

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

Summary of a workshop held 18-19 March 2014, University of Washington, Seattle

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Purpose of this Document

A workshop sponsored by the Department of Energy was convened at the University of Washington to discuss the state of knowledge of clouds, aerosols and air-sea interaction over the Southern Ocean and to identify strategies for reducing uncertainties in their representation in global and regional models. The Southern Ocean plays a critical role in the global climate system and is a unique pristine environment, yet other than from satellite, there have been sparse observations of clouds, aerosols, radiation and the air-sea interface in this region. Consequently, much is unknown about atmospheric and oceanographic processes and their linkage in this region.

Here, we summarize meeting discussions about challenges, specific scientific questions related to these challenges, and considerations for organized programs.

The intent of this document is to capture the range of ideas presented. Comments recorded here do not necessarily represent a consensus view. The workshop Scientific Steering Committee is currently drafting a white paper on Southern Ocean scientific issues, and this document will make recommendations that reflect a consensus among the committee members. We expect the white paper will be released in late summer or early fall of 2014.

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Organization of the Meeting and Presentation Materials

Approximately 60 scientists, including graduate students, postdoctoral fellows and senior researchers working in atmospheric and oceanic sciences at U.S. and foreign universities and government laboratories, attended the Southern Ocean Workshop. It began with a day of scientific talks, partly in plenary and partly in two parallel sessions, discussing the current state of the science for clouds, aerosols and air-sea interaction in the Southern Ocean. After the talks, attendees broke into two working groups; one focused on clouds and meteorology, and one focused on aerosols and their interactions with clouds. This was followed by more plenary discussion to synthesize the two working group discussions and to consider possible plans for organized activities to study clouds, aerosols and the air-sea interface in the Southern Ocean.

The agenda and talk slides, including short summaries of the highlights of the parallel session talks developed by the session chairs, are available at <http://www.atmos.washington.edu/socrates/presentations/SouthernOceanPresentations/>.

Challenges

Prior to the meeting, the Scientific Steering Committee developed an initial list of Southern Ocean scientific issues or challenges. Plenary speakers were identified to address each of these challenges, and these challenges were also used as a starting point for later discussions. The list of challenges presented here includes this initial list, as well as additional challenges raised during the presentations and discussions. The order does not represent a prioritization of the issues.

1. **GCM Southern Ocean biases:** Large and systematic shortwave radiation and SST biases are found in climate models over the Southern Ocean, particularly in Austral summer. These biases are predominantly due to errors in the representation of clouds in the models. Models simulate too little low-lying cloud in the cold sector of cyclones (perhaps due to inadequate representation of the microphysics of supercooled and mixed-phase cloud and/or aerosol/cloud interaction) and also appear to underestimate the optical thickness of mid-top clouds (Bodas-Salcedo et al. 2013). Zonal-mean radiation biases interact with the location of the Southern Hemisphere jet in climate models (Ceppi et al. 2012), potentially influence the tropical circulation (Hwang and Frierson, 2013) and correlate with climate sensitivity (models with the largest biases have smaller climate sensitivity, Trenberth and Fasullo 2010).
2. **Controls on CCN and IN in a region isolated from continental and anthropogenic aerosol sources:** Uncertainties in pre-industrial 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 the Earth's climate sensitivity (Kiehl 2007) or to test climate model simulations of anthropogenic aerosol impacts on climate change. However, processes that determine cloud-forming aerosol properties in pristine environments such as the Southern Ocean are poorly understood. Modeling studies and limited observations from ACE-1 suggest that the majority of CCN in this region are nucleated in the free troposphere from DMS and continental sulfate sources, and then are entrained into the boundary layer (Korhonen et al. 2008, Clarke et al. 1998).

However, the relative importance of local sources vs long-range free-tropospheric aerosol transport (e.g. from continental regions) is uncertain and some modeling studies (Pierce and Adams, 2006; Merikanto et al., 2009) attribute most of the Southern Ocean CCN to sea salt.

3. **Role of ocean biogenic processes in CCN concentrations:** Large seasonal cycles in the concentration of cloud condensation nuclei (Ayers and Gras 1992), aerosol composition (Sciare et al. 2009), and cloud droplet concentration (Boers et al. 1998) are observed in liquid clouds over the Southern Ocean, with peak values occurring during summer. Many climate models fail to reproduce this observed annual cycle of droplet concentration over the Southern Ocean. It is hypothesized to be due to biological emission of dimethyl sulfide (DMS) and other aerosol precursors from the ocean during warmer months. However, we currently have only a rudimentary understanding of the upper ocean microbiological processes driving this seasonality.
4. **Role of ocean biogenic processes in IN concentrations:** Due to the scarcity of land, ocean-produced aerosols dominate over the Southern Ocean. 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 (Burrows et al., 2013). Some recent work suggests that ocean-produced biological aerosol particles may serve as ice nuclei (Knopf et al., 2011; Prather et al., 2013), but little has been done to systematically characterize ocean-derived particles for their ice-forming ability. Published measurements of ice nuclei concentrations over the Southern Ocean are limited to a single set of observations from the years 1969-1972 (Bigg, 1973), and new in situ measurements with modern instruments are needed to validate the historical measurements and accurately determine the concentration and composition of ice-nucleating particles in this region.
5. **Supercooled liquid clouds:** The frequency of occurrence of supercooled liquid water clouds is very high over the Southern Ocean, and higher than at comparable latitudes in the Northern Hemisphere (Hu et al. 2010). This may be due to the scarcity of efficient ice nuclei such as dust particles. Limited in-situ observations (e.g., Chubb et al. 2013, Grosvenor et al. 2012) record extensive cloud layers composed of supercooled liquid water with cloud-top temperatures down to -22°C , especially at higher latitudes. This has large implications for cloud/radiation interactions, precipitation, and satellite retrievals for cloud properties.
6. **The role of the synoptic setting for cloud-aerosol processes:** The ACE-1 study documented multilayer thermodynamic and aerosol structure in the lower troposphere with boundary layer clouds overlaid by a surface-modified layer (Russell et al. 1998), perhaps produced by deeper-penetrating clouds elsewhere. Aerosol concentrations and processes in the two layers were clearly different. Satellite imagery shows strong modulation of cloud and boundary-layer properties by the changing synoptic setting as midlatitude cyclones sweep across the Southern Ocean; how this affects aerosol transports, sources and processing is not well understood.
7. **Uncertainty and Variability in Air-Sea fluxes:** Air-Sea fluxes are important to processes in the ocean, cryosphere, and atmosphere. At present, the magnitude and variability of

surface fluxes at high southern latitudes are poorly known with significant implications for climate and numerical weather prediction modeling (Bourassa et al. 2013). In particular, the high wind speeds, the presence of sea ice, the small size of ocean eddies and the strong thermal and salinity gradients across the polar oceanic front all present significant challenges to the modeling of air-sea fluxes at high southern latitudes.

8. **Accuracy of satellite observations:** Satellite observations are the primary source of cloud, aerosol, precipitation and meteorological observations over the Southern Ocean. Active and passive remote sensing from space (CloudSat cloud radar, CALIPSO lidar, GPM dual-frequency precipitation radar, and the suite of microwave, visible and IR polar-orbiting passive sensors) provide observations used in the retrieval (or estimation) of many geophysical properties of clouds, aerosols, radiation, surface fluxes and precipitation over the Southern Ocean, as well as variability in these properties. However, there are significant concerns on the accuracy of many satellite datasets over the Southern Oceans (e.g., Mace 2010). These concerns are due in part to the fact there has been little ground-based or in situ validation of satellite datasets over the Southern Oceans, coupled with the fact that both satellite and other datasets show that cloud properties in this region frequently differ from those in other regions, including over the Northern Hemisphere extratropical oceans. In particular, the Southern Ocean appears to have a higher surface wind speeds, greater occurrence of multi-layer clouds (Heidinger and Pavolonis 2005, Marchand et al. 2010) and mixed-phase clouds with supercooled liquid water (Hu et al. 2010, Morrison et al. 2010, Chubb et al. 2013). Satellite cloud and precipitation property retrievals, as well as estimates of radiative fluxes, for multi-layer and mixed-phased cloud-types are prone to large errors because of the difficulty in robustly identifying when these conditions occur, as well as, the additional degrees of freedom (unknowns) that must be determine or specified as part of the retrieval.

Science questions

The working groups were tasked with identifying specific scientific questions. These questions do not represent consensus hypotheses but questions posed by individual attendees. The order of the questions does not represent a prioritization of the issues.

Question 1: What factors (sources, cloud processing, precipitation, transport, and dynamics) control the aerosol, CCN, and IN over the Southern Ocean?

To what extent is the Southern Ocean aerosol-cloud system a good proxy for the preindustrial environment?

What controls the seasonal cycle, variability and evolution of aerosol, CCN and IN?

To what extent do wind, sea state and precipitation in Southern Hemisphere affect the CCN and IN?

How does the surface ocean biology and carbon pool affect the CCN and IN composition?

How important are local sources of aerosols compared with long-range transport in the free-troposphere?

How important are secondary aerosol formation processes compared with primary emissions from sea-spray in determining the concentration of CCN and cloud droplets?

What are the concentrations of aerosol precursor gases in the marine boundary layer (e.g., DMS, NMHCs)? What is their lifetime? Does the contribution of new particle formation in the MBL play a significant role in determining CCN concentrations?

Are the aerosol, CCN and IN characteristics different between the MBL and the overlying atmosphere?

What are the key sinks of cloud-forming aerosols in the MBL over the Southern Ocean?

Question 2: What controls the prevalence of supercooled water in the Southern Ocean clouds?

What are the relative roles of warm, cold and mixed-phase cloud processes in the formation, amount and distribution of precipitation?

Are biogenic particles dominant in the production of ice over the Southern Oceans? At what temperatures?

Are the controls of the amounts of supercooled water in Northern and Southern Hemisphere different?

What are roles of primary and secondary ice production processes in Southern Oceans?

What is the relative importance of different mechanisms (liquid nucleation and riming, primary ice nucleation, secondary ice nucleation) for producing ice in the Southern Ocean?

How frequently are large supercooled drops found in the clouds over the Southern Ocean? What are the size distributions of the supercooled drops in these clouds?

What are the meteorological conditions supporting the existence of supercooled water clouds?

Question 3: What are the differences in aerosol-cloud interactions between the Northern Hemisphere and the more pristine Southern Hemisphere?

What is the origin of the detectable difference in cloud droplet number concentrations in the storm tracks between the Northern and Southern Hemispheres? What is the role of aerosol sources, meteorological influences, oceanic conditions, and SST gradient?

What is the role of the warm rain process in the production of precipitation in the supercooled clouds over the Southern Ocean? Is precipitation susceptibility of warm clouds different over the Southern Ocean?

What is the relative importance of different mechanisms (liquid nucleation and riming, primary ice nucleation, secondary ice nucleation) for producing ice in the Southern Ocean clouds, and how does this compare to their relative importance of these effects over the Northern Ocean?

Questions 4: How do synoptic, boundary layer and surface processes affect Southern Ocean aerosol and clouds?

What are the prevalent boundary layer structures over the Southern Ocean? How well are they represented in NWP analyses and re-analyses?

There is a wide spread in current estimates for the magnitude of air-sea fluxes over the Southern Oceans, which reflects both uncertainties in inputs (e.g. wind speeds) and parameterizations. What is the magnitude of air-sea fluxes over the Southern Oceans? How do air-sea fluxes vary on diurnal, seasonal, and longer time scales? Can better parameterizations be developed for this region?

How are the different Southern Ocean cloud types associated with synoptic and boundary layer conditions?

What is the vertical structure of aerosols during the passage of synoptic systems and do models represent it well?

What is role of deeper frontal cloud and circulation systems and associated precipitation on the Southern Ocean aerosol budget?

How frequently does the buffer layer form (Russell et al. 1998), and what controls its coupling with other layers? How does the presence of a buffer layer affect aerosol fluxes to/from the free troposphere?

How often are surface aerosols reflective of in-cloud conditions due to a well-mixed boundary layer? How often are they defined by sea spray?

How does the sea state influence the characteristics of the boundary layer? Do high concentrations of sea spray exist?

Does strong vertical shear have important consequences for Southern Ocean clouds and aerosols, e. g., by organizing cloud circulations, or differential advection of aerosol layers, or turbulent mixing?

How do SST fronts, warm core eddies or cold core eddies influence the atmospheric boundary layer?

The Southern Ocean can have very deep (e.g. 600 m) mixed layers, which one might speculate can be gateways for transferring heat or CO₂ from the atmosphere to the ocean. How does the upper ocean heat content or ocean mixed-layer depth influence the atmospheric boundary layer over the Southern Oceans?

Question 5: How well do satellite retrievals describe the Southern Ocean clouds, aerosols and meteorology, and to what extent can they be improved?

How can we determine the vertical profile of phase and cloud properties in clouds with supercooled water at the top or in multi-layer clouds?

How does synoptic regime (e.g., cold vs. warm frontal regions) affect air mass and cloud properties and precipitation development, and subsequently retrieval algorithms?

Can we characterize and reduce uncertainties in the retrieval of cloud and precipitation microphysics (effective radius, number concentration, water content, light precipitation rainfall rates, precipitation susceptibility) in large zenith angles over Southern Oceans?

How well do we need to be able to detect aerosols to provide useful information about CCN in a pristine environment? How can we improve upon the detection limit of aerosols?

Are statistical distributions of the frequency of occurrence of supercooled water measured in-situ consistent with those estimated from satellite remote sensing?

How good are satellite-derived surface winds, and air-sea fluxes from reanalyses?

How well can we detect sea spray and quantify upper-ocean properties using satellite observations?

Question 6: What are the causes of GCM biases in cloud, aerosol, precipitation, and radiative properties over the Southern Ocean?

How can the representation of different processes (boundary layer structure, shallow convection, thermodynamic phase and precipitation processes, aerosols sources/sinks) be improved to reduce these biases?

What are the climatic implications of these biases?

What cloud types are most responsible for GCM cloud biases?

To what extent is albedo underestimation in climate models related to errors in cloud cover, condensate and phase, cloud overlap assumptions, and cloud microphysical properties?

How important are mixed-phase vs liquid vs ice cloud processes in determining the radiative properties of Southern Ocean clouds and do GCMs capture the balance of processes? How important are they in precipitation processes?

What is the radiative impact of the supercooled water over the Southern Ocean?

How well do models represent the vertical profiles of aerosols during the passage of synoptic systems?

What is the turbulent structure of clouds in cloud-air outbreaks in the Southern Ocean? Is this structure different than that in the Northern Hemisphere?

Observational Strategy

Addressing the scientific issues and questions raised in the previous section demands an increase in observations in the Southern Oceans. Some of these scientific questions will require careful observations from airborne platforms (for example, measurements of ice nuclei concentrations and aerosol physical characteristics) and some questions require observations that will capture variations of the seasonal cycle, in order to elucidate processes differences that generate these variations. No single measurement campaign or program is likely to cover this breadth of activity.

Meeting attendees discussed a variety of measurement strategies composed of a combination of

- 1) Intensive but short duration airborne observations
- 2) Periodic observations from ships
- 3) Continuous ground-based observations from island sites or moorings
- 4) Satellite monitoring

We discuss the objectives and possible opportunities for each of these components in this section. Given the remote nature of Southern Oceans, observational programs will be expensive and likely require multi-agency and multi-national cooperation.

Key targets for observational study

From discussions at the workshop, we can group the areas needing improved observations into the following four general objectives:

- (i) To characterize the physical properties of lower-tropospheric cloud systems around midlatitude cyclones over the Southern Ocean.
- (ii) To characterise microphysical and chemical properties of aerosols and aerosol precursor compounds, including DMS, that may play a role in regulating CCN and IN over the Southern Ocean and to investigate their relative significance for cloud formation, maintenance and radiative properties.
- (iii) To assess the quality of satellite cloud, aerosol, precipitation, and upper ocean products, and to develop new ones.
- (iv) To evaluate and improve the skill of models at different scales to reproduce the observed properties of the Southern Ocean cloud systems, aerosol physicochemical properties, and aerosol-cloud-precipitation interactions.

Possible observational components:

The challenges discussed above indicate a need for improved measurements to (a) improve our understanding of the physical and chemical processes occurring over the Southern Ocean; (b) provide observational datasets suitable for evaluating and improving large-scale models and satellites retrievals.

A Southern Ocean measurement program is needed to address the challenges in understanding the sources and sinks of aerosol particles that affect clouds. This requires an improved quantification of 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 boundary layer context for these processes. There are strong gradients in aerosol and cloud properties (and in model biases) between 45°S and Antarctica (60-70°S); ideally this entire gradient should be sampled.

The cloud processes and aerosol vertical profiling require airborne observations. To span the range from 45-65°S, at least one long range aircraft is needed. Understanding surface-derived aerosols is best addressed using sampling of the air-sea interface by ships, while documenting the seasonal

cycle requires extended measurements either on an island or a ship, supplemented by fixed buoy observations that can span multiple years.

Existing or currently planned observational components

A limited set of extended in-situ observations are already being made or planned. Australia operates a research station at Macquarie Island (54°S, 159°E) that takes meteorological measurements and daily balloon soundings, and also operates three Antarctic stations. Cloud radar and lidar observations are planned at Macquarie Island (2016) and Davis (2019) as part of the Australian Antarctic Division's proposed Antarctic Clouds and Radiation Experiment (ACRE). Another Australian project, CAPRICORN, running from 2015-2018, involves one-month cruises into the Southern Ocean with a new research vessel, the Australian R/V Investigator, equipped with extensive atmospheric measurement and remote sensing instrumentation, including a cloud radar, lidar, microwave radiometer, soundings, and aerosol measurement capabilities, as well as the possibility of hosting other instruments. A long-term NSF Ocean Observatories Initiative 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 (Argentina). 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 Institution of Oceanography.

Possible future observational components

There were extensive discussions at the workshop about possible new platforms for Southern Ocean observations. To document the seasonal range of aerosols, the installation of the DOE ARM Mobile Facility (AMF) on a ship or icebreaker supplying stations in the Antarctic was suggested. Although observations would not be possible in the wintertime, such a strategy could provide multiple cruises, including measurements of aerosol, chemistry and biogeochemistry over much of the seasonal cycle. Candidates for the shipboard platform 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 that transit between Argentina and US bases in Antarctic. Careful attention will need to be paid to choose the best platform by examining available space on the different platforms as well as flow distortion issues.

For aircraft observations, a number of scenarios were discussed. The biggest difficulty will be getting observations as far south as possible, a problem exacerbated by the general unavailability of suitable airfields over the Southern Oceans. Candidate platforms such as the NSF/NCAR C-130 and G-V aircraft were identified, with simultaneous involvement of both as optimal. The C-130 or suitable alternative would be best suited for sampling clouds and aerosols in the marine boundary layer and lower free troposphere. The G-V or other suitable long-range platform would be best suited for collecting cloud and remote sensing observations, making a combination of constant altitude legs and deep saw tooth patterns that would also allow for sampling of mid-level clouds. The synergy between the two would permit simultaneous acquisition of both in-situ and remotely sensed data on cloud and aerosol properties that would improve process level understanding and allow us to better understand remote sensing data. The possibility of using the NASA ER-2 as a high altitude aircraft, collecting data that would be suitable for satellite evaluation studies and data of relevance to GPM validation issues should also be considered. There was general agreement that aircraft

intensive observational periods should occur at the same time as the Australian R/V Investigator and/or another research vessel provides surface-based observations of aerosols, oceanographic properties, surface fluxes, and ground-based remote sensing.

Unmanned Aircraft Systems (UASs) could also make significant contributions to the project goals. In particular, the use of UAS at Macquarie Island should be explored so that sampling of aerosol vertical profiles in the boundary layer could be executed. It would also be useful to supplement the 2016-2017 ACRE Macquarie instrumentation with a variety of surface radiometers available from ARM, including microwave radiometers, surface broadband radiometers and either a sun photometer or a Multifilter Rotating Shadowband Radiometers. The use of UAS from either the R/V Investigator or ships executing supply missions to the Antarctic should be further explored.

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