Community Review of Southern Ocean Satellite Data Needs

Running header: Southern Ocean Satellite Data Needs

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Abstract (<200 words)

Through widespread engagement, this review represents the Southern Ocean community’s satellite data needs for the coming decade. Including perspectives from a range of stakeholders (both research and operational), it is designed as an important strategy paper that provides the rationale and information required for future planning and investment. The Southern Ocean is vast but globally connected, and the communities that require satellite-derived data in the region are diverse. This review includes many observable variables, including sea ice properties, sea surface temperature, sea surface height, atmospheric parameters, marine microbe observations, marine biology and related activities, terrestrial cryospheric connections, sea surface salinity, and a discussion of coincident and in situ data collection. Recommendations include commitment to data continuity, increase in particular capabilities (sensor types, spatial, temporal), improvements in dissemination of data/products/uncertainties, and innovation in calibration/validation capabilities. Full recommendations are detailed by variable as well as summarized. We provide a starting point for scientists to understand more about Southern Ocean processes and their global roles, for funders to understand the desires of the community, for commercial operators to safely conduct their activities in the Southern Ocean, and for space agencies to gain insight into planning Southern Ocean-related acquisitions and mission.
Note: Currently aiming for review article in Antarctic Science (20 journal pages ~= 30 Google Doc Pages).
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1 Introduction and Motivation

This review represents the Southern Ocean community’s satellite data needs for the coming decade. It is designed to stand as an important strategy paper that provides the rationale and information required for future strategic planning and investment.

The Southern Ocean (defined herein as south of 30°S) has a profound influence on the global ocean circulation and the Earth’s climate. It uniquely connects the Earth’s ocean basins and plays a key role in global overturning circulation, thereby regulating the capacity of the ocean to store and transport heat, carbon, and other properties that influence climate and global biogeochemical cycles. Global climate and sea-level are influenced strongly by ocean-cryosphere interactions in the Southern Ocean. Changes in sea-ice extent or volume result in changes in the Earth’s albedo, water mass formation rates, air-sea gas exchange rates, and effects on marine organisms from microbes to whales (for more detailed information on the importance of the Southern Ocean in the global climate and biogeochemical system, see Rintoul et al., 2012).

Given the central role that the Southern Ocean plays in the global climate system any changes in the region will have global consequences. The Southern Ocean Observing System (SOOS) Initial Science and Implementation Strategy (Rintoul et al., 2012) provides an overview of how an effective observing system could be built for the Southern Ocean and highlights the importance of remote sensing in providing fundamental observational data in this remote region, where in situ observations will likely always be sparse and hard to obtain. Nevertheless, remote sensing of the Southern Ocean is not without significant challenges and much work is needed to enhance cross-calibration and independent validation with in situ data, improve algorithms and geophysical corrections, ensure continuity of time series, and drive development of better sensor technology and global climate prediction models.

There are many similarities between Arctic and Antarctic/Southern Ocean remote sensing, but different geographical settings do introduce unique challenges to each. Although differences exist in the validity and accuracy of specific algorithms and corrections between the northern and southern hemisphere polar oceans, data requirements are largely the same. Yet, many missions focus predominantly on Arctic objectives, owing to the strong commercial and operational rationale, as well as the national priorities of the key data providers. In general, data acquisition for operational services generally take priority over research needs. Additionally, while for example the numerical weather prediction (NWP) network is well-served and implemented globally, the global operation of oceanic and cryospheric sensors is not always warranted. Copernicus observation requirements, for example, are currently only justified by services relevant to EU users in specific geographic zones. Whilst for instance, the satellites are cited as providing routine global coverage, the data acquisition strategies and resulting datasets are not characterized by “all the time, everywhere.” A clear example of this is that Sentinel-2 will be switched off everywhere south of the southern tip of Chile, raising the question about the means to obtain optical coverage of the Southern Ocean, or Antarctic ice-shelves? Today there are no operational high priority Copernicus user service requirements to drive these data acquisitions. Addressing this oversight is crucial to ensure a well-balanced bipolar science data collection strategy from the Copernicus Sentinels. Similarly, RADARSAT-2 (commercial) and RADARSAT Constellation mission are equally focused on the Arctic, owing predominantly to the commercial customer base.
In order to address these and other disparities in Polar remote sensing, and to articulate the satellite needs specific to the Southern Ocean, SOOS (an initiative of the Scientific Committee on Oceanic Research (SCOR), the Scientific Committee on Antarctic Research (SCAR)), and the World Climate Research Programme’s Climate and Cryosphere (WCRP, CliC) projects, sanctioned this community review in order to provide a consolidated user voice. It articulates a comprehensive overview of satellite data requirements for the Southern Ocean (including scientific, commercial, and operational rationales) towards achieving the objective of ensuring continuation and enhancement of Southern Ocean satellite data. The content of this review has several key sources, including a survey tailored specifically to ensure community input (see Sect. 2). This review covers satellite data requirements for the open and sea-ice covered portions of the Southern Ocean, including the coastal and fast-ice zones, and oceanic connections to the continent through ice shelves. Terrestrial data requirements are largely outside the scope of this report.

Importantly, this review also links the observational priorities defined herein, to the global effort to identify essential variables for climate and ocean - specifically Essential Climate Variables (ECVs) and Essential Ocean Variables (EOVs). In particular, this review highlights connections with ECVs and EOVs of the Ocean Observations Panel for Climate (OOPC), the ECVs defined by the ESA CCI, and SOOS EOVs. It should be noted that there is currently no consistency in the definition of an ECV or EOV between communities. This report follows the SOOS definition whereby an EOV has a unit of measurement. Regardless of this difference in definition, the recognition of these variables as “essential” indicates global agreement in the priority for their inclusion in observing systems.

2 Community Consultation

Between 12 March and 26 June 2014, the survey introduced above was open to input from the entire Southern Ocean community, spanning a wide range of research and operational disciplines and goals. The survey received 59 unique responses from 19 countries worldwide. Full survey responses (except personal information) are available as a separate supplement (Pope et al., 2015); survey questions are the first line of the spreadsheet.

![Figure 1: Nationalities of survey respondents.](image)
Most survey respondents were researchers, while only two identified primarily as operational remote sensing users (“Icebreaker Science Liaison” and “National Antarctic program operations involving ships, aircraft and ground activity”). Expertise of respondents came from communities such as sea-ice research (13), oceanography (11), marine biology and ecology (8), glaciology / permafrost / snow science (6), sea-level change (5), ocean color remote sensing (5), climate science (5), ocean winds (2), data collection and management (2), numerical weather prediction (1), atmospheric chemistry (1), and geomagnetism (1); note, there is some overlap in areas of expertise.

To ensure that we accurately captured the Southern Ocean community response and to broaden feedback in key disciplines and user groups, we specifically contacted members of the community and solicited their opinions. There were no survey respondents who provided feedback on sea surface salinity, surface winds, or atmospheric parameters, and so 8 experts in these specialties were consulted to supplement a literature in this regard. In addition, a draft version of the review was made available for public consultation via major community listservs; [number] respondents in [all specialties commented in that final stage of review development. See Acknowledgements for all contributors.

3 Sea Ice

3.1 Importance of Sea-Ice Observations

One of the largest components of the cryosphere, sea-ice changes significantly on seasonal and annual timescales. Sea ice is a considerable reflector of incoming solar radiation, which regulates local and global energy balances. Sea ice growth and formation plays a role in air-ice-ocean heat fluxes and freshwater fluxes on seasonal timescales. Most importantly, approximately 7% of the Earth's surface or 10% of the Ocean surface is covered by sea-ice at some point within the year. As global temperatures are increasing at rapid rates, sea-ice response may also be an indicator of changing climate (IGOS, 2007).

Sea-ice cover around the Antarctic varies very strongly seasonally due to its dynamic growth and retreat throughout the year, especially in the Ross, Bellingshausen-Amundsen, and Weddell Seas. It is highly responsive to winds and atmospheric variability, and potentially highly influenced by large-scale climate variability patterns such as the El Niño-Southern Oscillation and Southern Annular Mode (SAM) (Maksym et al., 2012; Marshall, 2003). Due to the high level of turbulence in the Southern Ocean, Antarctic sea-ice contains more Frazil and First Year ice types (Massom, 2009). Individual sea-ice parameters (thickness, concentration, area, extent, ice edge, ice drift, and snow cover on sea ice) play a key role in our capability to accurately monitor sea ice behavior because they affect how well the sensors can accurately detect true conditions.

Operational monitoring includes providing support to fishing vessels, icebreakers, other cargo ships transporting supplies to scientific bases on the Antarctic continent, tourism ships, and military transits. As operations, industry, and tourist vessels continue to traverse through sea ice laden areas, it is important to have a clear knowledge of sea ice conditions so that non-ice strengthened ships have ample time to avoid these areas. The 2013-2014 seasonal statistics from the International Association of Antarctic Tour Operators (IAATO) estimated that there were approximately 37,000 seaborne clients traveling throughout different regions in Antarctica varying between operational, cruise, private, and expedition vessels (presented at the XV International Ice Charting Working Group meeting [https://nsidc.org/noaa/iicwg/presentations/IICWG-2014/]). Because Antarctic sea ice is not as observable year-round on visible and multispectral imagery due to seasonal restrictions, it is
normally monitored with the use of passive microwave data and sea-ice charts that use multiple data sources due to their ability to provide large-scale and global coverage year round.

The following sea-ice parameters described in this review are critical to the OOPC ECVs and the SOOS EOVs, as described in the SOOS Science Theme 5: *The future of Antarctic Sea Ice*. Sea-ice volume (including ice thickness and concentration) and snow cover are two of the main climate applications that need to be evaluated through the OOPC ECVs. Additionally, monitoring changes in sea-ice extent and volume are particularly important to the SOOS EOV due to the multi-faceted relationship of sea ice and the freshwater balance, albedo, oceanic CO$_2$ flux, and biological activity in the Southern Ocean.

### 3.2 Current Status of Sea-Ice Observations

Monitoring sea ice in the Southern Ocean includes data from low spatial resolution (high temporal resolution) passive microwave sensors and high spatial resolution (low temporal resolution) active radar satellites; as importantly, they are sensors that can collect both types of data even through cloud cover and during the polar night (Lubin and Massom, 2006). Types of radar satellite-derived data include: SAR (synthetic aperture radar), scatterometry, and radar altimetry. Passive microwave has been the main source providing a comprehensive climate record because of its high temporal resolution. Passive microwave for sea-ice concentration, especially near-90 GHz for higher resolution (~5 km), is preferred because it can provide better operational information on thickness (for thin ice types); however it is sensitive to the density and grain size of the snow on top of the sea ice (Spreen et al., 2008). SAR is the preferred data source for sea-ice monitoring, because it has a higher spatial resolution and allows users to infer sea-ice types, characteristics, and smaller features not detected with passive microwave (Massom, 2009 and IGOS, 2007). Optical (visible) satellites (e.g., Moderate Resolution Imaging Spectroradiometer, MODIS) can be used but are unreliable due to the interference caused by frequent cloud cover and the prolonged darkness during the winter.

Since the 1970’s, passive microwave imagers have provided continuous sea-ice records which have allowed consistent records of derived sea ice concentration to be calculated for time series analysis (Parkinson and Cavalieri, 2012, Comiso and Nishio, 2008, and Comiso et al., 1999). More information can be found at Lubin and Massom (2006), Massom (2009), and Tedesco (2015) which provided comprehensive collections of a number of sources used to monitor the previous and current state of sea-ice concentration. Additionally, snow cover on sea ice is an important parameter because it affects how well sea-ice thickness and concentration can be accurately measured. Some current methods used to measure snow depth include LiDAR (Laser, Imaging, Detection And Ranging), active microwave, and passive microwave instruments (Comiso, Cavalieri, and Markus, 2003). Community feedback stated that the current snow depth estimates from microwave radiometry in use are based on a global empirical algorithm by Markus and Cavalieri, 1998, and Frost, et al. 2014.

Most knowledge of sea-ice thickness comes from in situ observations and upward sonar profiling by submarines in the Arctic, but in-situ data coverage for the Antarctic was and is very poor (Giles et al., 2008). Recent methods using spaceborne (i.e. Envisat, Cryosat-2, ICESat, etc) and airborne altimeters (e.g., Operation Icebridge), and autonomous underwater vehicles (AUV) have been shown to be effective (Falkingham, 2014; Williams et al., 2015, Zwally et al., 2008). However, these devices are limited in spatial and temporal coverage, and most uncertainties for converting altimeter data to ice thickness come from freeboard
estimates, snow cover, snow, water and sea-ice density and sea surface height (Kern and Spreen, 2015, Markus et al., 2011, and Kwok and Cunningham, 2008) as well as underlying assumptions, such as the hydrostatic equilibrium assumption. Some respondents use laser altimetry (ICESat) and radar altimetry (i.e. Envisat RA-2 and CryoSat-2) instruments for sea-ice thickness measurements. These sensors have produced good sea-ice thickness estimates compared to in situ measurements such as AUV, ULS, EM-data, airborne altimetry, and other data sources (Price et al., 2015, Kurtz, et al., 2014, Kurtz and Markus, 2012, Markus et al., 2011, and Zwally et al., 2008). For thinner sea ice (<20cm) some respondents rely on thickness estimates from SSMI, SSM/IS, or AMSR-E. They have also expressed that although SMOS (Soil Moisture and Ocean Salinity) data has performed well in the Arctic, it is still being further tested for thin ice capabilities in the Antarctic.

Antarctic sea-ice edge changes have been identified in various case studies (Howell et al., 2010; Remund and Long, 1999; Haarpainter et al., 2004; Worby and Comiso, 2004; Ackley et al., 2003) but the rate of change and specific processes are not fully understood. Active microwave imagery from SAR instruments is preferred, however it has a low temporal resolution and does not provide synoptic coverage. There also tends to be more noise at the edge with active microwaves due to the ocean surface roughness from capillary waves (Sandven et al., 2006). The NASA QuikSCAT scatterometer product was found to perform well for sea-ice edge detection by ice charting services, especially with the use of the Brigham Young University (BYU) Scatterometer Image Reconstruction (SIR) algorithm which increased the spatial resolution, helped to resolve the noise problem at the edge, and provided daily global coverage (Remund and Long, 2014). Scatterometer data have also proven useful in mapping multi-year ice (in the Arctic) (Swan and Long, 2012).

There are nine sea-ice charting services for the Southern Ocean, and they meet or have met informally at the annual International Ice Charting Working Group (IICWG) meeting. These organizations provide sea-ice products based upon their finances and regions of interest. Sea-ice charts can contain either sea-ice concentration, ice types, or both. Some charts also include accompanying information such as areas of the marginal ice zone, sea surface temperature, and icebergs. For areas with shared interests between more than one country, they have adopted efficient methods to share the workload support. Though some sea-ice charting agencies may provide limited support to their vessels, they all provide some type of imagery support. Currently, the National Ice Center (NIC, USA) and Arctic and Antarctic Research Institute (AARI, Russia) are the only institutes that produce comprehensive coverage of the Southern Ocean. They are now working together with the Norwegian Ice Service (NIS, Norway) to produce a collaborative Antarctic sea-ice product. This will allow organizations to share efforts, as well as provide a higher temporal resolution Southern Ocean product. Additional information for this effort can be found in section 3.3 of this paper.

### 3.3 Primary Locations of Data for Sea-Ice Observations

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Provider</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Sea Ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General sea-ice products available from the EU Copernicus Space Program</td>
<td>MyOcean</td>
<td><a href="http://www.myocean.eu">http://www.myocean.eu</a></td>
</tr>
<tr>
<td>ESA Sea Ice CCI-Antarctic</td>
<td>The Sea Ice CCI Project</td>
<td><a href="http://esa-cci.nersc.no/?q=products">http://esa-cci.nersc.no/?q=products</a></td>
</tr>
</tbody>
</table>

### Sea-Ice Thickness
<table>
<thead>
<tr>
<th><strong>Sea-ice freeboard (height of sea ice plus snow layer above sea level) and thickness data derived from ICESat laser altimetry data</strong></th>
<th>NASA Cryosphere Science Research Portal</th>
<th><a href="http://neptune.gsfc.nasa.gov/csb/index.php?section=272">http://neptune.gsfc.nasa.gov/csb/index.php?section=272</a></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antarctic Sea Ice observation data from vessels</strong></td>
<td>Antarctic Sea Ice Processes and Climate (ASPeCt)</td>
<td><a href="http://aspect.antarctica.gov.au/">http://aspect.antarctica.gov.au/</a></td>
</tr>
<tr>
<td><strong>Ice, Cloud, and land Elevation/Geoscience Laser Altimeter System (ICESat/GLAS)</strong></td>
<td>NSIDC</td>
<td><a href="http://nsidc.org/data/icesat/data.html">http://nsidc.org/data/icesat/data.html</a></td>
</tr>
</tbody>
</table>

### Sea-Ice Concentration

| **Sea Ice Passive Microwave Products** | NASA Distributed Active Archive Center (DAAC) at NSIDC | http://nsidc.org/data/seaice/pm.html#pm_seaice_conc |
| **MODIS-derived Sea-Ice Concentration** | National Snow and Ice Data Center (NSIDC) | http://nsidc.org/data/modis/data_summaries/index.html#sea-ice |
| **Daily AMSR-E Sea Ice Maps** | University of Bremen | http://iup.physik.uni-bremen.de:8084/amsr/amsre.html |
| **Sea-Ice Conc for Arctic and Antarctic (ASI-AMSRE)** | Integrated Climate Data Center (ICDC) | http://icdc.zmaw.de/seaiiceconcentration_asi AMSRE.html?&L=1 |
| **Sea-Ice Conc for Arctic and Antarctic (ASI-SSMI)** | Integrated Climate Data Center (ICDC) | http://icdc.zmaw.de/seaiiceconcentration_asi ssmai.html?&L=1 |

#### in situ Sea-Ice Concentration from ship-based observations

| **Sea-ice concentration** | Ocean and Sea Ice SAF High Latitude Processing Centre (OSI SAF) | http://saf.met.no/p/ice/index.html |
| **Sea-Ice extent and concentration** | Sea Ice Index NSIDC | http://nsidc.org/data/seaice_index/ |

### Snow Cover

| **European Space Agency (ESA) global database of snow parameters for climate research purposes** | Finnish Meteorological Institute (FMI) GlobSnow | www.globsnow.info |
| **Snow cover extent** | NOAA Operational Microwave Integrated Retrieval System | http://www.ospo.noaa.gov/Products/atmosphere/mirs/snow.html |

#### in situ Snow Thickness from ground measurements and ship-based observations

| **AMSR-E/Aqua Daily L3 12.5 km Tb, Sea-Ice Conc., & Snow Depth Polar Grids** | NSIDC | http://nsidc.org/data/docs/daac/ae si12_12km_tb_sea_ice_and_snow.gd.html |

### Sea-Ice Edge

| **QuikSCAT Ice Extent Products** | BYU Center for Remote Sensing | http://www.scp.byu.edu/data/Quikscat/Ice/Quikscat_ice.html |
| **Operational Ice Edge** | National Ice Center | http://www.natice.noaa.gov/products/ |

#### in situ Sea-Ice Edge coordinates from ship-based observations

Passive microwave sea-ice edge | Ocean and Sea Ice SAF High Latitude Processing Centre (OSI SAF) | http://saf.met.no/p/ice/index.html
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**Operational**

- Sea ice imagery from active and passive microwave sensors, visible, sea-ice charts, sea-ice edges, and iceberg data. | Polarview | http://www.polarview.aq/antarctic
- Weddell Sea Sea-ice Charts | Norwegian Ice Service (NIS) | http://polarview.met.no/
- Comprehensive Antarctic sea-ice charts | U.S. National Ice Center (NIC) | http://www.natice.noaa.gov/Main_Products.htm
- Collaborative Antarctic Sea-Ice Charts with Russian, United States, and Norway input | Arctic and Antarctic Russian Institute (AARI) | http://ice.aari.aq/antice/
- Portal for operational sea ice information | JCOMM Ice Logistics Portal | http://www.bsis-ice.de/IcePortal/

**Sea Ice Drift**

- Sea-Ice Drift vectors for Arctic and Antarctic | Integrated Climate Data Center (ICDC) | http://icdc.zmaw.de/seaicedrift_satobss_global.html?&L=1

**in situ Sea-Ice Data**


### 3.4 Limitations of Current Sea-Ice Observations

Geophysical caveats limit accurate sea ice detection from satellites. As sea ice becomes thicker, changes in the crystalline structure, brine content, and snow cover affect its ability to be accurately detected from space (Massom, 2009). When environmental effects such as ocean and wind forcings create pressure ridges and rafting features, this further complicates how well we are able to measure the sea-ice thickness and volume. Additionally, though various passive microwave frequencies can detect specific sea-ice signatures, geophysical properties within sea ice, especially sea-ice types in the outer pack ice, cannot currently be resolved with any specific frequency due to the wet surfaces and thin sea-ice types which tend to develop in the marginal ice zones and polynyas (i.e. frazil, shuga, grease, nilas, brash) and occur at sea-ice boundaries (Weeks, 2010). These are explained in further detail by Meier and Markus (2015) and Massom (2009).

There is more ambiguity when identifying sea ice during the melt season (Austral spring) and the summer, as well as sea ice in the marginal ice zone and the ice edge due to an underestimation of sea-ice concentration (Carsey, 1992). Radiometric signatures for areas with thin ice tend to overlap with open water signatures, leading to underestimating actual sea ice concentration. The low resolution of passive microwaves also increases the likelihood of pixel mixing over large areas. Satellite-derived sea-ice concentration for thicker ice types is hindered by the flooding problem between the ice and snow interface caused by heavy snow cover which also causes ambiguity in radiative properties of sea ice when trying to measure sea-ice thickness and concentration (Massom et al., 2001 and Massom, 2009).
In situ measurements for satellite validations are always needed but are especially sparse for sea-ice thickness. Thickness is difficult to parameterize and uncertainties with remotely sensed data exist due to the above mentioned radiometric signal mixing for thin and deformed ice, as well as snow cover. Some of what is required is being collected, but inferences have to be made due to the difference of scales between surface-based measurements and remote sensing resolutions. Sea-ice thickness measurements with laser and radar altimetry for the Antarctic may be possible with accurate knowledge of snow thickness and ice and snow density, however, it is still unclear how to resolve the relationship between sea-ice elevation and thickness (Massom, 2009 and Zwally et al., 2008). Thick snow cover in Antarctic sea ice has been shown to represent a significant issue for the use of radar altimetry techniques to measure thicknesses of thick first year ice and above but may show some potential with new techniques used on the Cryosat 2 radar altimeter (Willatt et al., 2011 and Price et al. 2015). However, a remaining problem is the difficulty to resolve the snow depth and density needed to make sea-ice thickness calculations from satellite-derived freeboard and elevation estimates (Massom, 2009). Leonard and Maksym (2011) suggested that obstacles in measuring snow cover can be due to its variability with the rate of accumulation influenced by the strength of blowing winds and surface and sea-ice roughness. The use of the L-band radiometer (1.4 GHz) for sea ice < 50 cm may be able to be used to derive sea-ice thickness for level ice, specifically during the freeze-up period but needs further validation when applying this model to Antarctic sea ice due to the snow cover (Tian-Kunze et al. 2014).

Respondents also addressed the need for reliable sea-ice motion data. Sea-ice drift is critical to sea-ice formation and deformation because, depending on the level of turbulence, it influences the development of specific ice types (i.e. pancake ice related to turbulent conditions, whereas nilas forms in calm waters), and pressure ridges.

Another impediment is that it has always been difficult to travel to Antarctica to collect systematic large datasets required for scientific purposes. Analysis for Antarctic sea ice and location of the ice edge has not been given the same attention as in the Arctic because there are fewer commercial operations, virtually no inhabitants, and the location is difficult to access (IGOS 2007). Thus, there is an outstanding need from the community to improve our data on the historical and present location of the sea-ice edge, types, and coverage, which will help to further improve current climate models.

One of the main challenges that many of the respondents mentioned are that there are few satellite receiving stations in the Antarctic which makes it difficult to obtain a large amount of useful real-time high resolution data that can be used for science or operational purposes. Additionally, when trying to validate sensors for satellite-derived sea-ice measurements, high-resolution data are preferred but normally have smaller footprints than passive microwave satellite data. This makes it difficult to match the acquisition time and location over a ground sampling site, in order to do a direct comparison because ice is always moving, especially thinner ice types.

Operationally, this lack of high spatial resolution data is problematic, because they are needed to facilitate safe navigation through sea ice. Without high resolution imagery, systematic sea-ice forecasting is difficult. The majority of SAR satellite passes are located in the Weddell Sea, the Bellingshausen Sea, and the Ross Sea. Though the comprehensive monthly coverage of these limited regions may be able to assist with some science efforts, it is not sufficient for these areas, which show the largest changes in Antarctic sea ice, or for operational and navigational purposes. Many recommendations for the development of sea-ice observations were stated in IGOS 2007 and continue to be relevant despite increased field campaigns from
3.5 Recommendations and Additional Requirements for Sea-Ice Observations

The survey respondents stated that, from a scientific perspective, the Amundsen/Bellingshausen Sea and the Ross Sea regions are key regions for sea-ice loss and gain. However, they added that there is also a need to understand what is happening with the ice at all longitudes. As an example, the Ross Sea area has not received satellite coverage that other areas, such as the Antarctic Peninsula or Bellingshausen Sea have received, despite its ecological and logistical importance.

Additionally, seasonal and regional variations of both passive and active microwave signals are dominated by snow processes and atmospheric forcings (Wilmes, 2014). As stated in the limitations, when thick snow cover on sea ice in the Southern Ocean causes flooding in the interface between the sea ice and snow, it tends to introduce more ambiguities when interpreting sea-ice concentration, extent, and thickness from satellite-derived data (Meier and Notz, 2010).

- **Ongoing in situ data collections:** Among the main recommendations for *in situ* data for improved sea-ice products are having access to better knowledge of: 1) Density distribution of snow and ice for conversion of freeboard (from satellite altimetry) into thickness, 2) Accuracy of snow depth, 3) Accuracy and validation of freeboard, and 4) Areas of flooding at the snow-ice interface. Better understanding of snow depth and snow properties is critical for calculating thickness retrieval uncertainties and for improving algorithms. A respondent suggested the development of a Southern Hemisphere Climatology for snow cover, since one does not currently exist.

In order to improve knowledge of sea-ice thickness estimates, suggestions from the community include implementing more sonar data from autonomous underwater vehicles (AUV) (i.e. underwater gliders) and buoys (i.e. Argo floats). In the event that snow cover over sea ice in the Southern Ocean becomes better understood, there will always be a geophysical caveat in the electromagnetic spectrum, which may introduce more errors when deriving sea-ice thicknesses for sea-ice types affected by surface flooding between the sea-ice surface and snow cover.

The ASPeCt sea-ice data archive, established by the Scientific Committee on Antarctic Research (SCAR) in 1997, is a valuable *in situ* dataset for the community (Worby et al., 2008; Worby and Allison, 1999). The ASPeCt archive is a comprehensive data set consisting of sea-ice ship-based observations and profile measurements for all regions around Antarctica. Continued support and the implementation of the ASPeCt protocol on ships and future cruises was highly recommended by the operational and research communities because it provides crucial validation data. Additional systematic data collection devices have been developed that could augment ship-based observations (Weissling et al, 2009).

Another suggestion from a respondent was that increased validation and ground truth data could be collected using autonomous platforms from stations on sea ice for validation (time series) and airborne data to fill the gap of observational scales (between transects and satellites). Improvements to future monitoring programs can be aided if expanded data collections correspond to icebreaker operations in the
Antarctic, typically during the Spring and Summer season between November to February.

Survey respondents noted that the use of in situ measurements could be improved with more ancillary data, products, and documentation, as this information is difficult to find when trying to match in situ observations with coincident satellite data. A need for more data from locations of sea-ice polynyas and leads was expressed as well. The respondents also emphasized that the lack of coordinated acquisitions could be resolved, but we should focus on initiating multiple proposals to be written for the individual sensors. These efforts should also include simultaneous measurements with drifting buoys, which will help validate classification and process studies.

- **Easier Data Access:** Some other problems ensue when observing ice concentration from different satellites because data are dispensed in various levels. For example, in the case of AMSR-E, AMSR, and AMSR-2, data from the Japanese Aerospace Exploration Agency (JAXA) are administered in swath format after the ice concentration algorithms have been applied. The next level of processing is gridded daily averages. Respondents suggested it would be helpful to have an intermediate step between these two levels, where the data are gridded, but have not been averaged in time, keeping original time stamps. Another suggestion is that researchers would like sea-ice data to be provided along with error estimates and adequate documentation so they can be used appropriately.

- **Better dissemination of sea-ice products and information for operations:** Recommendations from the operational community are to establish a better system or data tools for products to be delivered to vessels to aid in navigation for ship and yacht operators, who require real time information. Current global coverage with daily products are available for passive microwave data and ice charts (longer intervals) which can be helpful for planning, but the spatial resolution (in kilometers), time lag and data transfer make them less useful for navigation. Due to the number of ship operators in a specific area at one time, a stronger preference towards real-time data and tools for image annotation would be ideal. Although SAR is preferred, it is either only acquired or accessible upon request. This makes it difficult to quickly retrieve images in real time. The availability of optical data is convenient and survey respondents suggested that optical data could be used as a good model for SAR retrieval. Ideally, high resolution data, especially those that show leads and pressure ridges, should be obtainable as often as possible, but it is more critical to have them available during December-May when there is more ship traffic.

Overlapping needs for dissemination of sea-ice information apply to both research and operational communities. Sea-ice charts can be useful to the science community because they provide a consistent archive of sea-ice concentration and extent. However, information on how to use ice charts is not easily accessible, and a plain language guide for non-operational users is not available at present. The Environment Canada’s Manual of Ice (MANICE, [https://ec.gc.ca/glaces-ice/default.asp?lang=En&n=4FF82CBD-1](https://ec.gc.ca/glaces-ice/default.asp?lang=En&n=4FF82CBD-1)) would be an excellent model to use to develop a similar document for sea ice in the Southern Ocean. Additionally, respondents requested that operational people should be involved in validation work, because they have a great stake in accurate observations, and researchers and others will better appreciate products that can facilitate their workload if they trust those products.
• **Continuity of current sensors and restoring previous sensors:** Due to the importance of passive microwave data for sea-ice monitoring, continuity of these sensors is necessary, either from AMSR 2 or DMSP (the SSMIS series). The DMSP F20 is the last SMMIS due to launch, but by 2020 there is an increasing risk of having a gap in passive microwave observations.

Given the dynamic nature of the ice edge and difficulty monitoring its behavior, respondents from the survey suggested it would be ideal to employ a similar scatterometer device to that of NASA’s QuikSCAT, which has similar incidence angles and operated in the Ku-band. Current scatterometer products (i.e. ASCAT) are designed using different incident angles and frequency, thus they may not comparable to the QuikSCAT data. According to the operational sea-ice charting community, qualitative comparisons between passive microwave datasets, ice charts, and the QuikSCAT Ku-band scatterometer showed that the Antarctic ice edges were more clearly defined and slightly more extensive on scatterometer images in all regions than that seen on the passive microwave (Ozsoy-Cicek, et al., 2009). Another option to improve extent mapping, suggested by the community, would be to implement an edge detector algorithm on other satellites, originally used on the Geodetic Satellite (GEOSAT) Geodetic Mission (GM). It is inexpensive, the algorithm is relatively simple, and the data were easily disseminated. Therefore, it could be applicable to other satellite data sources for ice edge detection and real time dissemination (Hawkins and Lybanon, 1989).

• **Increased temporal resolutions of sensors:** As stated above, the community requested that this report highlight the need for more receiving stations that cover areas all around Antarctica. A specific area identified that needs more coverage is the Ross Sea.

Regarding sea-ice thickness, respondents agreed that although daily continuous observation is not possible, it would be ideal if ice thickness data (for all types) were available on a monthly basis. A recommendation from the survey suggested that SAR HH polarization is preferred all year round with observations of 1-3 days if possible. Sea-ice thickness for mass balance estimates would benefit from weekly measurements, specifically during transition seasons. The L-band microwave radiometry for thickness of thin ice is preferred daily and continuously; however, improvement beyond existing products is to be expected by further developing retrieval algorithms for extending thickness ranges beyond the current limit of ~50 cm. Future monitoring of sea-ice thickness should include validating SMOS thin ice products, which may be useful in winter.

• **Need for uncertainty estimates in data products:** The community's response to needs regarding sea-ice concentration measurements are that validation data are always helpful, but ice concentration is relatively well established at this point, so validation is not as necessary as for other sea-ice aspects. However, including reliable uncertainty estimates for each grid point would provide significant improvements to all products. Additional needs expressed from the community were geared toward developing more accurate retrieval algorithms Antarctic-wide, for the use of microwave observations to interpolate clear-sky retrieval over cloudy regions. Recommendations from the community suggest that the utility of sea-ice concentration data would benefit if validation work compared sea-ice concentration from SAR, where possible, with concentration from passive microwave.
Additionally, due to how snow cover on sea ice influences how well we can measure satellite-derived sea-ice thickness, it would be helpful to develop better precipitation estimates and uncertainties.

- **Implementation of multiple frequencies on satellites:** Some survey respondents suggested that improvements for all sea-ice monitoring could be facilitated with the use of more Wide Swath multifrequency SAR data (L-Band, C-Band, X-Band, and Ku-band), and preferred twice daily. Multiple frequencies would be helpful in order to highlight different features. After the start of Sentinel-1, any improvements to access to the future L-band data could be used to emphasize features like cracks, ridges or rubble fields. For process studies, respondents recommended creating additional options to supplement any missing data with optical and infrared sensors (i.e. Landsat and MODIS) or provide combined products (i.e. passive microwave and visible and infrared or scatterometer). Sea-ice classification studies require a lower temporal resolution but it is more important to coordinate the acquisitions of the individual sensors to be able to combine them in an easier way.

The outcome from the 4th IICWG Ice Analysts meeting concluded that availability of daily imagery unspoiled by weather effects is critical. Therefore, the operational community should collaborate on availability of real-time radar mosaics from Sentinel and Radarsat 2 for the Southern Ocean, as well as contacting Cosmo Sky-MED operations for possible collaboration on navigation safety in the Southern Ocean.

- **Coincident in situ, airborne, and spaceborne validation:** An overall agreement between the operations and research communities is that collecting coincident airborne vs. spaceborne validation along satellite overpasses would improve validation success for sea-ice thickness. However, algorithms for altimetry are still developing and a better understanding of the return signal and how it interacts with the surface (e.g. snow cover, ridges, etc.) is needed. Combining coincident data from ULS data with relevant satellite overpasses would also be helpful for validating altimetry. For sea-ice concentration, synergistic use of active and passive microwave data may help to avoid reported biases in the marginal ice zone due to wet ice during late Spring and Summer.

- **Missing Parameters for sea-ice monitoring:** A significant parameter missing for sea-ice monitoring is ice motion. Additionally, any improved information on the status of snow-cover and the ice-snow interface (e.g. distribution of: flooded areas, potential presence of ice layers in the snow, hoar frost, meteoric ice, gap layer, ice types, deformed and undeformed sea ice at fine spatial resolution for understanding volume) would be helpful to provide better sea-ice forecasts. A comment from a community member stated that there are copious extra parameters in sea-ice products that one can use for error estimates, even if it is not exactly clear how they can be applied. A recommendation for future missions is to make a lot of initially superfluous data available to scientists along with the actual parameters that the project is supposed to deliver.

4 **Sea Surface Temperature**

4.1 **Importance of Studying Sea Surface Temperature Observations**

Sea Surface Temperature (SST) is an important physical parameter for a range of practitioners, and thus physical oceanographers, biogeochemists, sea-ice scientists, ecosystem modellers, and glaciologists specifically addressed SST issues in the survey. In the polar regions, SST plays a role, for example, in ocean dynamics, biological activity in the upper
ocean, air-ocean exchange, and ice-ocean exchange. SST is also identified as an EOV by OOPC and ESA CCI and is generally agreed globally to be critical for all aspects of observational science, from physical to biological oceanography.

### 4.2 Current Status of Sea Surface Temperature Observations

SST is typically derived from passive thermal infrared measurements based upon assumptions about ocean surface emissivity (e.g., Reynolds et al., 2007) or from passive microwave radiometry (e.g., Wentz et al., 2000). However, when sea ice is present in higher concentrations, SST is also treated as an empirical function of sea-ice concentration derived from other remote sensing methods (Reynolds et al., 2007).

Survey respondents identified the available datasets (see below) as helpful for the Southern Ocean-wide consistent records they provide to look at long-term (interannual to interdecadal) change, as well as the ability to average into weekly, monthly, and seasonal averages for trend detection and use with numerical models. For continuity reasons, these datasets are important to include in future mission planning. For case studies or higher resolution, it is worthwhile pointing out that infrared brightness temperatures are also available more opportunistically from other sensors, for example Nimbus in the 1960s (Gallaher and Campbell, 2013), MODIS, or the entire Landsat record.

### 4.3 Primary Locations of Data for Sea Surface Temperature Observations

Survey respondents called for SST measurements for a wide range of applications. Daily, low-resolution, synoptic SST measurements are already collected for the Southern Ocean via a range of infrared and passive microwave sensors, many of which have open data policies (Pope et al., 2014).

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Host</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSR-E (Advanced Microwave Scanning Radiometer – Earth Observing System) passive microwave SST products for 2002-2011 in both swath and gridded formats (0.25-degree) at daily, weekly, and monthly resolution</td>
<td>National Snow and Ice Data Center (NSIDC)</td>
<td>(Wentz and Meissner, 2004) <a href="http://nsidc.org/data/amsre">http://nsidc.org/data/amsre</a></td>
</tr>
<tr>
<td>DMSP SSM/I-SSMIS (Defense Meteorological Satellite Program Special Sensor Microwave Imager - Special Sensor Microwave Imager Sounder) daily brightness temperature products collected from 1987 to the present</td>
<td>NSIDC</td>
<td>(Armstrong et al., 1994; Brodzik and Armstrong, 2008; Cavalieri et al., 1999; Maslanik and Stroeve, 2004) <a href="http://nsidc.org/data/NSIDC-0001">http://nsidc.org/data/NSIDC-0001</a></td>
</tr>
<tr>
<td>NOAA Extended Reconstructed Sea Surface Temperature (ERSST)</td>
<td>NOAA ESRL</td>
<td><a href="http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html">http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html</a> (Smith et al., 2008)</td>
</tr>
</tbody>
</table>
4.4 Limitations of Current Sea Surface Temperature Observations

Many survey respondents called for higher spatial and temporal resolution for SST measurements. Daily monitoring of heat fluxes are needed because they significantly impact sea-ice stability and movement. Higher temporal resolution would allow coupling of SST measurements with other data sources in order to study diurnal processes. Higher temporal resolution would also help to reduce the sampling bias in thermal infrared SST records caused by cloud cover.

While many platforms are out-performing their planned lifetimes, this cannot be relied upon; according to respondents, more platforms are needed. Higher spatial resolution was cited as necessary for breaking down issues with SST due to the presence of sea ice, as well as studying smaller-scale eddies than can be resolved with currently available data. The combination of both higher temporal and spatial resolution is important for many applications. In addition to new research avenues, higher temporal and spatial resolution would help address the desire for increased calibration and validation of SST products with in situ measurements.

In addition to improvements to infrared and microwave data available for SST products, users identified other improvements in facilitation of using SST data. Some users requested more real-time availability of SST data for forecasting applications. Others wanted improved cloud-masking of certain products, more robust validation of published SST products, and more uniformity in uncertainty estimates placed on different SST products. Data loss from cloud cover is a key issue for the Southern Ocean, as it can considerably bias sampling. Additionally, there are often inconsistencies with these parameters across different products which make associated model error estimates very difficult to interpret.

Also, many survey respondents called out specific study areas for targeted increased SST acquisition, which taken together cover most of the Southern Ocean (i.e. the Ross Sea, Weddell Sea, Scotia Sea, western Antarctic Peninsula, Amundsen Sea, Bellingshausen Sea, Drake Passage, Queen Maud Land Coast, East Antarctic Coast, Kerguelen area, South Georgia, Marion Island, etc.). Other users, motivated by process-based scientific questions highlighted the sea-ice edge and polynyas in particular as important for higher resolution SST studies in order to understand air-ice-ocean heat fluxes.

4.5 Recommendations and Additional Requirements for Sea Surface Temperature Observations

There are three major recommendations for SST measurements: maintaining continuity in currently valued datasets, investigating solutions for higher temporal and spatial resolution observations, and increasing directed acquisitions in areas of interest:

- **Maintaining continuity in currently valued dataset:** Almost universally, the synoptic availability of Southern Ocean SST measurements was highlighted as important for scientific use. Respondents recommended that continuity of monthly averaged data would be very valuable to examine long-term climatologies related to these influences, but work needs to be done on mission standards needed to achieve
particular scientific goals. Continued investment in successful SST programs is vital for the Southern Ocean community.

- **Investigating solutions for higher temporal and spatial resolution observations:** As discussed above, higher temporal resolution of SST measurements would have significant impacts for studies in the Southern Ocean. Survey respondents suggested changes to imaging infrastructure to address these challenges, including larger constellations, more base stations, and considering non-sun-synchronous platforms.

- **Increasing directed acquisitions in areas of interest:** SST plays a vital role in all near-surface Southern Ocean processes. Therefore, widespread increased acquisition in areas of large research investment, current change, and important processes is important. The ice edge, transitional seasons, and polynyas were specifically called out by survey respondents. In addition, see above for particular regions of interest.

5 Sea Level / Sea Surface Height

5.1 Importance of Sea Surface Height Observations

Many survey responses discussed the importance of sea level or sea-surface height (SSH), including oceanographers, glaciologists, and climate scientists. Recently, understanding sea-level change was listed as the first priority science question in the US National Academy of Sciences 2015 Decadal Survey of Ocean Sciences (National Research Council, 2015). SSH is a parameter related to ocean water density (i.e., salinity, temperature), local fluxes, and variable gravity, and as such is an important physical parameter to be able to measure with satellite remote sensing. In addition to studying regional SSH itself in response to changes to the Antarctic Ice Sheet, SSH is important for studying mesoscale variability and geostrophic currents, as well as being useful for logistical operations in some regions (e.g., Antarctic Peninsula, Ross Sea). However, this research area appears to be fairly niche among survey respondents. Nevertheless, SSH is also identified as an EOV by SOOS and an ECV by OOPC and ESA CCI.

5.2 Current Status of Sea Surface Height Observations

Survey respondents identified two main types of SSH measurements used in the Southern Ocean: altimetry (e.g. Rye et al., 2014) and gravimetry (e.g., Rietbroek et al., 2006). Altimetry can either be based on laser technology or radar technology – the two being suited to different environments and being available for different time periods. However, available SSH data are often averaged across multiple years due to lack of (ancillary) data and the difficulty in measuring sea surface height in the presence of sea ice.

5.3 Location of Data for Sea Surface Height Observations

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Provider</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICESat Laser altimetry</td>
<td>NSIDC</td>
<td><a href="http://nsidc.org/data/GLA15">http://nsidc.org/data/GLA15</a></td>
</tr>
<tr>
<td>Operation Icebridge altimetry</td>
<td>NSIDC</td>
<td><a href="http://nsidc.org/data/icebridge/">http://nsidc.org/data/icebridge/</a></td>
</tr>
<tr>
<td>Southern Ocean Radar Altimetry</td>
<td>Physical Oceanography Distributed Active Archive Center (PODAAC)</td>
<td><a href="http://podaac.jpl.nasa.gov/">http://podaac.jpl.nasa.gov/</a></td>
</tr>
<tr>
<td>Southern Ocean Gravimetry</td>
<td>PODAAC</td>
<td><a href="http://podaac.jpl.nasa.gov/">http://podaac.jpl.nasa.gov/</a></td>
</tr>
</tbody>
</table>
5.4 Limitations of Sea Surface Height Observations

Survey respondents repeatedly referenced limitations to currently available SSH measurements in the Southern Ocean. “Existing altimeters remain ambiguous in the Southern Ocean due to the sea state” (i.e., presence of sea ice or large waves) “and lack of knowledge on how well the altimeter waveforms are tracked in these settings.” Confidence in gravimetric SSH derivation (e.g., resolving mm/yr displacements) is impossible without improvement in understanding of seafloor geodesy (Note: seafloor geodesy is also recognized by SOOS as an EOV). Coastal and island tidal gauges can be used to validate SSH retrievals, but these are limited. There were many requests for improvements in SSH measurement with satellites and coincident datasets.

Introduction of uncertainty by the presence of sea ice means that the highest confidence is currently had for summer retrievals, but survey respondents requested year-round data coverage. This may require significant improvements in spatial resolution of SSH measurements and other observations to confirm the presence of smooth, open water.

5.5 Recommendations and Additional Requirements for Sea Surface Height Observations

There are two major recommendations to improve understanding in Southern Ocean sea levels in both the short and longer term:

- **Further research and development:** The most important recommendation germane to SSH measurements in the Southern Ocean is further research and development into addressing SSH measurement capabilities, in order to overcome the limitations discussed above.

- **Directed data acquisition:** Spatially, synoptic coverage is important for many researchers. Individual regions identified as important were the Amundsen-Bellingshausen region, the Antarctic Peninsula, and the Weddell Sea (~120°W to 0°). Some data sets are not available for the highest latitudes, which was identified as problematic. Similar to SST coverage requests, high latitude polynyas were identified as priority regions of study because they give insight into SSH in largely ice-covered regions.

- **Increased resolution:** Increased spatial and temporal resolution of all types of products is requested. This will begin to be alleviated by continued Cryosat-2 acquisitions, as well as future Sentinel and ICESat-2 data collection, and could be addressed in the short term by increased acquisitions of current missions. Some respondents called for daily altimetry data, but most respondents converged around requesting 10-14 day repeat measurements.

6 Atmospheric Parameters

6.1 Importance of Atmospheric Observations

Satellite-derived products are essential for understanding Southern Ocean cloud, precipitation, aerosol and surface fluxes, and for the evaluation and improvement of global climate models used for future climate projections (e.g., Kay et al., 2014). Indeed, the WCRP is currently coordinating a Grand Challenge on “Clouds, Circulation, and Climate Sensitivity” (Bony and Stevens, 2012). Atmospheric and oceanic circulation are inherently intertwined, playing important roles in transporting heat and water, modulating radiation transfer, and facilitating aerosol movement and associated processes. Therefore, atmospheric parameters are directly related to the majority of other parameters discussed in this paper. As an example, clouds and
biological primary productivity share a complex interaction, with cloud-modulated solar radiation driving ocean primary productivity and, in turn, phytoplankton blooms enhancing marine cloud formation by contributing cloud condensation nuclei (Meskhidze and Nenes, 2006). There are a large range of atmospheric properties identified as ECVs by the OOPC, including water vapor, pressure, precipitation, energy budget, cloud properties, ozone, aerosols, and other gas concentrations. ESA ECVs include aerosol properties, clouds properties, greenhouse gases, and ozone.

In addition to clouds, fluxes, and aerosols, large-scale atmospheric circulation in the Antarctic plays an important role in understanding trends / changes in sea ice and ocean state. Key examples include large-scale modes of variability and related circulation anomalies (such as the Southern Annular Mode and the El-Nino Southern Oscillation), as well as smaller scale features like the Amundsen - Bellingshausen Sea low. Complementary to atmospheric data, scatterometer winds (see below) are an important atmospheric data source over the Southern Ocean beyond the sea-ice edge.

6.2 Current Status of Atmospheric Observations

A long, continuing time series of atmospheric observations dating back to the late 1970’s are provided by microwave radiometers such as SSM/I, SSMIS, and AMSR and microwave sounders such as AMSU and ATMS. They provide operational observations of atmospheric temperature and moisture. Note that ocean surface winds are covered in their own separate section.

A white paper on observational interests and needs for Southern Ocean clouds, aerosols, and radiation was recently produced by a community workshop (SOCRATES Planning Team, 2014). The key observing need outlined in that report include aerosol composition and amount, cloud optical depth, cloud supercooled liquid water path, absorbed shortwave radiation, and the vertical structure of clouds, temperature, and humidity. While aerosol composition and amount (e.g., Kahn et al., 2010), cloud optical depth (Marchand et al., 2010), and liquid amount in supercooled water clouds (Hu et al., 2010) are all available from satellite observations, there are some reliability concerns with these products (Sect. 5.4). Shortwave radiation balances are based on CERES observations (Clouds and the Earth’s Radiant Energy System, e.g. Hartmann and Ceppi, 2014). Vertical structure of clouds, temperature, and humidity are currently observed by NASA’s A-train sensors (e.g. CALIPSO [Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations], CloudSat, Aqua, etc.), but this group of satellites is aging and the follow on European EarthCARE mission has been delayed. Launched in February 2014, the Global Precipitation Measurement (GPM) mission is providing dual frequency radar and multi-spectral microwave observations of precipitation over much of the Southern Ocean (to 65 degrees S).

The assimilation of global positioning system (GPS) radio occultation (RO) soundings into numerical weather prediction models can have a substantial positive impact on weather analyses and forecasts across the Southern Hemisphere (e.g., Chen et al. 2014) where the vastness of oceanic areas results in relatively scarce coverage of conventional atmospheric observations (surface weather data, radiosonde profiles, etc.). This impact arises because of the high vertical resolution, absolute calibration, no instrument drift, and all weather capability of GPS-RO. Most GPS-RO soundings are currently provided by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), a constellation of six microsatellites launched in 2006, but aging rapidly.
While by no means direct observations themselves, in addition to direct satellite observations, atmospheric reanalyses are another important source of information for the Southern Ocean research community. The most widely used are ERA-40 and NCEP/NCAR (multiple versions). Both of these have the advantage of starting in the mid-20th century. More recent reanalyses include: ERA-Interim, CFSR, MERRA, and JRA. See section below for locations of data. ERA-Interim is preferred by the polar community given its continuity to near-present, although in some cases it may be outperformed by NCEP CFSR or JRA-55 (Bracegirdle and Marshall, 2012).

### 6.3 Primary Locations of Data for Atmospheric Observations

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Provider</th>
<th>Citation</th>
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<tbody>
<tr>
<td>NASA data center providing atmospheric composition and dynamics remote sensing data and information including, but not limited to, A-Train, AIRS, Aura, GPM, Nimbus, OCO-2, and TRMM.</td>
<td>Goddard Earth Sciences Data and Information Services Center (GES DISC)</td>
<td><a href="http://disc.sci.gsfc.nasa.gov/">http://disc.sci.gsfc.nasa.gov/</a></td>
</tr>
<tr>
<td>A resource to provide researchers with help to obtain, read and analyze reanalysis datasets created by different climate and weather organizations.</td>
<td>Atmospheric Circulation Reconstructions over the Earth (ACRE) Initiative</td>
<td><a href="http://reanalysis.org/">http://reanalysis.org/</a></td>
</tr>
<tr>
<td>Research Data Archive featuring a range of atmospheric data, including in situ measurements and many reanalysis datasets.</td>
<td>National Center for Atmospheric Research (NCAR)</td>
<td><a href="http://rda.ucar.edu/">http://rda.ucar.edu/</a></td>
</tr>
<tr>
<td>National Climatic Data Center, hosting a range of climate and historical weather data and information.</td>
<td>NOAA</td>
<td><a href="http://www.ncdc.noaa.gov/">http://www.ncdc.noaa.gov/</a></td>
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### 6.4 Limitations of Current of Atmospheric Observations

While many of the key atmospheric parameters of relevance to the Southern Ocean community are currently available to some extent, there is significant room for improvement. In particular, aerosol properties, cloud optical depth, cloud supercooled liquid amount, and precipitation were highlighted by two contributors as retrievals needing further work to improve reliability. Sensors which can inform researchers about the transport of aerosols into the Southern Ocean region were identified by one contributor as critical; while CALIPSO can do this to an extent, more work should be done to address this research question (e.g. using multiple wavelengths, depolarization measurements, etc.). In addition, the current generation of atmospheric profilers also have difficulty detecting and quantifying low level clouds and precipitation. Frequent mixed-phased conditions over the Southern Ocean lead to large discrepancies between satellite estimates of precipitation (Behrangi et al., 2014; Haynes et al., 2009). Also, satellite-based observations of increased aerosol optical depths over the Southern Ocean (Smirnov et al., 2011) may possibly be contaminated by cloud effects (e.g. Witek et al., 2013), but this is not fully explained (Toth et al., 2013).
In addition, although other sensors collect data on atmospheric properties, relevant sensors (i.e. CALIPSO, CloudSat) were launched in 2006 and are now nearing a decade old, while the Aura MLS (Microwave Limb Sounder) is two years older, and the AIRS (Atmospheric Infrared Sounder) sensor is 2 years older still. Future mission plans are still under development. Similarly, for GPS RO, the follow-on COSMIC-2 mission has tropical and polar constellations of which the tropical one is currently scheduled for a 2016 launch while the polar constellation, very important for Southern Ocean weather forecasting, is more uncertain. It is crucial for space agencies to ensure data continuity and a compatible legacy for studying atmosphere-Southern Ocean interactions.

6.5 Recommendations and Additional Requirements for Atmospheric Observations

There are two major recommendations for Southern Ocean remote sensing of atmospheric parameters:

- **Focused calibration and validation**: The community agrees that there is significant atmospheric algorithm calibration and validation to be done for many key parameters, as described above.
- **Planning for continuity**: Urgent planning and investment in data continuity of atmospheric sounders is crucial for understanding atmospheric parameters and air-ocean interactions. Work needs to be done in mission planning to understand the thresholds and length of time-series needed to have confidence in trend observations.

7 Marine Microbes - Chlorophyll, Primary Production, and Biogeochemistry

7.1 Importance of Studying Marine Microbes

Marine microbes are the lynchpin of the marine ecosystem. Nevertheless, until the advent of satellite-based ocean color remote sensing their global influence was not fully appreciated. Phytoplankton make up less than 1% of the photosynthesising biomass on Earth and yet undertake approximately 50% of the Earth's primary production (Falkowski 2012, Field et al., 1998). This incommensurate contribution to the global carbon cycle makes these tiny marine organisms as important as all the plants on land combined. Unlike land plants, the physical size and cosmopolitan distribution of phytoplankton inhibit large-scale direct observation of them and therefore ocean color remote sensing has evolved as the most practical way to estimate chlorophyll concentrations (a proxy for phytoplankton biomass), primary production rates, and other biogeochemical properties in the surface ocean. In addition to discrete observations, there is a growing multi-decadal ocean color time series, which is allowing the investigation of climate scale phenomena. To this end, both the WMO GCOS and SOOS list ocean color observations and the products derived from them as ECVs and EOVs for the upper ocean.

7.2 Current status of Marine Microbe Observations

The remote sensing of marine microbes has been described as a landmark achievement in the history of oceanography (Barber and Kilting, 2000 NSF). Nevertheless, survey respondents pointed out that in the Southern Ocean and Antarctica ocean, color remote sensing is often impeded by the region’s unique bio-optical and physical properties. Community consultation highlighted that chlorophyll concentrations and primary production rates are two products that have attracted relatively strong research attention in recent decades and are relatively robust
and yet they are still significantly less reliable than their global counterparts. In addition to these few reasonably robust products the literature suggests that there are several novel and experimental products - such as calcite concentration, particulate organic carbon, microbial ecosystem size structure and functional types, and photosynthetic physiological parameters - that are at the cutting edge of our current capability, but are not yet operationally reliable or verified (McClain 2009).

7.2.1 Chlorophyll and Primary Production

There are several regional primary production and chlorophyll algorithms for the Southern Ocean and Antarctica (Johnson et al., 2013; Mitchell and Holm-Hansen, 1991; Dierssen and Smith, 2000; Gregg and Casey, 2004; Garcia et al., 2005; Marrari et al., 2006; Mitchell and Kahru, 2009; Kahru and Mitchell, 2010; Szeto et al., 2011; Behrenfeld et al., 2005; Arrigo et al., 2008; Arrigo et al., 1998; Munro et al., 2015). The development of Southern Ocean-specific algorithms has been driven, and at times limited by, the availability of high quality in situ data. A limited number of in situ samples are currently available and have been used to produce products with accuracies well above the standard NASA and ESA algorithms (Johnson et al., 2013). Unfortunately, the current products are at risk of becoming obsolete as the sensors they are designed for age and reach the end of their useful life - the currently aging ocean color capable sensors are a concern for the Southern Ocean community. The continuity of ocean color data streams is a concern and a major challenge for the Southern Ocean remote sensing community due to the difficulty of collecting in situ data for calibration/validation of new sensors in this region (a list of currently planned satellite sensors with ocean color capabilities is provided in Table X). This highlights the tyranny of remote sensing; the collection of calibration and verification data is never ending.

Even with decades of effort there are still large differences between satellite estimates of primary production and in situ estimates of primary production (Friedrichs et al., 2008). In the Southern Ocean and Antarctica these differences are largely driven by three things: uncertainties in the in situ measurements (varying techniques have been used and the sampling strategies are generally sparse in space and time); errors in the satellite radiometry and associated products used to generate the primary production estimates (such as the different satellite-derived products predicting the euphotic depth and thus the available light for phytoplankton growth; Soppa et al., 2013); and limitations that are inherent in the formulation/parameterization of the models currently used. The commonly used Vertically Generalised Primary Production Model (VGPM; Behrenfeld and Falkowski, 1997) relies on a statistical representation of the vertical distribution of primary production and an empirical function that links physiological variability to sea surface temperature – both of which are often unreliable in the cold waters of the Southern Ocean. Other approaches have been tried on the global scale (e.g., Antoine et al., 1996) using a single set of photosynthetic parameters, but these parameters cannot be valid everywhere and are probably not suitable for use in the Southern Ocean.

In Antarctica, the model proposed by Arrigo et al. (2008) is one of the current best estimates of primary production from remote sensing. Nevertheless, this model is largely unverified north of the Polar Front and most of the research community reverts to using the more readily available VGPM model of Behrenfeld and Falkowski (1997) or the carbon based model of Behrenfeld et al. (2005); both of these are known to perform poorly in high latitudes.

A key to the success of VGPM is that the data are easily accessible and researchers are able to download and use data quickly and easily without needing specialised knowledge or the ability to generate datasets themselves. The access to operational data streams is one of the
main limitations for the Southern Ocean remote sensing communities. National agencies rarely operationalize regionally specific products and many communities must rely on individual scientists that have the technical expertise to generate these products or who have set up operational processing streams to serve their products to the community.

One of the main constraints on developing more robust primary production products, both in the Southern Ocean and elsewhere, is the need to have reliable estimates of phytoplankton photo-physiology across both space and time (mainly chlorophyll specific absorption and quantum yield for absorbed-light model or photosynthetic parameters for photosynthesis-irradiance models; see details of the existing models of primary production models in Falkowski, 1998 and Sathyendranath and Platt, 2007). Ideally these data would be measurable from space, but this is not yet possible and most attempts have proven unreliable (Lee et al., 2014). Nevertheless, there is considerable effort by researchers being focused on accurately estimating primary production and as the technical challenges faced globally are shared by the Southern Ocean community there are likely to be rapid advances in this field.

7.2.2 Biogeochemical and Other Products

There has been a recent expansion in global biogeochemical and community structure products. These products are of great interest to the Southern Ocean and Antarctic community as they allow estimation of parameters like microbial size-classes and functional types using “abundance-based approaches” (Vidussi et al., 2001; Uitz et al., 2006; Nair et al., 2008; Aiken et al., 2009; Brewin et al., 2010; Hirata et al., 2011) and “spectral-characteristic approaches” (Gege, 1998; Bricaud et al., 2004; Alvain et al., 2005; Raitos et al., 2008; Bracher et al., 2009; Kostadinov et al., 2009; Pan et al., 2011); particulate organic carbon (POC; Mishnov et al., 2003; Behrenfeld et al. 2005; Stramski and Stramski, 2005; Pabi and Arrigo, 2006; Stramski et al., 2008) and colored detrital matter (Stramski et al., 1999; Loisie et al., 2002; Siegel et al., 2002, Loisel et al., 2006); dissolved organic carbon concentrations (Mannino et al., 2008; Del Castillo et al., 2008; Morel and Gentili, 2009; Fichot and Benner, 2011); calcite concentrations and calcification rates (Balch et al., 2005, 2007, 2011); and euphotic zone depth (Soppa et al., 2013). These products remain largely un-operationalized, with the exception of the calcite concentration products of Balch et al. (2005) that are routinely produced by NASA for the MODIS-Aqua sensor. All of these models were developed using in situ data collected in the tropics and mid-latitudes and regrettably with little to no verification in the Southern Ocean or Antarctica, especially south of 60°S. The barriers to accessing cutting edge products restrict the verification and research needed to advance these products. Nevertheless, these products remain useful and with a focused effort on verification and operationalization they can provide highly relevant and important insights for the study of Southern Ocean and Antarctic biogeochemistry.

Table X: Ocean color capable sensors planned from 2016 onwards. Adapted from the adapted from the IOCCG web site: http://www.iocccg.org/sensors/scheduled.html

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Agency</th>
<th>Satellite</th>
<th>Scheduled Launch</th>
<th>Spatial Resolution (m)</th>
<th># of bands</th>
<th>Spectral coverage (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLCI</td>
<td>ESA/</td>
<td>Sentinel 3A</td>
<td>Oct 2015</td>
<td>300/1200</td>
<td>21</td>
<td>400 - 1020</td>
</tr>
<tr>
<td></td>
<td>EUMETSAT</td>
<td>Sentinel 3B</td>
<td>2017</td>
<td>260</td>
<td>21</td>
<td>390 - 1040</td>
</tr>
</tbody>
</table>
### 7.3 Location of Data for Marine Microbe Observations

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Provider</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global data from the MODIS-Aqua &amp; Terra, MERIS, CZCS, OCTS, and SeaWiFS sensors along with their global models of chlorophyll concentration and some other derived products such as calcite concentrations</td>
<td>Ocean Color Web - The Ocean Biology Processing Group (OBPG) at NASA's Goddard Space Flight Center</td>
<td><a href="http://oceancolor.gsfc.nasa.gov/cms/">http://oceancolor.gsfc.nasa.gov/cms/</a></td>
</tr>
<tr>
<td>Global ocean productivity estimates from the Vertically Generalized Production Model (VGPM) of Behrenfeld and Falkowski (1997), along with some other productivity products</td>
<td>The Oregon State University Ocean Productivity Home Page</td>
<td><a href="http://www.science.oregonstate.edu/ocean.productivity/">http://www.science.oregonstate.edu/ocean.productivity/</a></td>
</tr>
<tr>
<td>Global phytoplankton function type products are produced</td>
<td>The PHYSAT products webpage</td>
<td><a href="http://log.univ-littoral.fr/Physat">http://log.univ-littoral.fr/Physat</a></td>
</tr>
</tbody>
</table>
and distributed by their creators Alvain et al. (2005)

<table>
<thead>
<tr>
<th>GlobColour - European Node for Global Ocean ColourSeaWiFS/MODIS/MERIS merged data sets</th>
<th>ESA GlobColour is an ESA (European Spatial Agency) data user element project.</th>
<th><a href="http://www.globcolour.info">http://www.globcolour.info</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>The ESA ocean colour CCI (Climate Change Initiative) project</td>
<td><a href="http://www.esa-oceancolour-cci.org">http://www.esa-oceancolour-cci.org</a></td>
<td></td>
</tr>
<tr>
<td>The NASA UCSB “Measures” project</td>
<td><a href="http://wiki.eri.ucsb.edu/measures/index.php/Main_Page">http://wiki.eri.ucsb.edu/measures/index.php/Main_Page</a></td>
<td></td>
</tr>
</tbody>
</table>

### 7.4 Limitations of Current Marine Microbe Observations

It is clear from the literature and from the survey respondents that there are many challenges facing ocean color remote sensing in the Southern Ocean. The unique bio-optics, microbial community structure and photo-physiology, lack of regularly verified and operationalized products, the physical location, and the scarcity of in situ samples for verification are major limitations to the development and use of ocean color remote sensing in the Southern Ocean and Antarctica. Even so, progress is being made at a rapid pace and with >25% of survey respondents referring to ocean color as data that are essential to their work in the Southern Ocean and Antarctica. Each of these limitations is expanded on below (see also IOCCG, 2015).

Two of the key barriers to the use of ocean color data are the complex computing skills required by researchers and the infrastructure currently needed to access or to create many of the products currently available. The scarcity of these skills is highlighted by the success of initiatives like Software Carpentry and Data Carpentry that are dedicated to teaching scientists how to code and to handle large datasets effectively. The majority of ocean color remote sensing products developed for the Southern Ocean and Antarctica never make it into an operational system that is centralised, supported, and updated with the latest research knowledge or verification data. This results in individual scientists or institutes developing processing chains and data services in an ad-hoc way. There are several examples of scientists currently working in isolation producing ocean color remote sensing data products: Phytoplankton function type products are produced and distributed by their creators Alvain et al., primary production products are produced and distributed by their creators Behrenfeld et al., and chlorophyll products are created by Johnson et al and are hosted in yet another repository, the Integrated Marine Observing Systems. The myriad of products or techniques that are published but never reach the operational stage and remain unsupported has a large impact on the scientists who use ocean color data. Ecosystem and climate modellers were some who voiced concerns that the difficulty in accessing Southern Ocean specific ocean color data is a serious impediment to their current and future research activities. Several initiatives launched by NASA and ESA agencies (via their respective OceanColor and Globcolour websites) appear promising avenues for disseminating and promoting the use of centralised, validated and user-friendly ocean color products.
Sea ice has a large impact on ocean color remote sensing. Sea ice is extremely bright relative to the dark ocean resulting in an "adjacency effect" where ice-free pixels near an ice edge or open-water pixels including sub-pixel ice appear artificially bright. This has been investigated in the Arctic where it was revealed that ice adjacency influences pixels tens of kilometres away from an ice edge (Bélanger et al., 2007, Wang and Shi, 2009). The extent of the adjacency effect in the Antarctic has to our knowledge not yet been investigated but likely significantly compromises quality of ocean color data within a few kilometers of the ice edge in the biologically important ice edge blooms and marginal ice zone. Methods are being developed to correct for adjacency effects and have been implemented in the Arctic using the POLYMER algorithm (Frouin et al. 2012).

Due to the Southern Ocean’s high latitudes the Sun zenith angle is regularly greater than that for which atmospheric correction algorithms are designed to handle (usually a Sun zenith angle of 70°; Wang 2003). Most atmospheric correction algorithms are modeled on a parallel plane atmosphere. This simplifies the radiative transfer calculations required and is often a good approximation of the atmospheric conditions in the tropics and mid-latitudes (Wang 2003). Nevertheless, this approximation is not suitable for high latitude regions and results in much of the data from the southernmost reaches of the Southern Ocean being discarded as invalid for large parts of the year (Wang 2003). This is likely to significantly bias our understanding of Southern Ocean and Antarctic primary production towards the summer season.

The thermohaline and wind-driven mixing of the Antarctic Ocean often favour oligotrophic conditions with depleted surface nutrient concentrations (mainly iron and at a lesser degree, silicic acid or nitrate in coastal waters; Quéguiner, 2013), which result in the formation of Deep Chlorophyll Maximum (DCM) layers (Parslow et al. 2001, Schlitzer et al., 2002; Uitz et al. 2009). Not only can DCM's contain a large amount of biomass but also they often have very high primary production rates (Martin et al., 2010; Wright et al., 2010, Ardyna et al., 2011). Ocean color chlorophyll and primary production algorithms do not capture this elevated biological activity, as it is too deep for passive remote sensing methods to detect. This has led to biases in oligotrophic and stratified Arctic regions, especially during post-phytoplankton bloom periods (Hill and Zimmerman, 2010; Arrigo et al., 2011; Ardyna et al., 2013; Hill et al. 2013) and it is likely to have a similar impact in the Antarctic Ocean. Southern Ocean and Antarctic primary production algorithms should incorporate Southern Ocean specific parameterizations of the vertical chlorophyll distribution.

As described above, one of the main constraints to developing good primary production products for the Southern Ocean, and elsewhere, is the need to have good estimates of phytoplankton photo-physiology in both space and time. This is especially difficult in the remote Southern Ocean as it covers a vast area, and the microbes that exist in these complex biogeographic regions are physiologically unique (Rey, 1991; Szeto, 2011; Arrigo, 2008).

### 7.5 Recommendations and Additional Requirements for Marine Microbe Observations

Three major requirements of the Southern Ocean ocean color community are the need for maintaining and actually developing the ongoing collection of calibration and verification data, the need for extended observations of the vertical distribution of key properties (e.g., Chl and other pigments, algal groups, phytoplankton photo-physiology) the need for simpler access to regional products once they have been developed and verified, the need for better
spatial coverage (hence the need for merged products using several satellite sensors), and the need for higher spectral range and resolution in future satellite sensors.

- **In situ data collection:** One survey respondent stated, "current databases of radiometric and optical data for the Southern Ocean are extremely small." This is exemplified by the fact that less than 9% of samples in the SeaWiFS Bio-optical Archive and Storage System (SeaBASS) were collected in the south of 40°S (5098 of 60346 files, as of February 2015, that is 8.44%, contain data south of 40°S). The SeaBASS database is the peak archive of in situ oceanographic and atmospheric data used by NASA's Ocean Biology Processing Group (OBPG), and by the wider research community, for ocean color verification and product development. The fact that 30% of the world’s ocean area is represented by less than 9% of collected in situ data highlights the scarcity of data for Southern Ocean research. The collection of bio-optic and radiometric data in the Southern Ocean, and in Antarctica in particular, will go a long way to addressing the bio-optical limitations outlined in Section 7.4 above. Autonomous platforms can play a significant role here to get earlier to the point of having a significant amount of data in the SO. The Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission planned by NASA (horizon 2022-2013) should carry a hyperspectral ocean color sensor. A community vetted plan for extended data collection in the SO in preparation of PACE is being developed under the auspices of NASA (led by Greg Mitchell). This effort could provide opportunities for the international community to make a step in data collection in the SO. The requirement to regularly collect in situ samples is a recurring theme across all sections of the remote sensing community and yet, this is a difficult requirement to address. At the same time another recurring suggestion has been the automation of in situ data collection through the use of advanced robotics and autonomous platform technologies. The Argo program exemplifies this and the progress of bio-optically capable floats will likely be the only cost effective method to address this requirement (e.g., SOCCOM initiative or the Oceanographic Autonomous Observations/ERC remOcean programs, see the interactive map of the current deployed bio-Argo float in the Southern Ocean). The development and use of bio-optical floats that are capable of operating in the Southern Ocean and under ice in Antarctica is a high priority for this community. As current algorithms and products become obsolete, as the sensors they are designed for age and come to the end of their useful life, the need for an ongoing in situ data collection strategy, essential for the development of the next generation of algorithms, is becoming increasingly important.

- **Centralised Data Access:** Operational/central access to the latest and best Southern Ocean and Antarctic ocean color products is a priority. Efforts to build a more integrated and organised Southern Ocean ocean color remote sensing community are under way - Belgium recently proposed the initiation of a remote sensing center dedicated to providing high quality remote sensing data for the Southern Ocean and Antarctic Ocean (driven largely by Dr. Kevin Ruddick and SCAR) - but without the buy-in of data providers and national agencies the success of these efforts will be short lived. The need for international collaboration through national programs to provide operational and ongoing Southern Ocean and Antarctic Ocean color products cannot be overestimated, especially if these tools are to be used to effectively monitor change and to study the Southern Ocean ecosystem.
• **Increased spectral resolution of sensors:** Most of the Southern Ocean ocean color community seems relatively satisfied with the current spatial and temporal coverage, however there was a call for increased spectral resolution of the sensors currently available. Increased spectral resolution has the advantage of allowing more elaborate and complex products to be produced. For example, the Hyperspectral Imager for the Coastal Ocean (HICO) has shown that complex coastal water products for water clarity, bottom types, bathymetry, and phytoplankton types can be reliably derived from hyperspectral data (Garcia et al., 2014). These data have the potential to address the limitations currently experienced by primary production algorithms in the Southern Ocean, through the development of photophysiology estimates from space, and will also pave the way for the development of new algorithms for floristic and environmental conditions. Better spatial/temporal coverage is also desirable, which can be obtained from merging of observations from several sensors (e.g., Morel et al., 2007), and is important for study of highly dynamic regimes, as often encountered in the Southern Ocean.

8 Marine Biology and Related Activities

8.1 Importance of Marine Biology and Related Activities

The Southern Ocean is home to a wide range of living things. These organisms (including charismatic fauna) play important roles in the Southern Ocean ecosystem. In addition, marine resources are important for people around the world. Indeed, in response to increasing commercial interest in Antarctic krill resources, a keystone component of the Antarctic ecosystem and a history of over-exploitation of several other marine resources in the Southern Ocean, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established by international convention in 1982 with the objective of conserving Antarctic marine life. Marine resources and activities continue to be to focus of significant interest to this day. SOOS identifies a range of EOVs related to marine biology, include fisheries catch, fisheries distribution space, penguin abundance and foraging behavior, elephant seal behavior, and krill abundance.

8.2 Current Status of Marine Biology Observations

As described by survey respondents, remote sensing of biology is a relatively young field being pushed forward by technological innovations in synoptic medium resolution remote sensing (~15 m) and submeter optical imagery. For example, remote sensing has been used to study penguin populations (e.g. Fretwell et al., 2012, 2014b) and identify whales (e.g. Fretwell et al., 2014a) as well as 5 other species of polar animals (Larue and Knight, 2014). Freely available Landsat imagery (Wulder et al., 2012) and commercial submeter optical imagery from DigitalGlobe’s WorldView satellites are the drivers of this research. For penguin studies, once synoptic images were used to identify colony locations, only 2-3 targeted acquisitions per year in the summer (November – January) are needed; for future continent-wide studies, continued Landsat and/or Sentinel-2 multispectral measurements (although Sentinel 2 orbit parameters limit use in the Antarctic) will be required. Other animals, however, are less predictable with their habits and are therefore more difficult to study.

In additional to directly sensing animals, survey respondents identified the importance of remote sensing for tracking fishing vessel activity in the Southern Ocean. Thanks to its cloud-penetrating capabilities, SAR is suited to this application. Currently, vessels over 20 m in
length are identified as regularly as possible, but with a focus on the austral autumn (December – May). RADARSAT-2 Wide Swath imagery was specifically mentioned by one survey respondent for this application, but other SAR imagery can be used more opportunistically with the appropriate processing chain. Often the cost and tasking of SAR imagery is the limiting factor for identifying vessel activity in the Southern Ocean. The “Day/Night Band” on VIIRS (Visible Infrared Imaging Radiometer Suite) has been used in the Arctic for ship detection and fisheries management (Straka et al., 2015; Elvidge et al., 2015), and this could potentially be expanded to Antarctic monitoring.

8.3 Primary Locations of Data for Marine Biology Observations

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Host</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submeter Imagery</td>
<td>Commercial Providers, such as DigitalGlobe (available via the Polar Geospatial Center for NSF/NASA grantees)</td>
<td><a href="http://www.pgc.umn.edu/">http://www.pgc.umn.edu/</a>; <a href="https://www.digitalglobe.com/">https://www.digitalglobe.com/</a></td>
</tr>
<tr>
<td>Landsat multispectral imagery</td>
<td>USGS</td>
<td><a href="http://earthexplorer.usgs.gov/">http://earthexplorer.usgs.gov/</a></td>
</tr>
</tbody>
</table>

8.4 Limitations of Current Marine Biology Observations

Across all applications in this section, scarce high-resolution imagery (both optical and SAR) limited studies. In addition, spectral resolution limits the amount of information available about these small-scale biological systems. One request, for example, noted the possibility of hyperspectral data for application to studying penguin populations. Hyperspectral data would allow more specific identification and monitoring of a wider range of penguin species. In addition, because of the conservation-related nature of this work, the high cost of these commercially-available products was severely limiting.

Regarding temporal resolution, the seasonal requirements of these applications were already discussed above. While some biological studies are opportunistic, others only require low temporal resolution (~monthly in the summer), and fishing vessel monitoring was requested approximately every 10 days.

Spatially, acquisitions can be related to especially productive regions. Penguin monitoring is a coastal activity with known locations, and animals do tend to clump together as they are related through food-webs. In the ocean itself, the presence of krill and fish are related to both monitoring whales as well as finishing vessels, allowing for more directed acquisition of optical and SAR imagery. Fishing vessels in particular should be monitored in the Southern Ocean south of the Indian Ocean at latitudes higher than 60°S.

8.5 Recommendations and Additional Requirements for Marine Biology Observations

Community requests for remote sensing-based studies of marine biology and related activities can be summarized quickly with two main recommendations:

- **Low-cost availability to more imagery at higher resolution:** A conduit for practitioners to be able to request imagery and have it subsidized is seen as important for continued remote sensing applications to Southern Ocean marine biology and related activities.
● **Hyperspectral data:** Space agencies should consider the feasibility of a (high resolution) hyperspectral mission which includes coverage of the Southern Ocean region.

## 9 Terrestrial Cryospheric Connections

### 9.1 Importance of Terrestrial Cryosphere Observations

While this review largely focuses on the Southern Ocean itself, many terrestrial elements of the cryosphere interact with the ocean in important ways. Indeed, over 10% of respondents (6) identified with terrestrial cryospheric expertise. Ice shelves play an important role in ocean heat transport, salinity, and nutrient fluxes. From an operational side, ice shelves also produce the icebergs that float out to sea and/or become grounded in the coastal environment (see below). In addition, seasonal snow cover is important for the freshwater flux it provides to local flora and fauna. Even permafrost, a subsurface phenomenon, plays an important role in hydrological and sediment fluxes. Therefore, these elements of the cryosphere must be monitored, too, for a full understanding of the Southern Ocean system.

A notable parameter related to the terrestrial cryosphere is iceberg detection and tracking. Sourced from glaciers and ice sheets, icebergs sit at an interesting intersection between ice and ocean. Iceberg detection is necessary, especially in areas of concentrated ship activity (tourism, research support, et c) and/or ice shelf calving (e.g., Antarctic Peninsula, Ross Sea). The importance of operational parameters for shipping safety are addressed above in the sea ice sections. In addition to iceberg presence, combination of iceberg tracking with altimetry measurements has shown imbalances in ice fluxes as well as recent decreases in iceberg production (Tournadre et al., 2015).

SOOS identifies a range of properties related to the terrestrial cryosphere as EOVs (e.g. ice topography, ice velocity, basal melt/freeze rates, englacial temperatures, and bottom topography). The WMO GCOS also identifies glaciers and ice caps, ice sheets, and albedo as ECVs. ESA identifies both glaciers and ice sheets at ECVs, as well as soil moisture.

### 9.2 Current Status of Terrestrial Cryosphere Observations

Currently available terrestrial glaciological remote sensing data of interest to the Southern Ocean community is available in the form of raw data and in episodic products, as opposed to continuously updated products. For example, ice topography (Bamber et al., 2009; e.g. Zwally et al., 2014), glacier velocities (Rignot et al., 2011a, 2011c, 2012), grounding line location (Bindschadler et al., 2011; Brunt et al., 2010; Rignot et al., 2011b), glacier outlines (e.g. Cook et al., 2014), and bedrock (Fretwell et al., 2013) are all freely available. SAR imagery is available for purchase or on an ad-hoc basis, while satellite imagery is available from a range of commercial (high resolution, on-demand, e.g. DigitalGlobe) and public (low resolution, daily, e.g. NASA or ESA) providers. Due to the range of glaciological applications of remote sensing, survey respondents could not agree on what temporal or spatial resolution is of largest utility.

Two other important cryospheric elements are terrestrial snow cover and permafrost. There are products available for snow cover extent derived from both optical (e.g. [http://nsidc.org/data/modis/data_summaries/index.html#snow](http://nsidc.org/data/modis/data_summaries/index.html#snow)) and radar imagery (Nolin et al., 1998), but the data are largely too coarse for Southern Ocean applications. Snow was identified as important at weekly resolution in the austral summer, especially around the Antarctic Peninsula and sub-Antarctic islands; the small spatial scales involved in some areas
make high spatial resolution, and potentially both SAR and visible imagery attractive. Similarly, permafrost studies focus on the Peninsula and sub-Antarctic islands. Surface temperatures from thermal infrared sensors can be used to drive permafrost models, passive microwave sensors can study soil moisture, and repeat radar measurements can be used to study active layer thickness (Bartsch, 2014).

Iceberg monitoring and tracking data varies from derived satellite products to operational charts. An iceberg tracking database was established using iceberg data from the backscatter of scatterometer products in the Ku and C-band developed at the BYU Center for Remote Sensing. The BYU SIR and SIR filtering (SIRF) algorithms were applied to scatterometer data to track icebergs greater than 5 km in length (Stuart and Long, 2011 and Early and Long, 2001). The current BYU iceberg tracking product uses the SIRF algorithm on the Advanced SCATterometer (ASCAT) sensor. The US NIC has been tracking icebergs with the use of SAR, optical, passive microwave, and available scatterometer data. Iceberg tracking methods at the NIC have a different criteria where they track icebergs greater than 18.5 km. Future plans will include tracking icebergs at 37 km$^2$. The NIC is also responsible for establishing the familiar iceberg-tracking naming convention (i.e. A64, B17, etc..) that is used by the community.

The Antarctic Climate and Ecosystems Cooperative Research Centre and the Australian Antarctic Division group have been monitoring sea-ice drifts and icebergs in the Mertz region from the east out of the Ross Sea to the west and sea-ice drift onto the continental shelf with the use of specific iceberg tracking (i.e., SAR and optical imagery), radar altimeter, scatterometers, acoustic detection on an ad-hoc basis. Satellite altimetry information, either waveforms or high-resolution digital elevation models have also been used to quantify iceberg volumes (Tournadre et al., 2015, Enderlin and Hamilton, 2014). These data are available ad-hoc from data providers (e.g., ESA, NSIDC, DigitalGlobe) rather than as iceberg data products. Survey respondents noted the potential for coincident collection of shipborne iceberg radar observations, as well.

### 9.3 Primary Locations of Data for Terrestrial Cryosphere Observations

<table>
<thead>
<tr>
<th>Description</th>
<th>Host</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice sheet topography</td>
<td>NSIDC</td>
<td>(Bamber et al., 2009; e.g. Zwally et al., 2014)</td>
</tr>
<tr>
<td>Glacier Velocities</td>
<td>NSIDC</td>
<td>(Rignot et al., 2011a, 2011c, 2012)</td>
</tr>
<tr>
<td>Grounding Line Location</td>
<td>NSIDC</td>
<td>(Bindschadler et al., 2011; Brunt et al., 2010; Rignot et al., 2011b)</td>
</tr>
<tr>
<td>Glacier Outlines</td>
<td>NSIDC / GLIMS</td>
<td>(e.g. Cook et al., 2014), <a href="http://www.glims.org/">http://www.glims.org/</a>, <a href="http://www.glims.org/RGI/">http://www.glims.org/RGI/</a></td>
</tr>
<tr>
<td>Antarctic Bedrock</td>
<td>British Antarctic Survey</td>
<td>(Fretwell et al., 2013)</td>
</tr>
<tr>
<td>Terrestrial snow cover</td>
<td>NSIDC</td>
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</tr>
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<td>Iceberg locations</td>
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<td><a href="http://www.scp.byu.edu/data/iceberg/database1.html">http://www.scp.byu.edu/data/iceberg/database1.html</a></td>
</tr>
</tbody>
</table>

33
9.4 Limitations of Current Terrestrial Cryosphere Observations

The glaciology community is well-placed to identify shortcomings in the cryospheric products discussed here, whether low spatial resolution (e.g., snow cover), low temporal resolutions (e.g., DEMs), or lack of coverage (e.g., bedrock information). However, the real limitation to the use of terrestrial cryosphere-related products in the Southern Ocean research community is the lack of familiarity with otherwise discipline-specific data sets produced using a wide range of remote sensing techniques.

One of the major limitations for iceberg monitoring is that iceberg movement can have varying speeds due to ocean and atmospheric forcings, which are also affected by their size. Though icebergs can have a profound effect on regional sea ice conditions, it is difficult to detect an iceberg at the scale of approximately < 5 m long unless the user has prior knowledge of its existence and specifically orders high resolution data to follow its trajectory. Data acquisition can be available but is normally too expensive for the average user to obtain. For iceberg tracking, scatterometers have been extremely useful in detecting region-wide iceberg movements > 5 m. However, these patterns are biased due to the amount of regional iceberg calving, as well as the sensors’ inability to capture small bergy bits and growlers.

9.5 Recommendations and Additional Requirements for Terrestrial Cryosphere Observations

For the purposes of this review, we are considering the perspective of Southern Ocean research (as opposed to Antarctic glaciology, etc.) As such, the recommendations related to the terrestrial cryosphere are related to ocean research needs:

- **Ease of data access:** For the Southern Ocean community, the most important recommendations for terrestrial cryospheric connections are to continue to make appropriate remotely sensed parameters easily understandable and available to interdisciplinary researchers. This includes the computing considerations discussed in the Marine Microbes section.

- **Investment in products:** From an oceanographic perspective, survey respondents requested additional and updated derived products related to the terrestrial cryosphere, which can then be incorporated into models or maps. Many of these products exist in a snapshot state, but survey respondents requested more frequently updated information about ice shelf thickness, ice shelf extent, land/ice masks, iceberg production, and snow/land cover. Such processing is possible with both (stereo) optical imagery and SAR, but current processing methods and data costs limit applications to relatively limited regions. As such, improvements in data processing, either through efficient software or community facilities (such as the Polar Geospatial Center) should be investigated. Due to temporal and processing limitations discussed above, it is recommended to continue to invest in projects (such as NASA MEaSUREs), which support the development and processing of appropriate products (e.g. ice topography, thickness, velocity, etc.).

- **Community training:** Because of the range of data types and product provenance, support for community training programs is recommended for appropriate data use and increased adoption of interdisciplinary data products.

- **Increased (interferometric) SAR coverage:** For iceberg tracking and ice shelf monitoring, regular interferometric SAR mapping of the areas with high stress...
developments and potential iceberg calving can significantly benefit ice-ocean understanding as well as logistical operations (e.g., in the Ross Sea area). In addition, due to its versatility and ability to see through clouds, the majority of respondents also reference the important of cheaper, more frequently available SAR imagery for snow, ice, and permafrost applications related to the Southern Ocean.

10 Sea Surface Salinity

10.1 Importance of Sea Surface Salinity Observations

Sea Surface Salinity (SSS) observations can play an important role in understanding the upper ocean. Ocean salinity and temperature differences drive thermohaline circulations, and play a key role in the ocean–atmosphere coupling. SSS also responds to terrestrial runoff and, where surface runoff is minimal (as in most of the Southern Ocean), it is possible to observe freshening from melting sea ice and possibly icebergs. However, despite recognition from SOOS as an EOV and OOPC as an ECV, SSS was not addressed by any survey respondents. This is possibly the result of polar-specific datasets becoming only recently available for SSS (Brucker et al., 2014c). However, in situ observations from ships are available for several decades (e.g., Morrow and Kestenare 2014). Accordingly, all information presented here comes from literature sources and the secondary stage of community consultation.

10.2 Current State of Sea Surface Salinity Observations

L-band (~1.4 GHz) passive microwave observations are used in a wide range of cryospheric observations (e.g., sea ice thickness, soil freeze/thaw state, ice sheet surface properties, etc.). In addition, until recently (June 8, 2015), L-band observations from the Aquarius mission provided information about Southern Ocean SSS. After correction for external noise and atmospheric effects, brightness temperature is converted into SSS using ancillary data for the sea surface temperature, and a model for the sea water dielectric constant (Brucker et al., 2014c).

The weekly gridded products of SSS (see below) enable the monitoring of SSS changes in the polar regions, and possibly freshening resulting from the melting cryosphere (Brucker et al., 2014d). However, while the algorithm used in the Aquarius Level 2 processing for retrieving SSS performs well in the tropics and mid-latitudes (warm) oceans, L-band SSS retrieval in the polar (cold) oceans is challenging. SSS retrievals have not yet been specifically validated in cold water, and should be used with caution.

10.3 Primary Locations of Data for Sea Surface Salinity Observations

<table>
<thead>
<tr>
<th>Description</th>
<th>Host</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquarius L3 Weekly Polar-Gridded Sea Surface Salinity, Version 4</td>
<td>NSIDC</td>
<td>(Brucker et al., 2014b)</td>
</tr>
<tr>
<td>Aquarius L3 Weekly Polar-Gridded Brightness Temperature and Sea Surface Salinity, Version 4</td>
<td>NSIDC</td>
<td>(Brucker et al., 2014a)</td>
</tr>
</tbody>
</table>

Aquarius SSS products are available since August 2011 and are expected to be updated monthly through May 2015; Aquarius suffered a crucial malfunction in early June 2015. With the recent launch of the Soil Moisture Active Passive Mission (SMAP) on 31 January 2015, it remains to be seen what additional polar SSS observations may become available.
10.4 Limitations of Sea Surface Salinity Observations

Brucker et al., (2014d) provide a concise and informative summary of limitations to SSS retrievals in the Southern Ocean: “Polar ocean waters are cold and L-band observations are less sensitive to salinity in cold waters. In addition, salinity retrieval is less accurate for very rough sea surfaces. For instance, in the Southern Ocean there are strong winds and the oceanic circulation is dominated by the Antarctic circumpolar current, which reduce the quality of the SSS retrievals. Finally, the presence of sea ice and icebergs in the sensors’ field of view adds complexity to the monitoring of SSS in the high latitudes. … Therefore, one should be particularly careful when studying SSS in the vicinity of sea ice edge and ice sheet. Put simply, increasing [brightness temperature] due to the presence of ice can appear as erroneous freshening.” The low resolution of the polar SSS products amplifies the effects of retrieval contamination by land and ice.

In addition, as mentioned above, the Aquarius SSS retrievals have not been validated in the cold waters of the Southern Ocean. Also, radio frequency interference can contribute to uncertainty in SSS retrievals, but this influence in the Southern Ocean region is significantly smaller than in the Arctic. Corrections for external noise are still uncertain, and different orbital paths and incidence angles make this a challenging problem. Areas of low data density must also be filled with linear interpolation, although the gridding of a weekly product minimizes this problem. In summary, Southern Ocean SSS retrievals should continue to be used with caution.

10.5 Recommendations and Additional Products for Sea Surface Salinity Observations

Polar SSS retrievals from satellites are still relatively young, and so much work can be done to continue to improve these retrievals. There are many challenges to accurately retrieving SSS in the Southern Ocean from satellite observations, which leads to many available recommendations for improvement.

- **Increased validation:** There needs to be increased validation of Southern Ocean SSS retrievals with in situ measurements.
- **Better corrections:** Improved corrections for sea ice and land contamination must also be provided for applying SSS observations to areas of interest (e.g., ice edge and polynyas), stronger interpretation of seasonal SSS behavior, and detecting any longer term change detection.
- **Clarify future data availability:** The recent launch of SMAP opens up more possibilities for Southern Ocean SSS observations. Acquisition plans for the Southern Ocean remain to be set, and further information about SMAP capabilities in retrieving SSS in cold, polar waters is still an open question. Nevertheless, increased observation and continuity from SMAP measurements is of interest to the Southern Ocean community.

11 Surface Winds

11.1 Importance of Surface Wind Observations

Polar winds are a crucial component of atmospheric heat flow, ocean currents, biological activity, sea ice formation, gas exchange, and ultimately Earth’s climate. With the limited availability of weather stations and ship-based observations, satellite retrieval of wind information is essential for accurate yet widespread measurement. Satellite scatterometry enables daily wind vector observations over the ocean. For example, near-surface wind speeds
and directions have been used in the Southern Ocean to initialize weather and sea ice drift models (Bromwich et al., 2013). At high resolution, wind information can be used to study coastal and mesoscale wind features such as cyclones and storms (Long et al., 2003). Wind speed and direction have been highlighted by SOOS as an EOV and the WMO as an ECV.

11.2 Current State of Surface Wind Observations

The effects of surface winds on the roughness of the ocean surface can be used to derived surface wind speeds and directions. For example, originally designed to measure wind vector fields over the ocean at a nominal resolution of 25 km, the SeaWinds series of Ku-band scatterometer instruments can be used to reconstruct near-surface wind vector fields at resolutions as high as 2.5 km (Long et al., 2003). However, the SeaWinds scatterometer on the QuikSCAT satellite is no longer active, providing invaluable data regarding global climate from 1999 to 2009. Other vector wind sensors, also Ku-band scatterometers, include SeaWinds on Midori-II (2002-2003), Oceansat-2 (2009-2014), the earlier NSCAT on Midori-I (1997), and the briefly lived Seasat (1978) (Pope et al., 2014). C-band scatterometers can also be used to derive wind vectors. Sensors include AMI on ERS-1 (1992-1996) and ERS-2 (1995-2001), as well as ASCAT on MetOp-A (launched in 2007) and MetO-B (launched in 2009); MetOp-C is planned for launch in 2018.

11.3 Primary Locations of Data for Surface Wind Observations

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<tr>
<th>Description</th>
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<th>Citation</th>
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</tr>
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<td><a href="http://www.eumetsat.int/website/home/Data/Products/Atmosphere/index.html">http://www.eumetsat.int/website/home/Data/Products/Atmosphere/index.html</a></td>
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</tbody>
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11.4 Limitations of Surface Wind Observations

In the Southern Ocean, the presence of sea ice can affect scatterometer measurements to wind velocities and directions. Often resolved by discarding measurements within 50 km of sea ice, this results in large data gaps. Newer methods attempt to identify the relative contribution of
ice in each scatterometry measurement and can reduce the buffer to as little as ~10 km (Hullinger and Long, 2013). Although minimal for most of the Southern Ocean, the presence of land also contaminates wind vector retrievals (Owen and Long, 2009). In addition, the presence of liquid precipitation can also contaminate wind measurements, and Ku-band and C-band scatterometers experience different noise characteristics (Weissman et al., 2012). Many studies have sought to better understand, bypass, and correct for wind vectors that are adversely affected by rain, but there continues to be room for further improvement, whether through improved algorithms, data fusion (e.g., with AMSR), and/or new sensors.

In addition, while RapidSCAT on board the International Space Station (launched in 2014) is seen as a replacement for the Ku-band SeaWinds, it only includes coverage up to ~58°S. Therefore, a largest limitation to remote sensing of Southern Ocean wind velocities and directions is a lack of Ku-band scatterometry data. The planned CFOSat will be able to remedy this data gap, with its planned launch in 2018.

11.5 Recommendations and Additional Products for Surface Wind Observations

In order to be relevant for research, ocean wind retrievals from satellites must be well-validated and the algorithm provenance must be well described. In addition, interoperable longer time series are important for working across decadal timescales. In addition, for operational applications, surface wind retrievals need to be delivered in a timely fashion and in the appropriate formats. There are two main focused recommendations:

- **Improved retrievals algorithms**: The main improvements for Southern Ocean wind observations will come from improvements in retrieval algorithms to handle confounding signals in the scatterometer measurements.
- **Ku-band scatterometer data**: For continued high-quality surface winds measurements, and in particular for continuity of records, increased availability of Ku-band scatterometer data is essential.

12 Other Observations

There were a few data requests from survey respondents that did not fit into other larger categories. [Are there more that the community would like to identify?]

According to one respondent, magnetic field data in the Southern Ocean is needed for global induction and heat flow models. Airborne and in situ missions are required for full data utility.

13 Importance of Coincident Data

A theme across all Southern Ocean satellite applications is the need for coincident data collection. Nevertheless, what “coincident data” means varies between applications. A basic need for coincident data is for calibration and validation of satellite-derived products, ranging from basic physical parameters to specialized variables. Also, coincidently collected satellite data are required to fully observe the interdependent variables of complex systems.

13.1 Point or Profile Measurements

Survey respondents identified the desire for in situ measurements of almost every remotely sensed parameter for product calibration and validation; a time window of +/- 3 hours between in situ and satellite observations was identified in one survey response. In addition, in situ measurements of related variables (not measurable by satellites) were often singled out, too (e.g., cytometry counts, subsurface temperature and salinity, barometric pressure, air
temperature, etc.). Atmosphere-related variables require dedicated observations and fieldwork (SOCRATES Planning Team, 2014). The desire for point measurements also raised the concern that in situ measurements are best compared to very high-resolution remote sensing products, as opposed to the often low-resolution, synoptic data sets collected for the Southern Ocean. It is therefore important to have reliable methods to be able to work across spatial resolutions from a variety of satellite or other remote sensing platforms.

Out of all current in situ measurements, Argo floats were the most highly cited example of beneficial in situ data, and multiple responses suggested expanding Argo coverage. The challenge with the Argo system, however, is enough surface and near-surface data collection, which is not prioritized with the current Argo behavior (i.e. majority of time at depth). A related historical platform is the International Programme for Antarctic Buoys, whose data are currently held at NSIDC.

In addition, a wide range of other specific in situ platforms were identified as being important. Survey respondents identified buoys, gliders/AUVs, sondes, ships (of opportunity), (commercial) aircraft, drones/UASs, moorings, tide gauges, and even animal-based observations (e.g. seals, penguins, etc.). These unique platforms allow otherwise impossible interdisciplinary, process-based science in remote regions as well as “ground” truth for satellite products.

Surface based observations, principally surface pressure and sea surface temperature from ocean buoys, salinity, and air temperature should be done all around Antarctica but data collection should be focused in the Bellingshausen, Amundsen and Weddell Seas at the very least. While island-based observations are not spatially comprehensive, they are important datasets to provide validation for many variables (e.g., atmospheric). Also, human observations are necessary for animal population censuses as well as to confirm the presence of smooth, open water for remote sensing altimetry measurements. Relatedly, for correct interpretation of high-resolution satellite imagery, improved digital elevation models are essential for accurate orthorectification of satellite imagery. The Southern Ocean READER (http://www.antarctica.ac.uk/met/SCAR_ssg_ps/OceanREADER/) is a portal for links to temperature, salinity, and ocean current data from the Southern Ocean, but it has not been recently maintained and users must therefore find national or discipline specific data repositories which are up to date. Regarding sea ice conditions, additional data collection simultaneous to improved satellite collections should include in situ measurements of snow cover, sea ice thickness, pressure ridging, sea ice draft data, and sea winds (e.g. following ASPeCT; Weissling et al., 2009). Though the community is aware of this need, it is important to try to implement a greater coordination of this type of collection with all groups who are physically going out to these regions. Another specific complementary measurement noted by a survey respondent was that CCAMLR-compliant vessels submit their positions and headings, allowing for development of algorithms to identify vessels from SAR imagery. Further incentives for innovations in observations, such as the WCRP Polar Challenge to develop autonomous and scalable under-ice observations are needed to enhance Southern Ocean satellite observations.

Climate modelers in particular strongly encourage coordinated campaigns to include satellite and sea ice observations because there is still a disconnect between communicating how we can transfer knowledge on the small scale and data for modelers to use on a large-scale. Uncertainties are not well-communicated to the modelers, which makes it difficult to provide systematic forecasts. Additionally, it is difficult for many observations to be collected in a timely manner or on a large-scale that modelers can use directly. Significant overlap and a
combination of techniques are required to improve data assimilation transfer to models and eventually help to develop an integrated observing system. Though data collection is preferred all year round, the winter and autumn seasons are critical times for sea ice dynamics. It is especially important to have more validation information in the Ross Sea, Weddell Sea, Bellingshausen, and Amundsen Seas according to the sea ice modeling community.

### 13.2 Complementary Satellite-Derived Data

In addition to in situ measurements, survey respondents identified significant added value by combining multiple remote sensing datasets. On the basic end of the spectrum, coincident collection of optical and other parameters can allow visible, manual interpretation of, for example, sea ice concentration. In more complex applications, datasets can either be assimilated to improve model outputs or can be combined as inputs for physically-based models and then validated with another dataset. For example, many inputs are required for numerical weather prediction (NWP). In the most complex application identified in survey responses, one user wrote, “We are interested in understanding coupled model biases so need a comprehensive set of atmosphere and ocean parameters to assess process representation to attribute biases to causes.”

In addition, as mentioned above, high-resolution data are necessary for the most robust comparisons with in situ data. In order to bridge the gap to low-resolution synoptic observations, there need to be efforts made to collect both high resolution and low resolution data coincidentally (within the limits of the type of data being collected). Examples of implementing this suggestion include planning near-synchronous orbits for satellite constellations (e.g., NASA’s “A-train”) or timing airborne data collections to overlap with satellite overpasses. Further innovating in planning on this front is necessary.

### 14 Recommendations and Conclusion {Tentative}

The Southern Ocean is vast, and the communities that require satellite-derived data in the region are diverse. Through extensive community engagement, this review has endeavoured to bring together both the current best practice and future needs of a wide range of stakeholders, including observational scientists, modellers, and Southern Ocean operators. As one survey respondent astutely noted: “[Researchers] work with what we have available. The more we have available, the better the research in general.” This is not to say that researchers are greedy – but instead that more and better satellite data will systematically contribute to improved science and deeper understanding of the Southern Ocean, a critical component of the global climate system yet one that has historically been under-observed and understood.

Based upon survey responses and subsequent community consultation, this review includes many recommendations for the future of Southern Ocean remote sensing (see earlier sections for parameter-specific recommendations), including, in no particular order, to:

- Commit to continuity of all satellite data workhorses (using quantitative standards to determine the quality and quantity of data needed to observe trends), including visible imagers, ocean color sensors, scatterometers, passive microwave sensors, and active radar sensors,
- Increase the spatial and temporal resolution (potentially with the inclusion of non-sun-synchronous orbits) of key parameters (e.g., sea ice presence/thickness, SST, SSH, ocean color, ice sheet elevation, **others?**),
- Create a systematic, synoptic ice charting system for the entire Southern Ocean,
• Support the development of Southern Ocean-specific algorithms for crucial parameters (e.g., sea-ice thickness, primary productivity, biogeochemically important parameters like calcite and chlorophyll, salinity, others).
• Implement widespread, multi-sensor, consistent calibration and validation for campaigns for important products in the Southern Ocean,
• Encourage innovation in development of (automated) ancillary data collection (e.g. through the use of ships of opportunity and autonomous platforms),
• Facilitate and support operationalization of researcher-led product and algorithm development with agency support,
• Provide useable uncertainty estimates / documentation along with all products,
• Improve atmospheric correction models for high-latitude use,
• Consider investing in hyperspectral satellite data for polar regions,
• Reduce the cost and increase the availability of (high-resolution) SAR data for the Southern Ocean community (using free and commercial optical imagery as an example),
• Collect more multifrequency (Wide Swath) SAR imagery (especially L-band),
• Focus on both widespread, long-term monitoring, process-based studies (e.g., polynyas or marginal ice zone), and areas of environmental and human activity (e.g., Amundsen-Bellingshausen region, Weddell Sea, Antarctic Peninsula), and to
• Commit to best practice in fast, easy data access (both scientific and operational) and use (i.e., multiple levels of products and tools) for all Southern Ocean stakeholders.

These recommendations are a starting point for scientists to understand more about Southern Ocean processes and their global roles, for funders to understand the desires of the community, for commercial operators to safely conduct their activities in the Southern Ocean, and for space agencies to gain insight into planning Southern Ocean-related acquisitions and mission. Representing the collective voice of the Southern Ocean community, we hope that this review will serve as a resource to most effectively harness satellite data to understand the Southern Ocean and its important role in environmental and human systems.

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Author Contributions

P. Wagner and A. Pope are considered co-lead authors of this manuscript. L Newman and J. Baeseman developed and implemented the survey and composed the motivation and background sections. P. Wagner composed sections on sea ice and all related properties, as well as icebergs. A. Pope composed sections on community consultation, SST, SSH, SSS, atmospheric variables, cryospheric variables, surface winds, and marine biology applications. R. Johnson composed sections on ocean color and marine microbes. All authors collaboratively edited the documents and composed the abstract, conclusions, and final recommendations.
Appendix: Acronyms

AAD: Australian Antarctic Division
ACRE: Atmospheric Circulation Reconstructions over the Earth Initiative
AIRS: Atmospheric Infrared Sounder
ALOS: Advanced Land Observing Satellite, "Daichi"
AMC: Antarctic Meteorological Centre
AMI: Advanced Microwave Instrument
AMSR: Advanced Microwave Scanning Radiometer
AMSR-2: Advanced Microwave Scanning Radiometer 2
AMSR-E: Advanced Microwave Scanning Radiometer – Earth Observing System
ASCAT: Advanced Scatterometer
ASPECT: Antarctic Sea Ice Processes and Climate
ATSR: Along Track Scanning Radiometer
AUV: Autonomous Underwater Vehicle
AVHRR: Advanced Very High Resolution Radiometer
BYU: Brigham Young University
CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCAMLR: Commission for the Conservation of Antarctic Marine Living Resources
CERES: Clouds and Earth’s Radiant Energy System
CFSR: Climate Forecast System Reanalysis
CIS: Canadian Ice Service
CliC: Climate and the Cryosphere Project
COMNAP: Council of Managers of National Antarctic Programs
DCM: Deep Chlorophyll Maximum
DMSP: Defense Meteorological Satellite Program
ECMWF: European Centre for Medium-Range Weather Forecasting
ECV: Essential Climate Variable
EOV: Essential Ocean Variable
ERA-40: ECMWF reanalysis for the period September 1957 through August 2002
ERA-Interim: ECMWF reanalysis global atmospheric reanalysis from 1979, continuously updated in real time
ERS-1/2: European Remote Sensing Satellite 1/2
ESA: European Space Agency
ESRL: Earth Systems Research Laboratory
EU: European Union
EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites
GCOM: Global Change Observation Mission
GCOM-W1: Global Change Observation Mission Water 1, “Shizuku”
GCOM-W2: Global Change Observation Mission Water 2
GCOS: Global Climate Observing System
GES DISC: Goddard Earth Sciences Data and Information Services Center
GHRSST: Group for High Resolution Sea Surface Temperature
GMES: Global Monitoring for Environmental Security (now Copernicus)
HICO: Hyperspectral Imager for the Coastal Ocean
IAATO: International Association of Antarctica Tour Operators
ICEMAR: Sea Ice Service for Maritime Operations
IMOS: Integrated Marine Observing Systems
JAXA: Japanese Aerospace Exploration Agency
JPL: Jet Propulsion Laboratory
JRA: Japanese Reanalysis
LiDAR: Light Data And Ranging
LIMA: Landsat Image Mosaic of Antarctica
MERIS: Medium Resolution Imaging Spectrometer
MERRA: Modern-Era Retrospective Analysis for Research and Application
MODIS: Moderate Resolution Imaging Spectroradiometer
NASA: National Aeronautics and Space Administration
NCEP: National Centers for Environmental Prediction
NCAR: National Center for Atmospheric Research
NESDIS: National Environmental Satellite, Data, and Information Service
NIC: National Ice Center
NOAA: National Oceanic and Atmospheric Administration
NSCAT: NASA Scatterometer
NSF: National Science Foundation
NSIDC: National Snow and Ice Data Center
NWP: Numerical Weather Prediction
OBPG: Ocean Biology Processing Group
OOPC: Ocean Observations Panel for Climate Change
OSCAT: OceanSat Scatterometer
PALSAR: Phased Array type L-band Synthetic Aperture Radar
PGC: Polar Geospatial Center
POC: Particulate Organic Carbon
QuikSCAT: Quick Scatterometer
RADAR: Radio Distance and Ranging
RCC: Rescue Coordination Centre
READER: REference Antarctic Data for Environmental Research
SAR: Synthetic Aperture Radar
SASS: Seasat-A Scatterometer System
SCAR: Scientific Committee on Antarctic Research
SCOR: Scientific Committee on Ocean Research
SCP: Scatterometer Climate Record Pathfinder
SeaBASS: SeaWiFS Bio-optical Archive and Storage System
SeaWiFS: Sea-Viewing Wide Field-of-View Sensor
Scatterometer Image Reconstruction: SIR
Scatterometer Image Reconstruction Filter: SIRF
SMAP: Soil Moisture Active Passive (Mission)
SOCCOM: Southern Ocean Carbon and Climate Observations and Modeling project
SMARA: Argentine Navy Meteorological Service
SMMR: Scanning Multichannel Microwave Radiometer
SOCRATES: Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study
SOOS: Southern Ocean Observing System
SSH: Sea Surface Height
SSM/I: Special Sensor Microwave Imager
SSMIS: Special Sensor Microwave Imager Sounder
SSS: Sea Surface Salinity
SST: Sea Surface Temperature
UAV: Unmanned Aerial Vehicle
UAS: Unmanned Aircraft System
ULS: Upward Looking Sonar
USGS: United States Geological Survey
VGPM: Vertically Generalized Primary Production Model
VIIRS: Visible Infrared Imaging Radiometer Suite
WCRP: World Climate Research Programme
WMO: World Meteorological Organization
References


