, K., Kleidman, R. G., Griesfeller, J., Gaitley, B. J., Tan, Q., and Diehl, T. L.: Maritime aerosol network as a component of AERONET – first results and comparison with global aerosol models and satellite retrievals, Atmos. Meas. Tech., 4, 583-597, doi:10.5194/amt-4-583-2011, 2011.

Sun, Z. and Shine, K. P. (1994), Studies of the radiative properties of ice and mixed-phase clouds. Q.J.R. Meteorol. Soc., 120: 111–137. doi: 10.1002/qj.49712051508

Toth, T. D., J. Zhang, J. R. Campbell, J. S. Reid, Y. Shi, R. S. Johnson, A. Smirnov, M. A. Vaughan, and D. M. Winker (2013), Investigating enhanced Aqua MODIS aerosol optical depth retrievals over the mid-to-high latitude Southern Oceans through intercomparison with co-located CALIOP, MAN, and AERONET data sets, *J. Geophys. Res. Atmos*., **118**, 4700–4714, doi:10.1002/jgrd.50311.

Trenberth, K. E., and J. T. Fasullo, 2010: Simulation of present day and 21st century energy budgets of the southern oceans. *J. Clim.*, **23**, 440-454.

Twomey, S., 1974: Pollution and planetary albedo. *Atmos. Environ.*, **8,** 1251-1256.

Várnai, T., and A. Marshak, 2007: View angle dependence of cloud optical thicknesses retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS), *J. Geophys. Res.*, **112**, D06203, doi:10.1029/2005JD006912.

Winker, D. M., Tackett, J. L., Getzewich, B. J., Liu, Z., Vaughan, M. A., and Rogers, R. R.: The global 3-D distribution of tropospheric aerosols as characterized by CALIOP, Atmos. Chem. Phys., 13, 3345-3361, doi:10.5194/acp-13-3345-2013, 2013.

Witek, M. L., M. J. Garay, D. J. Diner, and A. Smirnov, 2013: Aerosol optical depths over oceans: A view from MISR retrievals and collocated MAN and AERONET in situ observations, J. Geophys. Res. Atmos., 118, 12,620‑12,633, doi:10.1002/2013JD020393.

Wofsy, S. C., et al., 2011: HIAPER Pole-to-Pole Observations (HIPPO): fine-grained, global-scale measurements of climatically important atmospheric gases and aerosols. Proc. Roy. Soc. A, 369, 2073-2086, doi:10.1098/rsta.2010.0313.

Xie, S., J. Boyle, S. A. Klein, X. Liu and S. Ghan, 2008: Simulations of Arctic Mixed-Phase Clouds in Forecasts with CAM3 and AM2 for M-PACE, J. Geophys. Res., 113, D04211, doi:10.1029/2007JD009225.

Yu, L., Z. Zhang, S. Zhong, M. Zhou, Z. Gao, H. Wu, and B. Sun (2011), An inter-comparison of six latent and sensible heat flux prodcuts over the Southern Ocean, Polar Research, 30, 1–27. doi: 10.3402/polar.v30i0.10167

Zelinka, M. D., T. Andrews, P. M. Forster, and K. E. Taylor, 2014: Quantifying Components of Aerosol-Cloud-Radiation Interactions in Climate Models, J. Geophys. Res., doi: 10.1002/2014JD021710, in press.

Zhang, J., and J. S. Reid (2006), MODIS aerosol product analysis for data assimilation: Assessment of over-ocean level 2aerosol optical thickness retrievals, J. Geophys. Res., 111, D22207, doi:10.1029/ 2005JD006898.

Zuidema, P., and Coauthors, 2005: An arctic springtime mixed-phase cloudy boundary layer observed during SHEBA. *J. Atmos. Sci*., **62**, 160-176.

Workshop on Clouds, Aerosols, Radiation and Air-Sea Interface of the Southern Ocean: Establishing Directions for Future Research

Roj Marchand, Robert Wood, Chris Bretherton, University of Washington, Seattle, Washington
Greg McFarquhar, University of Illinois, Urbana, Illinois
Alain Protat, Bureau of Meteorology, Melbourne, Australia
Steven Siems and Christian Jakob, Monash University, Melbourne, Australia
Bob Weller, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts

Wireless internet (University of Washington) information

UW NetID: event0895
Password: 8A9W+2G9H+5B2N

ALL MEETING ROOMS ARE IN THE HUSKY UNION BUILDING (HUB)

Tuesday March 18, 2014: Presentations on Prior Work done on Southern Ocean

800 to 815: Registration [HUB Lyceum]

Session 1: Workshop Introduction and SOCRATES [HUB Lyceum]

815 to 830: Greg McFarquhar, Introduction and Goals of Workshop, and Relationship to SOCRATES Proposal: Greg McFarquhar

830 to 845: Rob Wood, SOCRATES: Overarching goals and science hypothesis guiding development of a Southern Ocean experiment

845 to 900: Alain Protat, CAPRICORN (Clouds, Aerosols, Precipitation, Radiation and atmospheric Composition Over the SoutheRN Ocean)

Session 2: Plenary: Overview talks on the Southern Ocean [HUB Lyceum]: Chairs Chris Bretherton/Roj Marchand

900 to 920: Jennifer Kay, Processes controlling Southern Ocean shortwave climate feedbacks in CESM

920 to 940: Dennis Hartmann, Large-scale environment of Southern Hemisphere clouds

940 to 1000: Keith Williams, The causes of Southern Ocean flux biases in CMI5 and TAMIP simulations

1000 to 1030 Break

1030 to 1050: Nicholas Meskhidze, Sea spray aerosol and climate assessments: Model results and remotely sensed data

1050 to 1110: Steve Ghan, Importance of characterizing natural aerosol for estimates of anthropogenic aerosol indirect effects

1110 to 1130: Trish Quinn, The Sea surface carbon pool and organic matter enrichment in sea spray aerosol

1130 to 1150: Paul DeMott, Marine ice nucleating particles and the need for Southern Ocean measurements

1150 to 1210: Steven Siems and Greg McFarquhar, Observations of supercooled liquid water from in-situ and remote sensing observations

1210 to 1230: Carol Anne Clayson, Air-sea satellite flux datasets and what they do (and don't) tell us about the air-sea interface in the Southern Ocean

1230 to 1330: Lunch [HUB Lyceum, Box Lunch Provided]

Session #3 and #4 run concurrently

Session 3: Clouds and meteorology, [HUB Lyceum] Chairs: Roj Marchand/ Steve Siems /Alain Protat

1330 to 1345: Kali Furtado, Mixed-phase theory to application in a global model – effects on SO bias in the UM

1345 to 1400: Erica Dolinar, Evaluation of CMIP5 AMIP simulation clouds and TOA radiation budgets in the Southern mid-latitudes

1400 to 1415: Ryan Stanfield, Assessment of NASA GISS CMIP5 and post-CMIP5 simulated clouds using satellite observations

1415 to 1430: Paulo Ceppi, The response of the Southern Hemisphere eddy-driven jet to future changes in shortwave radiation

1430 to 1445: Ying Li, Instantaneous linkages between cloud vertical structure and large-scale climate over the extratropics

1500 to 1515 Break [HUB Lyceum]

1515 to 1530: Roj Marchand, Recent changes in Southern Ocean clouds

1530 to 1545: Daniel McCoy, The effect of Southern Ocean cloud properties on the upwelling shortwave

1545 to 1600: Jay Mace, Southern Ocean cloud processes as derived from A-Train

1600 to 1615: Steven Siems, Analysis of Boundary layer structure and precipitation from analysis of meteorological observations over Macquarie Island

1615 to 1630, Adrian James McDonald, Atmospheric science in the "Deep South" National Science Challenge

1630 to 1645: Kalli Furtado and Steve Abel, Aircraft observations and high resolution NWP simulations of Northern Hemisphere cold-air outbreaks

1645 to 1700: Tom Lachlan-Cope, Antarctic cloud measurements

1700 to 1715: Simon Alexander, The Antarctic Cloud Radiation Experiment (ACRE)

1715 to 1730: Scott Collis, Observing precipitating cloud systems at centimeter wavelengths: What we can do and lessons for Southern Hemisphere studies

1730 to 1745: Jeff Stith, NCAR tools for airborne cloud physics and some recent examples from Southern Ocean flights

1745-1800: Gijs de Boer, Small UAS for SOCRATES: Potential platforms and scientific applications

Session 4: Aerosols and their interaction with clouds [HUB 250], Chairs Greg McFarquhar/Rob Wood/ Chris Bretherton

1330 to 1345: Theodore Wilson, Ice nuclei in the sea surface microlayer

1345 to 1400: Susannah Burrows, The potential influence of marine biological activity on ice nuclei concentrations over the Southern Ocean

1400 to 1415: Cassandra Gaston, Single-particle insights into the influence of biological activity on sea spray aerosol mixing-state

1415 to 1430 Lynne Russell, Particle sources and growth

1430 to 1445: Yan Feng, Characterization of deposition and mineralogy of dust export to the Southern Ocean

1445 to 1500: Tony Clarke, Aerosol properties, processes and fields over the Southern Oceans

1500 to 1515: Break [HUB Lyceum]

1515 to 1530: Greg Roberts, Aerosol and CCN observations at Palmer Station

1530 to 1545: Barry Huebert (presented by Tim Bates), How could one test the hypothesis, *primary marine aerosols dominate CCN*, with in situ observations?

1545 to 1600: Jorgen Jensen, Sea spray and warm rain in cold clouds over the windiest ocean

1600 to 1615: Harvey Mike, SOLAS (Surface Ocean Aerosol Production) SOAP experiment and biogenic aerosols

1615 to 1630: Jim Hudson, Detailed CCN spectral measurements

1630 to 1645: Rob Wood, The seasonal cycle of warm cloud microphysics and aerosols over the Southern Ocean

1645 to 1700: Richard Moore, Model and satellite-based sensitivity of cloud properties to aerosol changes in the Southern Ocean

1700 to 1715: Chris Bretherton, LES of boundary-layer cloud-aerosol interaction under Southern Ocean-like conditions

1715 to 1730 Yongxiang Hu, CALIPSO Phytoplankton Particulate Backscatter Coefficient Measurements of the Southern Oceans

1730 to 1745: Xiaohong Liu (given by Steve Ghan), Effect of aerosols on the phase partitioning of mixed-phase clouds through comparison of Community Atmospheric Model (CAM5) and CALIPSO observations: implication for cloud radiative forcing in the Southern Ocean in CAM5

1745 to 1800: Chris Hostetler, The NAAMES ship-aircraft mission concept and ocean profiling and aerosol/cloud lidar

Wednesday March 19, 2014:

Session 5: Plenary [HUB Lyceum]

0800 to 0830: Review of Session 3

0830 to 0900: Review of Session 4

0900 to 0920: Sarah Gille, Oceanographic issues in the Southern Oceans

0920 to 0935: Chris Fairall, Cloud, aerosol and surface-flux observations from ships

0935 to 1000: Break

Attendees will divide into two or three breakout discussion groups. Exact themes for the breakout groups are yet to be determined. Each group will address the topics listed below before rejoining for plenary discussions.

1000 to 1230: Breakout Session 1 [HUB Lyceum, Room 250, Room 332**]**

Formulate key questions on role of aerosols/clouds/air-sea interactions in Southern Oceans

1230 to 1330: Lunch [HUB Lyceum, Box Lunch Provided**]**

1330 to 1415: Summary of Breakout Session 1 [HUB Lyceum**]**

15 minute summary talks from each of the groups, 15 minutes general discussion

1415 to 1615: Group Discussion [HUB Lyceum**]**

What are needed measurements/retrievals/simulations needed to address hypotheses?

1615 to 1630: Break [HUB Lyceum**]**

1630 to 1700: Summary discussion, science questions and wrap-up

March 20: Steering Committee Meeting

800 to 1100: Meeting of Steering Committee

Workshop on Clouds, Aerosols, Radiation and Air-Sea Interface of the Southern Ocean: Establishing Directions for Future Research

ORGANIZERS

Roj Marchand, Robert Wood, Chris Bretherton, University of Washington, Seattle, Washington

Greg McFarquhar, University of Illinois, Urbana, Illinois

Alain Protat, Bureau of Meteorology, Melbourne, Australia

Steven Siems and Christian Jakob, Monash University, Melbourne, Australia

Bob Weller, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts

Tuesday March 18, 2014: Presentations on Prior Work done on Southern Ocean

Session 1: Workshop Introduction and SOCRATES

815 to 830: Greg McFarquhar, Introduction and Goals of Workshop, and Relationship to SOCRATES Proposal: Greg McFarquhar (ppt)

830 to 845: Rob Wood, SOCRATES: Overarching goals and science hypothesis guiding development of a Southern Ocean experiment (ppt)

845 to 900: Alain Protat, CAPRICORN (Clouds, Aerosols, Precipitation, Radiation and atmospheric Composition Over the SoutheRN Ocean) (ppt)

Session 2: Plenary: Overview talks on the Southern Ocean:
Chairs Chris Bretherton/Roj Marchand

900 to 920: Jennifer Kay, Processes controlling Southern Ocean shortwave climate feedbacks in CESM (ppt)

920 to 940: Dennis Hartmann, Large-scale environment of Southern Hemisphere clouds

940 to 1000: Keith Williams, The causes of Southern Ocean flux biases in CMI5 and TAMIP simulations (ppt)

1030 to 1050: Nicholas Meskhidze, Sea spray aerosol and climate assessments: Model results and remotely sensed data (ppt)

1050 to 1110: Steve Ghan, Importance of characterizing natural aerosol for estimates of anthropogenic aerosol indirect effects (ppt)

1110 to 1130: Trish Quinn, The Sea surface carbon pool and organic matter enrichment in sea spray aerosol (ppt)

1130 to 1150: Paul DeMott, Marine ice nucleating particles and the need for Southern Ocean measurements (ppt)

1150 to 1210: Steven Siems and Greg McFarquhar, Observations of supercooled liquid water from in-situ and remote sensing observations (ppt) Observations of supercooled liquid water - part 2

1210 to 1230: Carol Anne Clayson, Air-sea satellite flux datasets and what they do (and don't) tell us about the air-sea interface in the Southern Ocean (ppt)

Session 3: Clouds and meteorology,
Chairs: Roj Marchand/ Steve Siems /Alain Protat

1330 to 1345: Kali Furtado, Mixed-phase theory to application in a global model – effects on SO bias in the UM (ppt)

1345 to 1400: Erica Dolinar, Evaluation of CMIP5 AMIP simulation clouds and TOA radiation budgets in the Southern mid-latitudes (ppt)

1400 to 1415: Ryan Stanfield, Assessment of NASA GISS CMIP5 and post-CMIP5 simulated clouds using satellite observations (ppt)

1415 to 1430: Paulo Ceppi, The response of the Southern Hemisphere eddy-driven jet to future changes in shortwave radiation (ppt)

1430 to 1445: Ying Li, Instantaneous linkages between cloud vertical structure and large-scale climate over the extratropics (ppt)

1515 to 1530: Roj Marchand, Recent changes in Southern Ocean clouds

1530 to 1545: Daniel McCoy, The effect of Southern Ocean cloud properties on the upwelling shortwave

1545 to 1600: Jay Mace, Southern Ocean cloud processes as derived from A-Train (ppt)

1600 to 1615: Steven Siems, Analysis of Boundary layer structure and precipitation from analysis of meteorological observations over Macquarie Island (ppt)

1615 to 1630, Adrian James McDonald, Atmospheric science in the "Deep South" National Science Challenge (ppt)

1630 to 1645: Kalli Furtado and Steve Abel, Aircraft observations and high resolution NWP simulations of Northern Hemisphere cold-air outbreaks (ppt)

1645 to 1700: Tom Lachlan-Cope, Antarctic cloud measurements (ppt)

1700 to 1715: Simon Alexander, The Antarctic Cloud Radiation Experiment (ACRE) (ppt)

1715 to 1730: Scott Collis, Observing precipitating cloud systems at centimeter wavelengths: What we can do and lessons for Southern Hemisphere studies (ppt)

1730 to 1745: Jeff Stith, NCAR tools for airborne cloud physics and some recent examples from Southern Ocean flights (ppt)

1745-1800: Gijs de Boer, Small UAS for SOCRATES: Potential platforms and scientific applications (ppt)

Session 4: Aerosols and their interaction with clouds,
Chairs Greg McFarquhar/Rob Wood/ Chris Bretherton (ppt)

1330 to 1345: Theodore Wilson, Ice nuclei in the sea surface microlayer

1345 to 1400: Susannah Burrows, The potential influence of marine biological activity on ice nuclei concentrations over the Southern Ocean (ppt)

1400 to 1415: Cassandra Gaston, Single-particle insights into the influence of biological activity on sea spray aerosol mixing-state (ppt)

1415 to 1430 Lynne Russell, Particle sources and growth

1430 to 1445: Yan Feng, Characterization of deposition and mineralogy of dust export to the Southern Ocean

1445 to 1500: Tony Clarke, Aerosol properties, processes and fields over the Southern Oceans

1515 to 1530: Greg Roberts, Aerosol and CCN observations at Palmer Station

1530 to 1545: Barry Huebert (presented by Tim Bates), How could one test the hypothesis, primary marine aerosols dominate CCN, with in situ observations?

1545 to 1600: Jorgen Jensen, Sea spray and warm rain in cold clouds over the windiest ocean

1600 to 1615: Harvey Mike, SOLAS (Surface Ocean Aerosol Production) SOAP experiment and biogenic aerosols

1615 to 1630: Jim Hudson, Detailed CCN spectral measurements

1630 to 1645: Rob Wood, The seasonal cycle of warm cloud microphysics and aerosols over the Southern Ocean

1645 to 1700: Richard Moore, Model and satellite-based sensitivity of cloud properties to aerosol changes in the Southern Ocean

1700 to 1715: Chris Bretherton, LES of boundary-layer cloud-aerosol interaction under Southern Ocean-like conditions

1715 to 1730 Yongxiang Hu, CALIPSO Phytoplankton Particulate Backscatter Coefficient Measurements of the Southern Oceans

1730 to 1745: Xiaohong Liu (given by Steve Ghan), Effect of aerosols on the phase partitioning of mixed-phase clouds through comparison of Community Atmospheric Model (CAM5) and CALIPSO observations: implication for cloud radiative forcing in the Southern Ocean in CAM5

1745 to 1800: Chris Hostetler, The NAAMES ship-aircraft mission concept and ocean profiling and aerosol/cloud lidar

Wednesday March 19, 2014:

Session 5: Plenary [HUB Lyceum]

0800 to 0830: Review of Session 3 (ppt)

0830 to 0900: Review of Session 4

0900 to 0920: Sarah Gille, Oceanographic issues in the Southern Oceans

0920 to 0935: Chris Fairall, Cloud, aerosol and surface-flux observations from ships (ppt)

0935 to 1000: Break

Attendees will divide into two or three breakout discussion groups. Exact themes for the breakout groups are yet to be determined. Each group will address the topics listed below before rejoining for plenary discussions.

1000 to 1230: Breakout Session 1 [HUB Lyceum, Room 250, Room 332]

Formulate key questions on role of aerosols/clouds/air-sea interactions in Southern Oceans

1230 to 1330: Lunch [HUB Lyceum, Box Lunch Provided]

1330 to 1415: Summary of Breakout Session 1 [HUB Lyceum]

15 minute summary talks from each of the groups, 15 minutes general discussion

Clouds and Meterology   Aerosols and Clouds   Science Questions

1415 to 1615: Group Discussion [HUB Lyceum]

What are needed measurements/retrievals/simulations needed to address hypotheses?

1615 to 1630: Break [HUB Lyceum]

1630 to 1700: Summary discussion, science questions and wrap-up

March 20: Steering Committee Meeting

800 to 1100: Meeting of Steering Committee