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The Southern Ocean is disproportionately important in its effect on the Earth system, impacting climatic, biogeochemical, and ecological systems, which makes recent observed changes to this system cause for global concern. The enhanced understanding and improvements in predictive skill needed for understanding and projecting future states of the Southern Ocean require sustained observations. Over the last decade, the Southern Ocean Observing System (SOOS) has established networks for enhancing regional coordination and research community groups to advance development of observing system capabilities. These networks support delivery of the SOOS 20-year vision, which is to develop a circumpolar system that ensures

time series of key variables, and delivers the greatest impact from data to all key end-users. Although the Southern Ocean remains one of the least-observed ocean regions, enhanced international coordination and advances in autonomous platforms have resulted in progress toward sustained observations of this region. Since 2009, the Southern Ocean community has deployed over 5700 observational platforms south of 40°S. Large-scale, multi-year or sustained, multidisciplinary efforts have been supported and are now delivering observations of essential variables at space and time scales that enable assessment of changes being observed in Southern Ocean systems. The improved observational coverage, however, is predominantly for the open ocean, encompasses the summer, consists of primarily physical oceanographic variables, and covers surface to 2000 m. Significant gaps remain in observations of the ice-impacted ocean, the sea ice, depths >2000 m, the air-ocean-ice interface, biogeochemical and biological variables, and for seasons other than summer. Addressing these data gaps in a sustained way requires parallel advances in coordination networks, cyberinfrastructure and data management tools, observational platform and sensor technology, two-way platform interrogation and data-transmission technologies, modeling frameworks, intercalibration experiments, and development of internationally agreed sampling standards and requirements of key variables. This paper presents a community statement on the major scientific and observational progress of the last decade, and importantly, an assessment of key priorities for the coming decade, toward achieving the SOOS vision and delivering essential data to all end-users.

Keywords: Southern Ocean, observations, modeling, ocean–climate interactions, ecosystem-based management, long-term monitoring, international coordination

IMPETUS AND PROGRESS TOWARD DEVELOPING A SOUTHERN OCEAN OBSERVING SYSTEM

The Southern Ocean has a profound influence on the Earth system (e.g., IPCC, 2013). It has wide-ranging climatic, ecological, and human impacts via its key role in the global circulation of heat, freshwater and nutrients, biogeochemical and carbon cycles, ocean productivity, and sea-level rise, as well as providing intrinsic value for conservation and management. Yet despite its importance, the Southern Ocean remains one of the most under-observed regions on Earth, leading to significant uncertainties in estimates of the future state of Southern Ocean processes and the consequences for the globe and its inhabitants (IPCC, 2013).

The Southern Ocean Observing System (SOOS) was established in 2011 as a partnership between the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR) to enhance delivery of the data required to reduce these uncertainties. This collaboration followed years of international discussions that were distilled and published in the OceanObs'09 White Papers (Rintoul et al., 2010), and then more comprehensively in the *Initial Science and Implementation Strategy* (Rintoul et al., 2012). Broad international involvement and enhanced coordination and collaboration were highlighted as key mechanisms to deliver integrated and sustained observations to all end-users. These

initial documents provided community-defined scientific drivers for SOOS and six Science Themes that are used to prioritize all subsequent SOOS efforts:

- (1) The role of the Southern Ocean in the planet's heat and freshwater balance.
- (2) The stability of the Southern Ocean overturning circulation.
- (3) The role of the ocean in the stability of the Antarctic Ice Sheet and its future contribution to sea-level rise.
- (4) The future and consequences of Southern Ocean carbon uptake.
- (5) The future of Antarctic sea ice.
- (6) Impacts of global change on Southern Ocean ecosystems.

The Vision

Southern Ocean Observing System involves many nations, significant resources, and multiple end-users, which makes its 20-year vision critical for enabling long-term strategic planning and preventing mission drift (Meredith et al., 2013). Although ambitious, the SOOS vision identifies the required networks and infrastructure to deliver a backbone of sustained, fundamental observations for use by a breadth of stakeholders across scientific, policy, and educational communities. It allows for inclusion of global initiatives that are advancing observing and data-acquisition technologies (e.g., the Digital Ocean initiative; Gysin, 2017). The long-term vision for SOOS (**Figure 1**) is

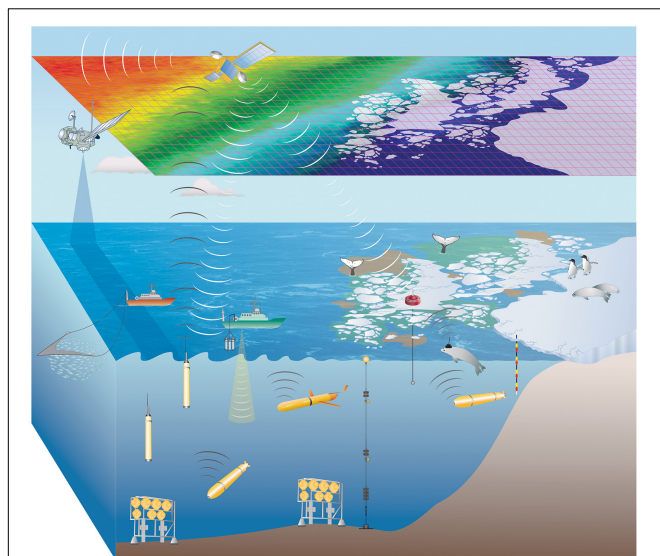


FIGURE 1 | Schematic of a cyberinfrastructure-based vision for SOOS (Meredith et al., 2013; reproduced with permission). Combined with satellite remote sensing, data from both autonomous and non-autonomous platforms would be relayed to ground stations in real time. Assimilating ocean models would produce near-real time state estimates of each of the parameters in the system and associated error fields would then be used to re-task the autonomous platforms in real time. This will maximize the spatial-temporal coverage of each of the parameters being measured, without specific need for human intervention.

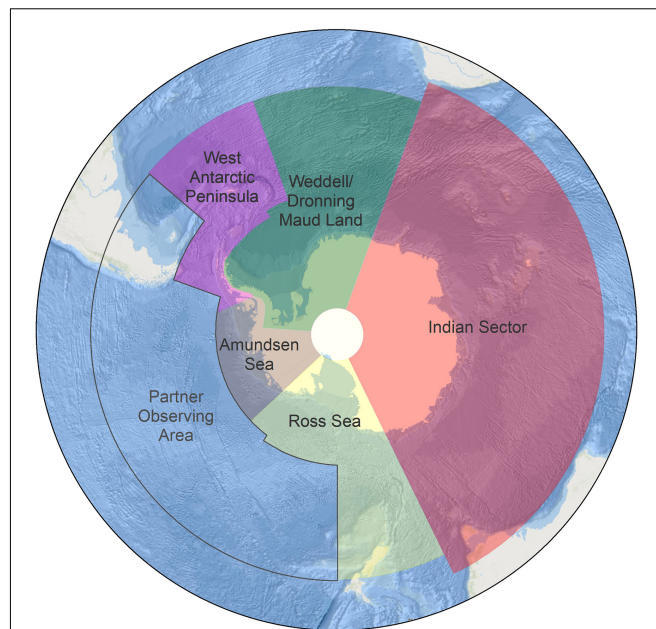


FIGURE 2 | Map of the five Regional Working Groups developed by SOOS to integrate the existing observational efforts in a region and facilitate efforts to address key gaps in observational coverage. The regions are based on the natural areas of focus for nations working in the Southern Ocean and facilitate regional coordination in (1) scientific information exchange, (2) technology transfer/collaboration, (3) standardization of measurements, and (4) sharing of data. The Partner Observing Area is a region not presently covered by a working group. In the interim, the SOOS Scientific Steering Committee will maintain oversight of the observational coverage of this region to ensure requirements are met. Base map data from ESRI, GARMIN, GEMCO, NOAA NGDC, and others.

to have a cyberinfrastructure-based program with increasing reliance on autonomous platforms as technology develops, as a means of readily delivering “essential” data to stakeholders, including in real time.

Achieving such a vision requires parallel advances in coordination networks, cyberinfrastructure and data management tools, observational platform and sensor technology, platform interrogation and data-transmission technologies, modeling frameworks, and internationally agreed sampling requirements of key variables. Toward this end, SOOS is working with the broader community to: develop regional networks for integration of international observational field activities (**Figure 2**); enhance observing capabilities (e.g., technology, methods)¹; build a robust data network that encompasses oceanographic and Antarctic expertise; deliver data discovery (**Figure 3**) and field coordination tools (**Figure 4**); facilitate advances in observing system design (section “Essential Ocean Variables and Observing System Design”); and collaborate with the global community to identify Essential Ocean Variables (EOVs) for the Southern Ocean, following the Framework for Ocean Observing (Lindstrom et al., 2012).

A Decade of Progress

Since 2009, the number of Southern Ocean observations collected has increased considerably, enabled by rapid progress

in the development, capability, and use of autonomous and robotic systems. SOOS has supported this progress by defining and promoting the vision around the systems that are needed, and also by endorsing and supporting the funding acquisition by various nations’ investigators [e.g., Research of Ocean-ice BOUNDry InTeraction and Change around Antarctica (ROBOTICA)², Japan; Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM)³, United States; Ocean Regulation of Climate by Heat and Carbon Sequestration and Transports (ORCHESTRA)⁴, United Kingdom; Research Center Dynamics of High Latitude Marine Ecosystems (IDEAL)⁵, Chile; Southern Ocean Seasonal Cycle Experiment (SOSCEX)⁶, South Africa; Marine Observatory in the Ross Sea (MORSea)⁷, Italy; Kerguelen Axis (K-Axis)⁸, Australia; Water-mass transformation and Pathways In The Weddell Sea

²<http://soos.aq/images/soos/downloads/endorsement/robotica-web.pdf>

³<https://socom.princeton.edu/>

⁴<https://www.bas.ac.uk/project/orchestra/>

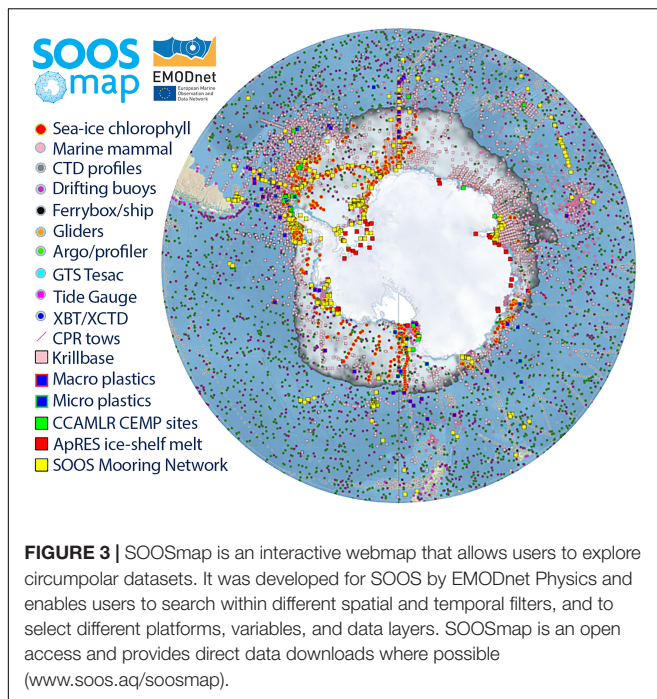
⁵<http://www.centroidideal.cl/antarctica/>

⁶<http://socco.org.za/research/>

⁷<http://morsea.uniparthenope.it/>

⁸<http://www.antarctica.gov.au/magazine/2011-2015/issue-29-december-2015/science/spotlight-on-the-k-axis>

¹More information on SOOS Capability Working Groups at <http://soos.aq/activities/capability-wgs>



(WAPITI)⁹, France; Polynyas, Ice Production, and seasonal Evolution in the Ross Sea (PIPERS)¹⁰, United States; Amundsen Sea Program¹¹, Korea; Dynamics of the Orkney Passage Outflow (DynOPO)¹², United Kingdom; Robotic Observations and Modelling in the Marginal Ice Zone (ROAM-MIZ)¹³, Sweden; and Investigation of Bottom Water Formation in Prydz Bay¹⁴, China]. In addition to these initiatives, sustained time-series programs are vital for revealing the ongoing change on decadal timescales; SOOS has supported the continuation of many of these, such as Rothera Time Series (RaTS, United Kingdom)¹⁵, Palmer Station Long-Term Ecological Research (LTER), United States¹⁶, Australia's Integrated Marine Observing System Southern Ocean Time Series (IMOS SOTS)¹⁷, and Potter Cove Time Series (Argentina/Germany)¹⁸, as well as internationally coordinated observing programs, such as Network for the Collection of Knowledge on Melt of Antarctic Ice Shelves: (UK-led international Southern Ocean program) (NECKLACE)¹⁹, OceanSITES²⁰, Argo²¹, Southern

Ocean Continuous Plankton Recorder program (SO-CPR)²², the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)²³, International Program for Antarctic Buoys (IPAB)²⁴ and Data Buoy Cooperation Panel (DBCP)²⁵, and Marine Mammals Exploring the Oceans Pole to Pole (MEOP)²⁶. Through the above-mentioned programs and many others, the international community has deployed more than 5700 observational platforms since 2009 (**Figure 3**; compared to approx. 3000 for the previous decade), significantly enhancing our understanding of the Southern Ocean and delivering essential data to core stakeholders.

The implementation of these programs over the last decade has enabled the community to make significant statements on the state of the Southern Ocean and how it is changing.

Themes 1 and 2: The Role of the Southern Ocean in the Planet's Heat and Freshwater Balance; And the Stability of the Southern Ocean Overturning Circulation

The Southern Ocean is warming faster than any other sector of the global ocean (Roemmich et al., 2015), accounting for 60–90% of the total modeled anthropogenic ocean heat uptake since the start of the industrial period (Frölicher et al., 2015). This warming is concentrated in the upper 2000 m north of the Sub-Antarctic Front (SAF) and is largely due to ongoing wind-driven thickening of the intermediate and mode-water layers and consequent deepening of isopycnals and consequent thickening of the intermediate and mode water layers (Desbruyeres et al., 2017; Gao et al., 2018). Observations and modeling efforts indicate that the prevailing westerly winds over the Southern Ocean have shifted poleward and strengthened, due to ozone depletion (Polvani et al., 2011) and CO₂ forcing (Bracegirdle et al., 2013). Despite this, no changes in the Antarctic Circumpolar Current (ACC) density structure (Böning et al., 2008) and lateral transport (Gille, 2014; Shao et al., 2015) have been definitively detected.

Increases in the westerly winds overlying the ACC are hypothesized to result in an increased net meridional overturning circulation (MOC) associated with enhanced poleward transport of heat by mesoscale eddies and a stronger equatorward return Ekman transport at the surface (Meredith et al., 2012; Gent, 2016). However, existing observations have not shown changes in the MOC, which is hard to explicitly observe due to the difficulty in resolving the small-scale but widely distributed contribution of eddies. Yet, satellite observations suggest that mesoscale eddy activity has increased with winds over recent decades (Hogg et al., 2015). Consistent with this increase, recent methods using indirect metrics, such as water mass age (Waugh et al., 2013; Waugh, 2014; Ting and Holzer, 2017), warming (Gille, 2008; Meijers et al., 2011), and circulation obtained using inverse methods (DeVries et al., 2017), are consistent with an increase in upwelling and overturning, although uncertainty is high.

⁹<http://wapiti-project.com/>

¹⁰<http://www.utsa.edu/signl/pipers/index.html>

¹¹<http://soos.aq/news/current-news/188-kopriamundsenproject>

¹²<https://www.bas.ac.uk/project/dynamics-of-the-orkney-passage-outflow/>

¹³<http://soos.aq/images/soos/downloads/endorsement/floating-glaciars.pdf>

¹⁴<https://www.ldeo.columbia.edu/~xyuan/Prydz/index.html>

¹⁵<https://www.bas.ac.uk/project/rats/>

¹⁶<http://pal.lternet.edu/>

¹⁷<http://imos.org.au/facilities/deepwatermoorings/sots/>

¹⁸<https://www.st.nmfs.noaa.gov/copepod/time-series/de-30401/>

¹⁹<http://www.soos.aq/activities/soos-at-sea/necklace>

²⁰A worldwide system of deepwater reference stations, <http://www.oceansites.org/index.html>

²¹A global array of free-drifting profiling floats, <http://www.argo.ucsd.edu/>

²²<https://data.aad.gov.au/aadc/cpr/>

²³<http://www.go-ship.org/>

²⁴<http://www.ipab.aq/>

²⁵<http://www.jcommops.org/dbcp/>

²⁶<http://www.meop.net/>

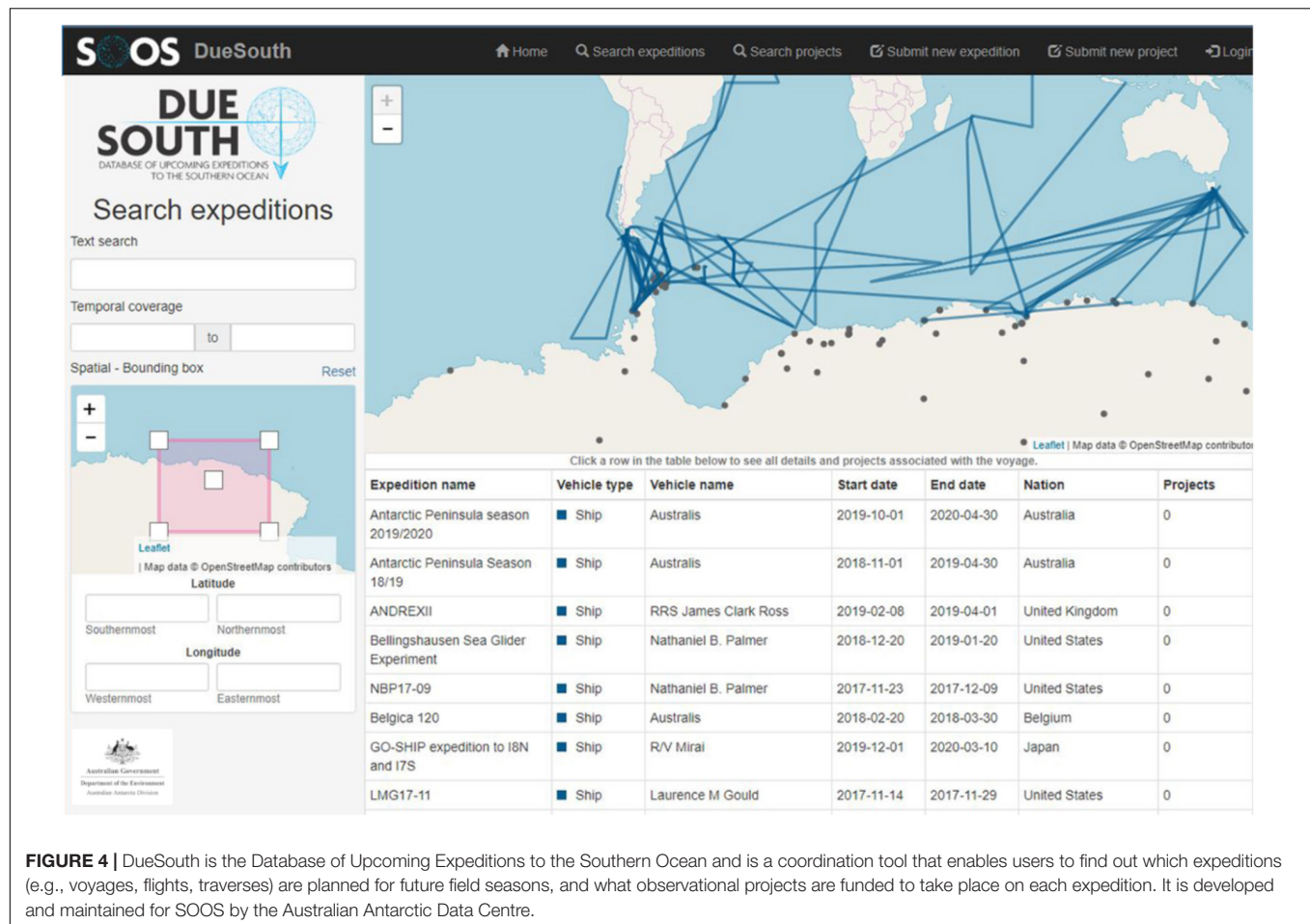


FIGURE 4 | DueSouth is the Database of Upcoming Expeditions to the Southern Ocean and is a coordination tool that enables users to find out which expeditions (e.g., voyages, flights, traverses) are planned for future field seasons, and what observational projects are funded to take place on each expedition. It is developed and maintained for SOOS by the Australian Antarctic Data Centre.

While the waters north of the SAF have warmed significantly, the sea-surface waters south of the ACC core and Polar Front have changed less than the global sea-surface temperature trend ($0.02^{\circ}\text{C}/\text{decade}$ cf. $0.08^{\circ}\text{C}/\text{decade}$ since 1950). This north-south temperature trend contrast reflects the continual renewal of the surface waters south of the Polar Front from below by old Circumpolar Deep Water (CDW) that has yet been largely unmodified by anthropogenic influences (Armour et al., 2016). This demonstrates that Southern Ocean circulation has a major impact on the distribution of climate change signals. Warming closer to the continent, notably in the Amundsen-Bellingshausen seas, has been observed on decadal timescales (Schmidtke et al., 2014) and has been linked to wind-driven increases in warm CDW upwelling onto the continental shelf (Jenkins et al., 2010). This has significant consequences for sea-level rise via accelerated ice-shelf melt but remains poorly observed and understood.

The Southern Ocean is also freshening (Durack and Wijffels, 2010), particularly in the upper layers and near Antarctica itself (Jacobs and Giulivi, 2010; Schmidtke et al., 2014). This has been attributed to an increase in precipitation (Helm et al., 2010), increased basal melting of ice shelves (Paolo et al., 2015), and enhanced sea-ice melt and export (Haumann et al., 2016), though the relative contribution of these processes is highly

uncertain. The bottom waters that are formed in coastal regions and exported to the global ocean are becoming warmer (Purkey and Johnson, 2010, 2013), fresher (Rintoul, 2007; Jullion et al., 2013; Menezes et al., 2017), and decreasing in volume (Purkey and Johnson, 2012, 2013), although these bottom waters remain sparsely sampled. Recent model experiments suggest that the observed warming and freshening are inconsistent with natural variability, and require increased surface fluxes of heat and freshwater that are driven by greenhouse gas forcing, and to a lesser extent, ozone depletion (Swart et al., 2018).

Theme 3: The Role of the Ocean in the Stability of the Antarctic Ice Sheet and Its Future Contribution to Sea-Level Rise

The Antarctic Ice Sheet is the greatest source of uncertainty in projections of future sea level (IPCC, 2013), with estimates ranging from zero to a catastrophic $5\text{ cm}/\text{year}$ (IPCC, 2013; Bakker et al., 2017; Shepherd et al., 2018). Observations and modeling during the last decade indicate increased ice-shelf basal melt through contact with warm, salty deep water (Rignot et al., 2013; Paolo et al., 2015). This thinning is accelerating (Paolo et al., 2015), threatening the West Antarctic Ice Shelf (WAIS) in particular, although recent research suggests more of the East Antarctic Ice Sheet is marine-based (i.e., its base lies below

sea level) than previously thought, earning itself the title of a “sleeping giant” in future global sea-level projections (Gulick et al., 2017; Rintoul et al., 2018). A full collapse of the WAIS would result in 3–4 m of sea-level rise over timescales estimated to be from many decades to centuries (DeConto and Pollard, 2016).

Although the largest ice shelves (Ross, Filchner-Ronne, and Amery) have remained within their observed historical ranges, many smaller ice shelves have thinned, decreased in extent or disintegrated, leading to increased rates of discharge of grounded inland ice to the ocean. Large changes have occurred in the Amundsen Sea Embayment, where warm salty deep water intrudes on the continental shelf (Pritchard et al., 2012; Shepherd et al., 2018). The five largest ice shelves in this region have lost between 10 and 18% of their volume (Paolo et al., 2015). The basal melt appears to co-oscillate with ENSO (Paolo et al., 2018). Ice shelves also decline through calving-front retreat, especially on the West Antarctic Peninsula (WAP) (Shepherd et al., 2010), where a number of ice shelves have disintegrated including Larsen-A and -B (Scambos et al., 2004) and Wilkins (Humbert and Braun, 2008).

Recent observations indicate that other parts of the Antarctic Ice Sheet are equally vulnerable, such as the Filchner-Ronne Ice Shelf (Hellmer et al., 2012; Darelus et al., 2016). In East Antarctica, warm water has been found beneath the Amery Ice Shelf (Herraiz-Borreguero et al., 2015), and on the shelf that accesses the ice-shelf cavity of the rapidly melting Totten Glacier (Greenbaum et al., 2015; Rintoul et al., 2016).

Theme 4: The Future and Consequences of Southern Ocean Carbon Uptake

The Southern Ocean is Earth's largest CO₂ sink (Sabine et al., 2004; Sallée et al., 2012); however, the magnitude of air-sea exchange appears extremely variable on short timescales. Data and model simulations suggest that the Southern Ocean CO₂ sink weakened between 1980 and the early 2000s, possibly due to changes in the Southern Hemisphere westerlies driving enhanced upwelling of CO₂-rich waters (Le Quéré et al., 2007). Analysis of multidecadal sea-surface pCO₂ [Surface Ocean CO₂ Atlas (SOCAT); Bakker et al., 2014] showed a reversal of this trend in 2002, with the Southern Ocean CO₂ sink apparently regaining its expected strength by 2012 (Landschützer et al., 2015).

Much uncertainty remains regarding the Southern Ocean's role in global carbon cycling due largely to data gaps, particularly in non-summer seasons and coastal regions (Takahashi et al., 2009). For example, recent profiling float measurements suggest significantly higher wintertime outgassing of CO₂ in the Antarctic Zone than previously estimated (Gray et al., 2018), which, if confirmed, imply a significantly weaker Southern Ocean CO₂ sink. Sea ice has been suggested to affect the Southern Ocean CO₂ sink (Delille et al., 2014), yet its role in air-sea CO₂ fluxes is not clear. Likewise, the role of (sub)mesoscale features (e.g., eddies) is under debate (Dufour et al., 2015; Li et al., 2017; Moreau et al., 2017). Further, CMIP5 Earth system models do not agree on the amplitude or sign of the Southern Ocean air-sea CO₂ fluxes (Anav et al., 2013).

Estimating Southern Ocean annual net community production (ANCP) is important for understanding the

role of the biological pump in sequestering anthropogenic CO₂ (Nevison et al., 2012). Previous ANCP estimates (Lee, 2001; MacCready and Quay, 2001; Dunne et al., 2007) provide no information on seasonal or interannual variability, yielding an incomplete picture of Southern Ocean's CO₂ drawdown. Estimates of ANCP from profiling floats²⁷ agree well with existing estimates for all biogeochemical zones of the Southern Ocean (Johnson et al., 2017b), and indicate that ANCP south of the “biogeochemical divide” (~50°S) (Marinov et al., 2006) removes dissolved inorganic carbon (DIC) from surface water to the deep ocean where it remains sequestered for long periods of time; changes in ANCP in this region can thus drive significant changes in atmospheric CO₂ concentrations.

Antarctic coastal regions, such as the WAP, are highly productive yet spatially and temporally variable. Long-term, multi-national observations have revealed the interconnectivity of climate oscillations and physical forcing mechanisms (wind-stress, temperature) in controlling WAP seasonal sea-ice coverage, seasonality, and properties (Stammerjohn et al., 2008; Meredith et al., 2017), which influence primary production, macronutrients, trace-metal cycling, and carbonate chemistry across the shelf (Venables et al., 2013; Hauri et al., 2015; Henley et al., 2017). More localized processes also impact nutrient and carbon cycling, including channeling of nutrient-rich deep-water by glacial troughs (Schofield et al., 2013), glacial meltwater influence on productivity (Kim et al., 2018), oceanic stratification and mixing (Cassarino et al., 2016), and exchange with shallow marine sediments (Henley et al., 2018; Sherrell et al., 2018). Sustained and multi-disciplinary research along the WAP and in other high-productivity coastal regions is necessary to fully understand the processes driving biogeochemical “patchiness” and the impact of longer-term climate forcing. Such research should include process-based and experimental studies for a better mechanistic understanding of nutrient cycling, e.g., the role of sediment fluxes and sea-ice formation.

Considerable progress has been made since Rintoul et al. (2012) outlined the need for new technologies for biogeochemistry and biology. Biogeochemical sensors deployed on SOCCOM and Southern Ocean and Climate (SOCLIM)²⁸ floats are beginning to address this need, measuring chlorophyll-a, nitrate, oxygen, light, optical properties, and pH. Air-sea CO₂ fluxes, ANCP, mesopelagic respiration, and particulate organic carbon export can now be estimated on seasonal to interannual scales, and around the Antarctic (Hennon et al., 2016; Johnson et al., 2017b; Poteau et al., 2017; Williams et al., 2017; Llort et al., 2018). Gliders are yielding seasonal, sub-seasonal, and sub-mesoscale information (Kaufman et al., 2014), and ice-capable bio-Argo floats can monitor biogeochemical cycles during ice-covered periods, increasing the temporal and spatial range of the available data (Briggs et al., 2017). Additionally, phytoplankton fluorescence sensors deployed on marine mammals provide winter data from otherwise-inaccessible coastal regions (Labrousse et al., 2018).

²⁷SOCCOM Project: <https://soccom.princeton.edu/>

²⁸SOCLIM field studies with innovative tools: <http://soclim.com/index.php>

Theme 5: The Future of Antarctic Sea Ice

Sea ice influences surface albedo and oceanic overturning circulation; affects stratification and properties of upper ocean; regulates heat, momentum, and gas transfer between the ocean and atmosphere; protects and stabilizes certain ice shelves (Massom et al., 2018); provides an important habitat for ice-associated species (Thomas, 2017); and has a major impact on safe shipping and operations. Antarctic sea ice exhibits substantial spatio-temporal variability (Stammerjohn and Maksym, 2016), principally driven by wind and modulated by ocean feedbacks (e.g., Goosse and Zunz, 2014; Holland et al., 2014). Between 1979 and 2014, the circum-Antarctic annual maximum sea-ice extent increased slightly, as a result of larger and opposing regional trends (Hobbs et al., 2016; Stammerjohn and Maksym, 2016). While sea-ice variability is strongly linked to large-scale modes of atmospheric variability, these links vary regionally and seasonally, and do not fully explain observed trends (Hobbs et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2017). Moreover, Antarctic sea ice has undergone recent strong variability that is poorly understood (Turner and Comiso, 2017) – fluctuating from record maxima in overall extent in 2012–2014, to unprecedented minima from 2016 until present (early 2019).

While sea-ice extent and concentration have been quantified to reasonable accuracy from space since 1979, more robust statements on the nature of sea-ice changes and their drivers (including their regional and seasonal dependence) are impeded by a lack of observations and process understanding. Atmosphere and ocean forcing are poorly observed and understood; sea-ice thickness (and volume) are poorly known, as is the distribution of snow-cover depth (Sturm and Massom, 2017; Webster et al., 2018); and surface flooding and resultant snow-ice formation are poorly quantified (Maksym et al., 2012). Sea-ice observations from ship-based underway observations²⁹ have provided a climatology for ice thickness and snow depth (Worby et al., 2008), but are biased to thinner sea ice (Williams et al., 2015) and are limited in space and time. Space-borne laser and radar altimetry are the key to large-scale monitoring of sea-ice thickness (Zwally et al., 2008; Kurtz and Markus, 2012; Ozsoy-Cicek et al., 2013; Kern et al., 2016), yet uncertainties (chiefly in snow depth and ice- and snow densities) are currently too large to derive reliable circum-Antarctic sea-ice thickness estimates (Giles et al., 2008; Schwegmann et al., 2016; Paul et al., 2018). Sea-ice motion and deformation determine ice production, thickness, and the transport of freshwater, but satellite products have insufficient accuracy, consistency, duration and/or spatial and temporal resolution to provide accurate long-term drift trends or large-scale ice deformation fields (Schwegmann et al., 2011; Holland and Kwok, 2012; Haumann et al., 2016; Spreen et al., 2017). Drifting sea-ice buoys can provide key information on both the seasonal evolution of the ice and snow-cover thicknesses (e.g., Maksym et al., 2012) and high-resolution observations of ice drift and deformation (e.g., Heil et al., 2008, 2016), but deployments are limited. Coastal polynyas play an important though regionally

dependent role in Antarctic sea-ice formation (Drucker et al., 2011; Tamura et al., 2016) and are closely coupled to fast ice (Nihashi and Ohshima, 2015).

Theme 6: Impacts of Global Change on Southern Ocean Ecosystems

The Southern Ocean, with its sea-ice cover, modulates nearly all ecosystems and life in Antarctica. While birds and some mammals breed on land, they all feed in the ocean. Changing air temperatures, wind patterns, sea ice, ocean frontal areas, and water-mass circulation therefore have profound and regionally specific effects on biota, impacting the adaptation capacity and survival of individual species, and promoting cascading effects throughout the ecosystem (Murphy et al., 2012; Constable et al., 2014, 2016; Gutt et al., 2015, 2017).

At the base of the food web, trends in phytoplankton differ among areas and latitudes. Kim et al. (2018) showed that while phytoplankton increased in the northern WAP, around Carlini Station (Potter Cove) in the South Shetlands (Schloss et al., 2014) and near Palmer Station, they decreased further south due to the differential impact of ENSO and the Southern Annular Mode on spring phytoplankton. This suggests important localized forcings. Similar comparative studies are not available for other areas of the Southern Ocean, which are differentially affected by sea ice, glacial meltwater (Hernando et al., 2015), iron availability, and other stressors such as CO₂ increase and the consequent ocean acidification (Hoppe et al., 2013; Trimborn et al., 2013, 2017; Hancock et al., 2018). Other than phytoplankton, bulk community composition and a deeper understanding of the microbial realm, including bacteria, archaea, and viruses, and the role of recalcitrant dissolved organic matter (microbial carbon pump, Jiao et al., 2010) are essential to the food-web carbon flux as well as to the ocean–carbon pump and CO₂ sequestration.

For first-order phytoplankton consumers, zooplankton, and micronekton (those organisms in the size range between zooplankton and higher predators – notably krill, and small mid-water fishes and squids), accurate biomass estimations remain a major challenge. A recent modeling effort (Klein et al., 2018) forecasted that a reduction in krill growth rate due to warming will propagate to the dependent predators (penguins, seals, whales, and fishes). The biomass of mid-water (mesopelagic) fishes and squids, how they will respond to climate change, and implications for higher trophic levels are increasingly recognized as gaps in our understanding of ocean ecosystems globally (St. John et al., 2016), and the Southern Ocean is no exception (Murphy et al., 2012).

Top predators are excellent sentinels of change, as their species composition, demography, behavior, and diet reflect the community structure (Constable et al., 2014, 2016). Climate-linked oceanographic features determine the distribution and abundance of their prey (reviewed in De Broyer et al., 2014), which affects foraging success, juvenile recruitment, breeding phenology, growth rates, and population stability (e.g., Ducklow et al., 2013; Hinke et al., 2017b). As ecosystems change, there will be both winners and losers (Costa et al., 2010; Melbourne-Thomas et al., 2013; Clucas et al., 2014; Constable et al., 2014). For example, while some Adélie and chinstrap penguin

²⁹Coordinated through the SCAR program “Antarctic Sea Ice Processes and Climate,” <http://aspect.antarctica.gov.au/>

populations have plummeted, gentoo penguin colonies have increased (Trivelpiece et al., 2011; Ducklow et al., 2013; Hinke et al., 2017b). Similarly, while Weddell seals near Palmer Station have declined, Antarctic fur seal and southern elephant seals have increased (Siniff et al., 2008). The increased intensity of winds has allowed wandering albatross to forage farther and faster, making their foraging trips shorter and increasing their foraging efficiency and breeding success (Weimerskirch et al., 2012). The foraging behavior and demographics of Antarctic fur seals and penguins have been monitored by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) as part of the management of krill fisheries. CCAMLR have produced long-term time series that can be used as an important baseline for future comparison (Trivelpiece et al., 2011; Ducklow et al., 2013; Hinke et al., 2017a,b).

The combined implications of changes across multiple trophic levels for the structure and function of Southern Ocean ecosystems are not well understood, and will require coordinated observations and modeling to resolve (see the sections “Assessing Status and Trends of Key Southern Ocean Taxa” and “Southern Ocean Modelling progress and priorities”).

DRIVERS OF THE FUTURE DEVELOPMENT OF SOOS

The next 10 years will see a step-change in the delivery of integrated, multidisciplinary Southern Ocean data. The SOOS Regional Working Groups and other networks developed over the last few years will become well-established, and will work with the community to design regional observing systems to collect sustained data and deliver them to all end-users. Importantly, the systems designed will need to be flexible, to take advantage of sensor and platform developments, new networks, funding or infrastructures, and to ensure continued impact of the data in addressing the most pressing issues for society. Toward this end, regular community review and updating of the scientific drivers of the observing system will be essential.

Southern Ocean Observations: Future Priorities

The SOOS Science Themes have provided clear focus for SOOS's activities over the last decade, and in many instances, remain priorities for the coming decade of observations. Taking into account the progress of the community in delivering knowledge relevant to those themes (sections “Themes 1 and 2: The Role of the Southern Ocean in the Planet's Heat and Freshwater Balance; and the Stability of the Southern Ocean Overturning Circulation,” “Theme 3: The Role of the Ocean in the Stability of the Antarctic Ice Sheet and Its Future Contribution to Sea-Level Rise,” “Theme 4: The Future and Consequences of Southern Ocean Carbon Uptake,” “Theme 5: The Future of Antarctic Sea Ice,” and “Theme 6: Impacts of Global Change on Southern Ocean Ecosystems”), the Southern Ocean community has identified eight key issues of focus for the coming decade. These issues are identified as major data bottlenecks in addressing the six themes, and are introduced in the following sections.

Observing Antarctic Bottom Water Production Processes

Conspicuous signals of climate change have been observed in Antarctic Bottom Water (AABW) including warming (Purkey and Johnson, 2010; Couldrey et al., 2013), freshening (Purkey and Johnson, 2013), and a reduction in volume (Purkey and Johnson, 2012). It is tempting to associate these changes with the observed freshening and warming over the continental shelves surrounding Antarctica (Schmidtke et al., 2014); however, our knowledge of the physical processes linking these changes is limited (e.g., van Wijk and Rintoul, 2014). *In situ* observations to describe and understand the processes involving forcings from the atmosphere and ice (both land-based and floating) and AABW are needed. New technologies are improving our knowledge of such physical processes, including animal-borne sensors, under-ice autonomous floats, microscale sensors attached to Conductivity, Temperature, Depth profiler (CTD), and more are becoming available such as under-ice autonomous underwater vehicles (AUV), remotely operated vehicles (ROVs), and gliders. **Figure 5** shows the observing system required to observe these production processes.

These processes involve large-scale physics to meso- and submeso-scale physics (e.g., Stewart and Thompson, 2014) with complicating factors such as the Antarctic Slope Current, patchy bathymetric data coverage, tides, and sea-ice variability. Diapycnal mixing is a key quantity, but knowledge of its spatial and temporal distribution is lacking, except for a limited number of field campaigns (Gille et al., 2007; Meyer et al., 2015). Observed mixing is yet to be attributed to generation mechanisms (e.g., current/topography interactions; Nikurashin and Ferrari, 2011). Earth system models poorly resolve Southern Ocean water-mass behaviors, including AABW formation, often leading to unphysical deep open-ocean convection (Heuzé et al., 2013) or large spread in an ensemble (Meijers et al., 2012). Observations of AABW, along with meso- and submeso-scale processes, are needed for better parameterization of water-mass transformation (see the section “Ecosystem Modeling Efforts”). The observation should cover air-sea and sea-ice fluxes for buoyancy transformation driving AABW formation (see the next section).

Reducing Uncertainties in Air-Sea and Air-Ocean-Ice Fluxes of Heat, Momentum, Freshwater, and Carbon

Southern Ocean *in situ* air-sea and air-sea-ice flux observations are rare (Bourassa et al., 2013), with almost no observations in autumn or winter (Gille et al., 2016; Swart et al., 2019) or in the sea-ice zone. Reanalyses and satellite-derived surface flux products therefore have major errors and vary considerably (Josey et al., 2013; Bentamy et al., 2017; Schmidt et al., 2017).

In 2015, the SOOS community identified fluxes as a priority observation gap, resulting in the development of the SOOS Southern Ocean Air-Sea Flux (SOFLUX³⁰) Working Group. SOFLUX has identified priorities for the coming decade, which are articulated in Swart et al. (2019). Specifically, SOFLUX noted that the climate-scale net air-sea heat flux of 0.6 W m^{-2} is

³⁰<http://soos.aq/activities/capability-wgs/soflux>

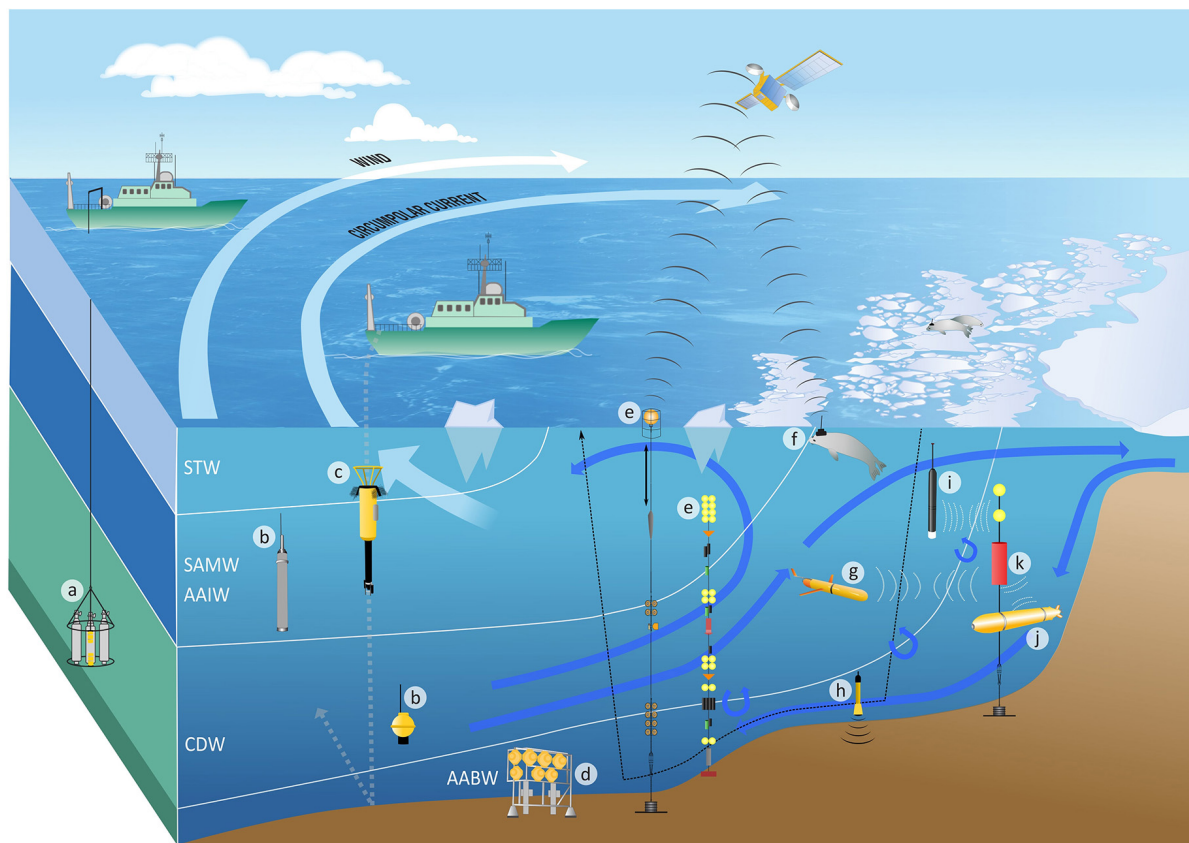


FIGURE 5 | A schematic of the observational platforms required to observe the AABW formation. **(a)** Conductivity–temperature–depth profiler often equipped with additional sensors such as dissolved oxygen, horizontal velocity (lowered ADCP – yellow cylinders), and temperature turbulence; **(b)** Argo profiler, both on core mission (depth < 2000 m) and deep mission (deeper); **(c)** microstructure profiler measuring energy and material dissipation rate; **(d)** bottom lander with a suite of instruments including water sample; **(e)** mooring system with physical (temperature, salinity, velocity) and biogeochemical (sediment trap, etc.) measurements, some with an underwater winch-driven surface buoy for ice avoidance; **(f)** animal tagged profiler; **(g)** glider; **(h)** bottom drifter, a float specially targeting AABW; **(i)** under-ice Argo profiler with acoustic locating capability; **(j)** autonomous underwater vehicle; and **(k)** a sound source for acoustic float locating. Modified from Meredith et al. (2013).

determined from Argo float measurements of ocean-heat content and not from direct flux measurements, and while the Argo-based level of accuracy is not expected, direct observations will provide validation for products based on remote sensing and reanalyses. Additionally, direct flux measurements provide process-level understanding, particularly intraseasonal variations associated with oceanic eddies and fronts or with the passage of atmospheric storms. This justifies targeted process studies aimed at measuring flux differences over the scale of the first baroclinic Rossby radius (e.g., 50 km or less).

The key priority for the coming decade is to obtain more *in situ* observations, particularly in winter. A significant increase in observations would occur if all Southern Ocean vessels were instrumented with a standard meteorological package (e.g., IMET system), and a thermosalinograph to provide the key variables needed for air-sea flux bulk formulae (i.e., air-sea temperature differences, wind speed, and humidity). Vessel flow-distortion calculations done prior to installation are needed for optimizing sensor locations to minimize airflow disruption, or to account for these errors. Wave gliders, saildrones, and

surface-flux moorings offer the possibility of year-round air-sea flux observations, but can be prone to potentially greater logistical and/or power challenges. Moored buoy flux observations are valuable for investigating temporal variability in air-sea fluxes, but they have only been deployed in two locations in the Southern Ocean (Schulz et al., 2012; Ogle et al., 2018). **Figure 6** represents this proposed optimal observing system, and further recommendations on priority flux observations can be found in Swart et al. (2019).

Understanding the Contribution of Oceanic Heat to Ice-Shelf Basal Melt

Drivers of ice-shelf melt are poorly understood (Kennicutt et al., 2014a). Transport of warm oceanic water to the ice-shelf front and base, and the importance of different processes and pathways (i.e., eddies, tides, winds, variability, and intensity of the Antarctic Slope Current and topography) need to be evaluated. Long time-series (> 10 years) of temperature, salinity, and current velocities are required in key locations near ice shelves, such as those shown in **Figure 7**. A number of locations in the Weddell and Amundsen

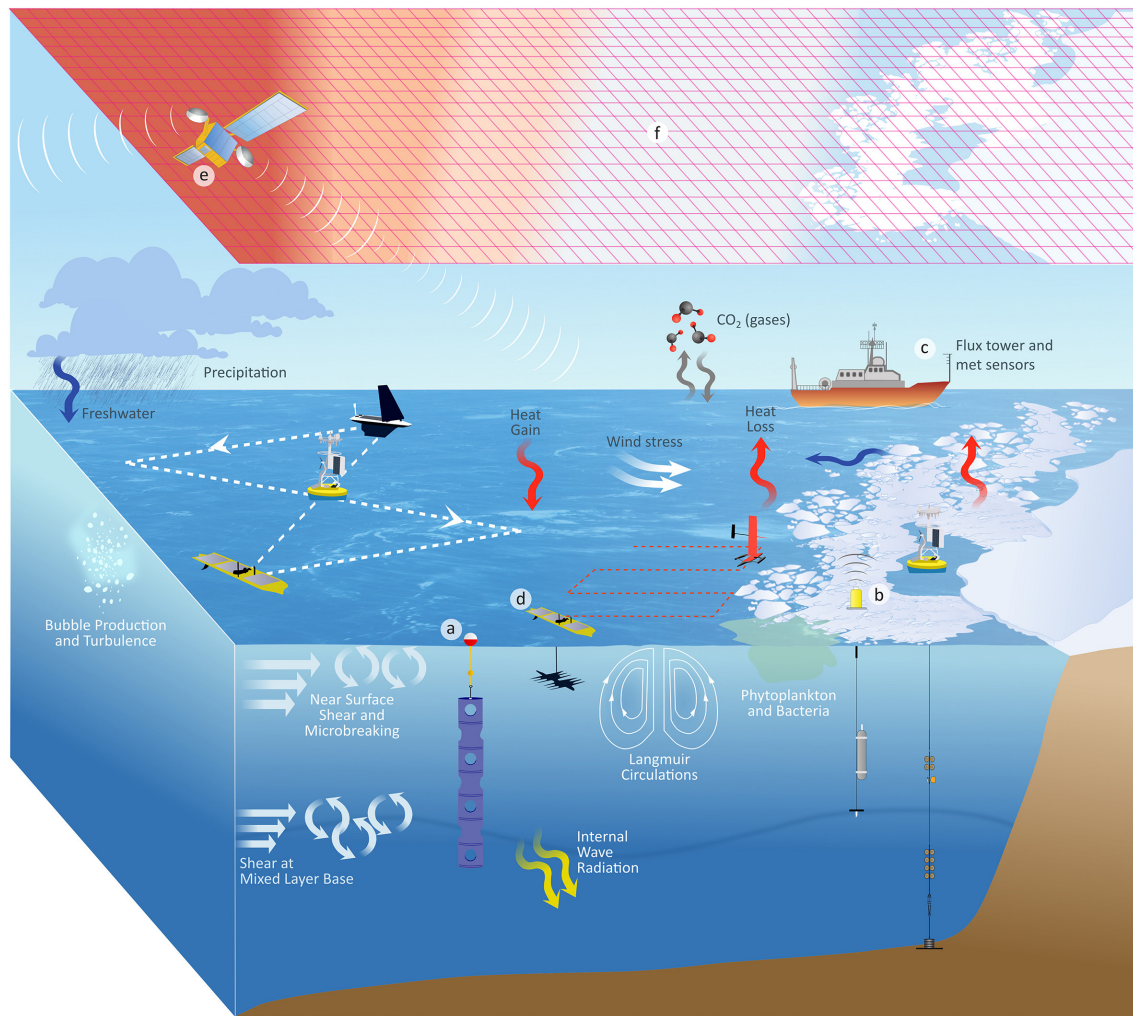


FIGURE 6 | Schematic of the key elements of a Southern Ocean air-sea flux observing system in order to reduce uncertainties in air-sea and air-sea-ice fluxes of heat, momentum, freshwater, and carbon (section “Reducing Uncertainties in Air-Sea and Air-Sea-Ice Fluxes of Heat, Momentum, Freshwater, and Carbon”). The optimal observing system would include buoys **(a)** in the open ocean, and ice-tethered profilers **(b)** in the marginal ice zone, as well as ships instrumented with flux covariance systems **(c)**. Autonomous surface systems **(d)** such as wave gliders and saildrones are proposed to provide a more extensive spatial network of flux sensors than enabled by ships and buoys alone and also for targeted process studies aimed at understanding air-sea flux variability across fronts or eddies, possibly surveying in the vicinity of a buoy. Satellite measurements **(e)** of surface wind, SST, and near surface variables provide global measurements that can fill spatial gaps between *in situ* observations. The grid overlaying the entire domain **(f)** is intended to indicate the role of assimilating models, such as reanalyses, in ingesting all available observations to provide a consistent gridded flux product. Modified from Meredith et al. (2013).

Seas and off East Antarctica have maintained mooring sites on the open shelf and through the ice shelf that have the potential to achieve important, long time series if they are sustained over the next decade.

Increased use of Autonomous Phase Sensitive Radars (ApRES; Nicholls et al., 2015) through the NECKLACE initiative will provide direct observations of the basal melt rate and help validate basal melt rates inferred from satellite observations. Gliders and floats with under-ice capabilities, together with AUV missions, have enabled measures of sub-ice shelf ocean circulation, processes controlling the ocean interaction with the ice shelf base, and exchange processes across the ice-shelf front that we

are currently lacking (e.g., Miles et al., 2015). Improvements in under-ice navigation/geolocation will lead to a rapid transition from pilot projects to large-scale arrays and longer duration missions.

To constrain numerical ocean and ice-sheet models, high resolution bathymetry on the continental shelves and within ice-shelf cavities, observations of ice-shelf draft, basal topography and roughness, and ocean observations that resolve the seasonal and intra-annual water mass and current variability are required. Increased use of autonomous technologies, long-range missions, improved under-ice navigation, and satellite transmission of the data will decrease the effort and cost involved in monitoring the transport of ocean heat toward the ice shelf bases.

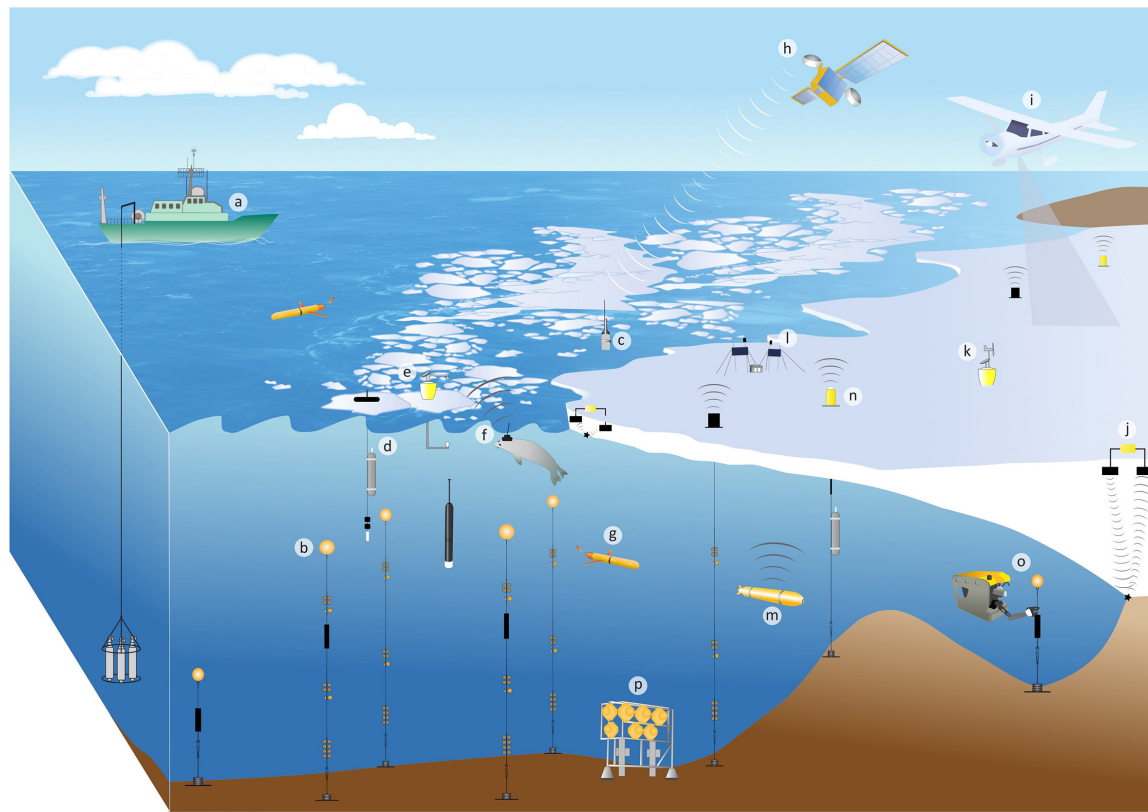


FIGURE 7 | A schematic of the integrated system of observational platforms required to determine the contribution of oceanic heat to ice-shelf melt for a generic ice-shelf configuration. An integrated system to observe the processes important for grounding line retreat and basal melt consists of three main components. Firstly, observing how ocean currents approach and exit the ice shelf cavity, achieved by a combination of ship-based observations, such as hydrographic sections (**a**); moored instrumentation (**b**) deployed in key locations across the front of the ice shelf (e.g., polynyas, dense overflows); ice-capable profiling floats (**c**); ice-tethered profilers (**d**) and ice-mass buoys (**e**) particularly in fast- or multi-year ice; seal tags (**f**); and gliders (**g**) for high-resolution transects on the shelf and slope. Secondly, determining changes in ice-shelf thickness, basal melt-rate, and grounding-line retreat, achieved by deployment of satellite (**h**) and airborne (**i**) remote sensing for ice shelf properties; ApRES radars (**j**) for direct basal-melt rates; automatic weather stations (**k**), GPS, boreholes, and other sensors (**l**) for other properties, such as snow accumulation. Finally, observation of processes within the ice-shelf cavity itself requires AUVs (**m**) for observations of water properties, as well as swath mapping of sea floor and sub-ice shelf topography; sensors/moorings deployed through boreholes (**n**) for sub-ice shelf properties, circulation, and direct basal melt data, including mooring with ITPs and telemetry; moorings deployed by ROVs in ice shelf cavity (**o**), which is not currently implemented but is a promising technological advance in the coming decade; and bottom landers (**p**) out the front of the ice shelf for a multitude of roles, such as communication gateways, imaging, water sampling, etc. This figure was modified from Meredith et al. (2013) and Rintoul et al. (2014) “seeing below the ice” 2014 strategy available at <http://soos.aq/resources/science-strategies?view=product&pid=26>.

Figure 7 schematically represents the integrated observing system required to understand and constrain ice-shelf basal melt.

The Partnership for Observation of the Global Oceans (POGO) has supported a SOOS working group Observing and Understanding the ocean below Antarctic Sea Ice and Ice Shelves (OASIIS³¹) to focus the international effort to enhance sustained observations of the ocean near and under major ice shelves. This group will make an important contribution to addressing the above-mentioned data gaps.

Toward a Better Understanding of Processes Controlling Antarctic Sea-Ice Variability and Change

Although climate models include sea-ice components, they exhibit low skill in simulating observed Antarctic sea-ice

properties and their spatio-temporal variability, i.e., seasonality, extent, concentration, and thickness (Shu et al., 2015; National Academies of Sciences, Engineering, and Medicine, 2017; Roach et al., 2018). This is due to a combination of poor process understanding and sub-optimal parameterization of the ice- and snow physics and embedded ecosystems, for example, the representation of ocean-ice-atmosphere interactions and feedbacks (Stammerjohn et al., 2012; Goose and Zunz, 2014; Holland et al., 2014, 2017; National Academies of Sciences, Engineering, and Medicine, 2017). In turn, this severely undermines confidence in model projections of future sea-ice cover and conditions around Antarctica (IPCC, 2013). Key observations and processes requiring attention include coupled ice-ocean processes driving short-term and seasonal advance and retreat (including wave-ice interaction in the marginal ice zone); the relative role of dynamic and thermodynamic processes in

³¹<http://soos.aq/activities/capability-wgs/oasiis>

driving the ice-thickness evolution; the thickness distribution of Antarctic sea ice and its snow cover; effect of snow processes on sea-ice properties and ice-mass balance; the role of polynyas as regional sea-ice “factories”; and pack-ice – fast-ice – ice-sheet interactions (**Figure 8**).

Of high priority are gap-filling, multi-disciplinary *in situ* experiments [e.g., in style of Antarctic Remote Ice Sensing Experiment (ARISE)³², Ice Station POLarstern (ISPOL)³³, PIPERS (see text footnote 10)] in combination with well-distributed but sustained monitoring programs [e.g., Antarctic Fast-Ice Network (AFIN)³⁴] to capture and resolve sea-ice characteristics, processes, and interactions at sufficient spatio-temporal scales to enable comparison with (and thus improvement of) model parameterizations, as well as

satellite-derived estimates. Such an approach is required to improve quantification and understanding of, for example, ice deformation and ice production; snow accumulation and distribution; autumn–winter ice formation and ice-edge advance, and spring–summer ice break-up and ice-edge retreat; and large-scale characterization of the sea ice. Autonomous technologies [e.g., long-range AUV and Unmanned Aerial Vehicles (UAVs)] have a crucial role to play in bridging the scale gap between floes [of the order of (1–100) m] and regional-scale satellite products and models [typical resolution (1–25) km], supplemented by (i) sophisticated mass-balance buoys that measure the evolution and drift of the coupled ocean-ice-snow-atmosphere system, and (ii) routine underway observations from instrumented icebreakers to measure snow- and ice thickness, floe-size distribution, and more. Around coastal Antarctica, the more stable fast-ice environment lends itself to sustained and internationally coordinated long-term observations at AFIN stations (Heil et al., 2011), which, together with supporting atmospheric and oceanographic data, may contribute to the WMO-endorsed

³²<http://www.antarctica.gov.au/science/cool-science/2007/antarctic-remote-ice-sensing-experiment>

³³<https://www.awi.de/ueber-uns/service/presse-detailansicht/presse/forschungsseisbrecher-polarstern-driftet-im-antarktischen-eis.html>

³⁴seaice.acecrc.org.au/afin/

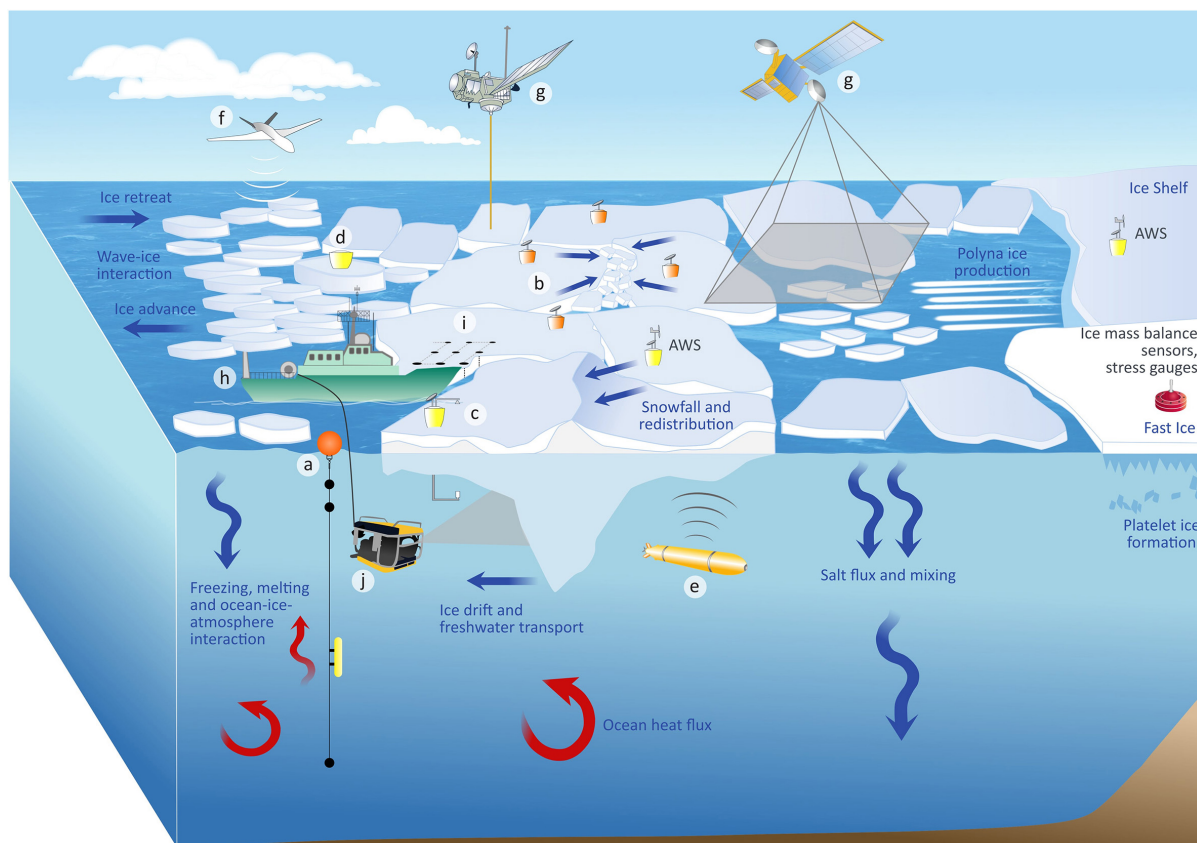


FIGURE 8 | Schematic of the platforms required to observe key sea-ice processes toward capturing circumpolar sea-ice variability (section “Toward a Better Understanding of Processes Controlling Antarctic Sea-Ice Variability and Change”) and deriving sea-ice thickness and volume (section “Observing Sea-Ice Thickness and Volume”). Due to the remoteness, vastness, and hostile conditions of the sea-ice zone, autonomous platforms will be crucial. They include high-resolution *in situ* sensors such as drifting buoys (a); ice-deformation arrays (b), mass-balance- and snow-buoys (c), wave buoys (d), and autonomous underwater (e) and airborne vehicles (f). Observations of snow depth, ice thickness, ice concentration, drift and properties from satellite altimeters, and radars and radiometers (g) are vital to sustain for long-term time series. Manned observation platforms include vessels (h) [for underway and *in situ* sea-ice sampling (i) including ROV deployments (j)], aircraft (e.g., EMBird and NASA’s Operation IceBridge), and near-coastal research stations (for fast-ice and sea-ice/ice-shelf studies). Modified from Meredith et al. (2013).

CryoNet initiative (Smith et al., 2018). Such long-term and internally consistent datasets not only provide key information on variability/change and processes responsible; they also enable calibration and validation of satellite-derived sea-ice thickness, as well as model verification.

Satellite remote sensing – calibrated and validated by targeted *in situ* observations (see above) – has a key role in both extending *in situ* observations in space and time, and in providing unique large-scale information on the Antarctic sea-ice environment (Lubin and Massom, 2006). Yet, important challenges remain, not only in improving satellite-derived products and quantifying uncertainties (see the section “Theme 5: The Future of Antarctic Sea Ice”), but also with respect to satellite data availability around Antarctica. For example, continuation of the crucial satellite passive microwave sea-ice concentration record (dating back to 1978) is not assured. Moreover, high resolution data required for sea-ice deformation, as well as polynya, fast-ice, and marginal-ice zone studies (e.g., synthetic aperture radar and high-resolution visible-thermal infrared data) are sparse over the Antarctic sea-ice zone. These, and other issues relating to data calibration/validation requirements over the next decade, are discussed in detail by Pope et al. (2017).

Observing Sea-Ice Thickness and Volume

The two most important reasons for not being able to obtain accurate estimates of circum-Antarctic sea-ice thickness (Giles et al., 2008; Schwegmann et al., 2016; Paul et al., 2018) are the lack of reliable snow depth and ice/snow-density data over broad scales, which are required for the sea-ice thickness retrieval, and the lack of sufficient *in situ*, UAV-, and air-borne sea-ice, and snow thickness measurements required for the training and evaluation of algorithms to derive sea-ice and snow thickness. The recent advent of ICESat-2, plus increased EMBird deployments and ongoing *in situ* observations of fast and pack ice (through the “AFIN” and “Antarctic Sea Ice Processes and Climate program,” respectively), provide a renewed impetus to tackle this in the near term.

Improved observations of snow-depth distribution will require sustained and much broader deployment of snow-depth and ice mass balance stations/buoys (IMBs) that capture sufficient spatial and temporal variability to evaluate satellite and modeled snow-depth products. Increased use of airborne, and particularly unmanned aerial systems (UASs), are needed to provide broader-scale snow distributions and to extend radar-derived snow-thickness estimates from NASA’s Operation IceBridge mission to other regions and seasons (Webster et al., 2018).

To develop and validate ice-thickness products (e.g., from ICESat-2 and CryoSat-2), long-range, long-endurance AUVs (section “Priorities for Future Observational Technologies”) or long-range aerial sampling (i.e., EMBird) will also be needed. Traditional aerial platforms, UASs, and AUVs are critical to both extend traditional *in situ* point measurements to satellite and model resolution scales and mitigate the logistical challenges of ship-based sea-ice measurement campaigns.

Additionally, wider networks of IMBs are required to provide crucial data for evaluation of satellite-derived ice-thickness products. More extensive drifting buoy networks are also critical in the sea-ice zone to evaluate and improve reanalysis products (which are key to understanding the drivers of sea-ice variability) and are much more sparsely deployed than in the Arctic. Ice-tethered and under-ice floats (SOCCOM and ice-capable Argo) can help determine coupling between ice production and upper-ocean properties. At present, few floats are deployed under sea ice, and almost no ice-tethered sensors have yet been deployed. Lastly, drifting buoy networks provide high-resolution deformation data. This is essential to evaluating satellite-based deformation products that have more limited temporal resolution.

Constraining the Seasonal Carbon Cycle

To constrain the Southern Ocean’s biogeochemical cycles, observations of oxygen, nutrients, dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), transient tracers (e.g., CFCs), particulate organic carbon, and ocean-color measurements are a priority. Stable isotope measurements of nitrate, as well as DIC and silicic acid, are becoming powerful tools for constraining past and present biogeochemical processes and ocean circulation, and substantial datasets are accumulating across the Southern Ocean over the annual cycle (e.g., Smart et al., 2015; Henley et al., 2018; Kemeny et al., 2018; Fripiat et al., 2019). Carbon isotopes and elements such as neodymium are also becoming increasingly important for paleo-circulation reconstructions (Basak et al., 2018), but modern measurements are scarce, such that there is a need to include these parameters in future observing efforts. In addition to traditional oceanographic sampling approaches, such as repeat hydrographic sections, moorings, underway measurements, and continuous plankton recorders, future efforts should include more under-sampled EOVs such as DIC and DOC, supplemented by data from bio-Argo floats, tagged marine mammals, and gliders (Figure 9; Roquet et al., 2014; Erickson et al., 2016; Johnson et al., 2017a).

Despite significant progress in new technologies for biogeochemical observations, recent studies indicate that at least 100 Biogeochemical-Argo floats (BGC Argo) are needed to detect climate-scale changes in air-sea CO₂ fluxes and Southern Ocean carbon and heat content (Mazloff et al., 2018). Even then, this will not cover coastal regions and may not resolve seasonal carbon dynamics well enough to reduce CO₂ flux uncertainty to the levels required to reveal climatic trends (Monteiro et al., 2015). In the next decade, a new generation of bio-Argo floats may help to fill these data gaps. For example, Air Launched Autonomous Micro Observer (ALAMO) floats could be launched from air into polynyas or open water adjacent to sea-ice zones, and Arvor-C floats are designed to operate in coastal environments. Improved battery capacity will increase sampling frequency, allowing for the study of blooms or sub-mesoscale dynamics and permitting the installation of new and/or additional sensors. Floats capable of profiling below 2000 m will help to constrain deep heat and carbon storage as well as deep

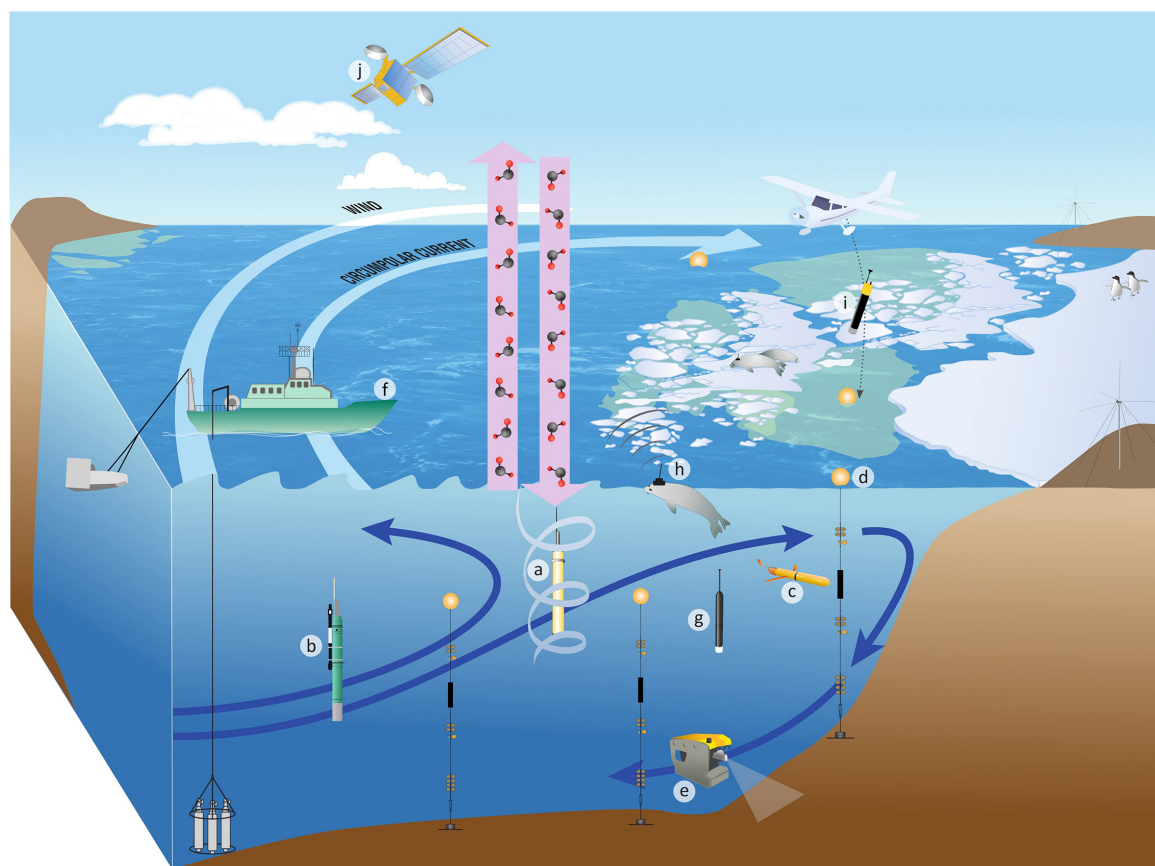


FIGURE 9 | Components of an optimal observing system to constrain and quantify biogeochemical cycling processes in the Southern Ocean. New methodologies such as biogeochemical sensors deployed on SOCCOM (a) and SOCLIM (b) floats, gliders (c), and moorings (d), and sampling from ROVs (e) must be integrated with traditional ship- (f) and station-based approaches. Ice-capable bio-Argo floats (g) and biogeochemical sensors deployed on marine mammals (h) are needed to extend the observational range in time and space. Airborne deployment of ALAMO floats (i) could increase spatial coverage substantially. All of these *in situ* approaches should be combined with existing and improved satellite-based measurements (j) of sea surface height, sea ice, sea surface temperature, and ocean color to develop an integrated biogeochemical observing system for the Southern Ocean. Modified from Meredith et al. (2013).

oceanic circulation. Observations from aircraft-mounted devices also have the potential to increase the coverage of high-resolution air-sea CO_2 and O_2 exchange measurements, together with ocean color and atmospheric data, e.g., the O_2/N_2 ratio and CO_2 Airborne Southern Ocean (ORCAS) study (Stephens et al., 2018).

Central to the Southern Ocean carbon cycle are the trace metals required for biological activity, with the most important being iron (e.g., Tagliabue et al., 2012). The GEOTRACES program³⁵ has vastly increased the number of available observations; nevertheless, data coverage remains poor compared to other ocean regions. Early trace-metal studies focused largely on the open Southern Ocean, but coastal areas such as the Ross and Amundsen Seas where ice shelves are melting are now receiving increased attention (Alderkamp et al., 2012; Mack et al., 2017).

³⁵Twenty-four GEOTRACES cruises and process studies occurring between 2006 and 2018 across all sectors of the Southern Ocean (Atlantic: 8; Indian: 12; Pacific: 7) (<http://www.geotraces.org/cruises/cruise-summary>)

Constraining Biological Energy Pathways

An ongoing challenge in observing ecosystems is that key processes and major components are difficult or impossible to observe directly, and uncertainties around indirect observation methods are not well characterized. This is true for important processes and rates – such as predator–prey interactions, consumption and energy use, and growth rates – and also for estimating abundance and biomass of many key taxa (see section “Assessing Status and Trends of Key Southern Ocean Taxa”). Ecosystem EOVs (eEOVs) provide a mechanism to address these challenges (section “Conclusion and Recommendations”) and models are also important in integrating, contextualizing, and optimizing observations (section “Southern Ocean Modelling”).

Improved data streams that constrain biological energy pathways by better characterizing the transfer of mass through food webs, into carbon export, and into fish stocks are a priority to inform Southern Ocean ecosystem modeling, assessment, and management (Constable et al., 2017; Figure 10). Potential consequences of shifts in energy pathways in the next 50–100 years include: (i) declines in krill that may negatively impact

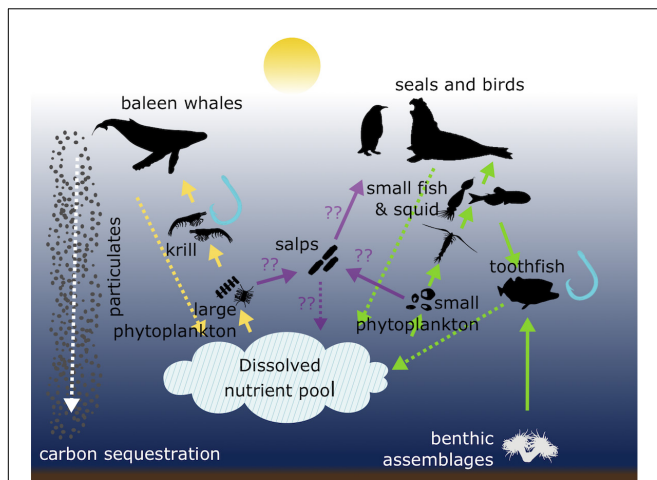


FIGURE 10 | Major biological energy pathways by which energy moves from primary producers to higher trophic levels in Southern Ocean ecosystems (integrated across seasons and across open water and sea-ice environments). These pathways include the well-studied Krill food-chain (yellow), as well as less well-studied pathways via small fish and squid (green), and potentially salps (purple). The relative dominance of these pathways underpins ecosystem structure and function and the provision of services such as fisheries (blue hooks) and carbon sequestration (white dotted arrow). However, these pathways and the factors that determine their relative dominance in space and time are not well resolved. Targeted observing effort will be required to fill this knowledge gap.

baleen whales, seals, seabirds, and krill fishery production; (ii) increases in copepods may result in increased toothfish catch; and/or (iii) increases in gelatinous salps may increase carbon sequestration and food for benthic communities (Constable et al., 2017). Observations that can resolve the likelihood of these outcomes include diet data (section 3.8) and biochemical tracers (isotopes, fatty acids, DNA, trace metals; see Pethybridge et al., 2017) together with targeted process studies that can inform estimates of the magnitude of biological fluxes at large scales.

Assessing Status and Trends of Key Southern Ocean Taxa

Rapid development of telemetry and remote-sensing technologies are yielding increasingly rich observational datasets for taxa at the bottom and top of Southern Ocean food webs (i.e., phytoplankton and predators). Mid-trophic level groups, however, represent a major data gap due to a lower observing effort and uncertainties around primary observing methods: nets and acoustic backscatter (Davison et al., 2015; Proud et al., 2018). For net data, catch depends upon the sampling method as much as what is in the water column, and relative catchability of different taxa (and size classes within taxa) is difficult to quantify but hugely influential on catch composition (Kaatvedt et al., 2012). Similarly, there are large uncertainties in converting acoustic backscatter information to estimates of community composition (biomass and abundance of different taxa) in the water column. Although initiatives like MESOPP³⁶ are working

to improve the models used to convert acoustic backscatter data to estimates of community composition, this remains a key challenge in ecosystem observing (Proud et al., 2018).

Identifying the drivers of changes in abundance requires information on foraging behavior and tactics, which need to be integrated with data on the relevant biophysical factors. Changes in diet inferred from stomach flushing (Miller and Trivelpiece, 2007, 2008), from tissue stable isotope analysis (Newsome et al., 2010; Ben-David and Flaherty, 2012), or from dietary DNA (Deagle et al., 2007) can be integrated with measurements of foraging behavior such as trip duration, movement patterns, and diving patterns using electronic tags (Miller et al., 2009; Hückstädt et al., 2012b; Kowalczyk et al., 2014). When coupled with demographic data, these provide a mechanistic understanding of how and why populations are changing and whether they can persist under climate change (Hückstädt et al., 2012a; Hinke et al., 2017b).

Other important gaps for biological observations that represent opportunities where the “value” of observation effort can be maximized include:

- Observations from under sea ice and fast ice (especially measures of under-ice production and habitat characteristics);
- Data on winter ecology or year-round studies;
- Co-located (and co-incident) sampling of multiple ecosystem components (e.g., net sampling, acoustics, profiles, predator observations); and
- System-level structural knowledge (i.e., measures of relative biomass of key taxa, links, and flux rates; see the section “Constraining Biological Energy Pathways”).

Figure 11 represents the observational capabilities and data required to address these gaps in knowledge.

Southern Ocean Modeling: Progress and Priorities

The ocean and climate modeling community has achieved great progress in simulating the Southern Ocean during the last 10 years (see Stammer et al., 2019); however, many processes remain poorly represented. The Southern Ocean is not only one of the harshest environments to observe, but also one of the most challenging to simulate, because of complex interactions between climate system components (ocean, atmosphere, sea ice, ice sheets), and the fundamental role of mesoscale and sub-mesoscale eddy fluxes in determining Southern Ocean circulation and its response to variable forcing. Realistic simulation of all dynamical interactions between components, delivering an explicit representation of eddy fluxes and isopycnal/diapycnal mixing, as well as ensuring that models can robustly represent the response of the overturning circulation to variation in wind and buoyancy forcing, constitute the major challenges for the next decade of physical oceanographic modeling of the Southern Ocean. All of the above can only be achieved with a hierarchy of model complexities and continued efforts toward the improvement of parameterizations of eddy-driven mixing.

³⁶www.mesopp.eu

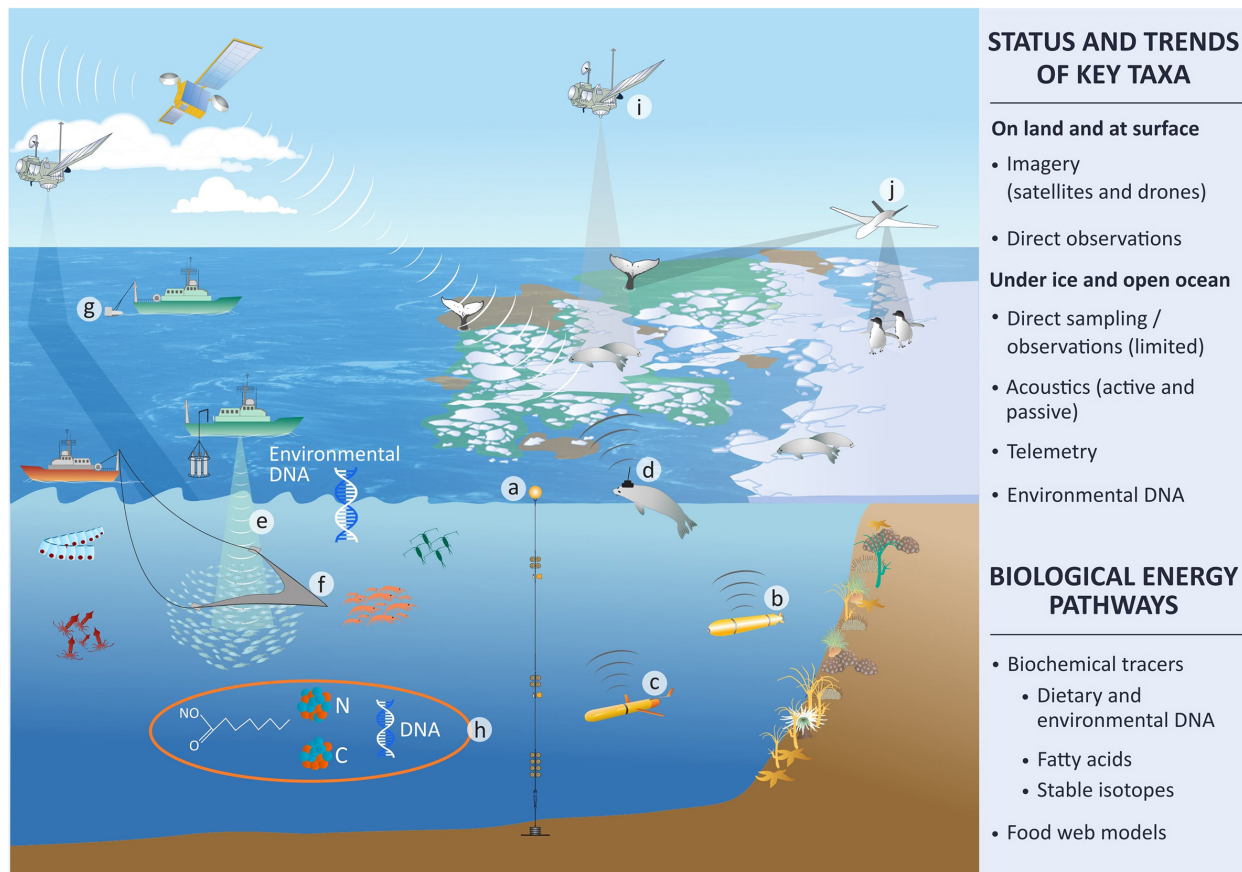


FIGURE 11 | Schematic illustration of the observation and models required to resolve key uncertainties regarding the impacts of global change on Southern Ocean ecosystems (adapted from Meredith et al., 2013). Mid-water taxa and food webs (particularly under seasonal ice and during the winter) are a key gap. Observations from platforms such as moorings (a), AUVs (b), gliders (c), and animal-borne instruments (d), along with improvements in acoustics (e) (including acoustic observation models) will help resolve status and trends of taxa, complementing traditional methods such as net sampling (f) and CPR (g). Integration of biochemical tracer data (such as dietary and environmental DNA, fatty acids, stable isotopes, h) and observations into food web models will be required to constrain biological energy pathways. Imagery from satellites (i) and drones (j) will greatly improve knowledge of marine mammals, penguins, and other seabirds in difficult to observe areas such as pack ice.

Past and present freshwater input from ice-shelf melt is not well-constrained by observations, leading to a wide range of possible values used in global climate model studies of impacts on sea ice, water-mass formation, and overturning circulation (e.g., Bintanja et al., 2013, 2015; Swart and Fyfe, 2013; Abernathy et al., 2016; Pauling et al., 2016, 2017). Similarly, the factors controlling the seasonality, spatial distribution, and volume of Antarctic sea ice are still uncertain, as are present day effects and implications of future changes in sea ice on other parts of the Earth system, such as atmospheric and ocean circulation (Kennicutt et al., 2014a). In fact, none of the Coupled Model Intercomparison Project Phase 5 (CMIP5) models can reproduce the satellite record of Antarctic sea-ice extent (Shu et al., 2015). An increased observational coverage, in both space and time, can guide and support improved simulations of Southern Ocean dynamics, near- to seasonal-term forecasting of sea-ice distribution, dynamics and thickness, upper ocean heat content, and detection and attribution analyses of observed changes. Furthermore, sustained and integrated observations can better

constrain and promote Southern Ocean state estimates, which are now starting to provide coupled biogeochemical-sea ice-ocean state information (Verdy and Mazloff, 2017).

Required Ocean Modeling Efforts

Recent modeling intercomparison studies have highlighted the pervasive biases and uncertainties in Southern Ocean dynamics and future projections (e.g., Meijers et al., 2012; Sallée et al., 2013; Downes et al., 2015; Farneti et al., 2015). Reliable simulations together with more confidence in future projections would have benefits beyond the Southern Ocean due to the fundamental role of the Southern Ocean in water-mass ventilation and carbon and heat sequestration. Polar climate change is largely dependent on surface fluxes, but their magnitude and variability are poorly constrained (Bourassa et al., 2013) due to spatial and temporal observational gaps, resulting in large uncertainties that limit our ability to assess the performance of our coupled climate models, to reduce model uncertainties and biases, and to guide model development.

Russell et al. (2018) stressed the importance of the westerlies in shaping the circulation, and heat and carbon fluxes in the Southern Ocean. However, the correct simulation of easterlies and katabatic winds is equally important in simulating sea-ice extent and advective freshwater fluxes, particularly for latent heat polynyas where a large fraction of AABW precursors are produced.

Heat and freshwater fluxes are responsible for the formation of Antarctic Intermediate Water (AAIW) and Sub-Antarctic Mode Water (SAMW), constituting the upper limb of the MOC (Sallée et al., 2010), and have a crucial role in deep and bottom-water formation. Limited understanding of these fluxes is a significant problem in the present generation of coupled climate models (Sallée et al., 2013). This is partly due to poorly constrained surface and sea-ice fluxes, with CMIP5 models showing large inter-model spread in both present-day simulations and future projections (Russell et al., 2018). Also, sea-ice freshwater flux is recognized as playing a major role in water-mass formation and transformation (Abernathy et al., 2016; Pellichero et al., 2018), sustaining a large part of the overturning circulation. Unprecedented observations in seasonally covered regions of the Southern Ocean should be used to evaluate model results. This is also true in the context of heat and carbon sequestration, given the availability of biogeochemical profiling floats (Gray et al., 2018). Recent estimates of meridional transports of mass, heat, and salt along the Atlantic sector, as well as new observational estimates of ACC transport across Drake Passage (Donohue et al., 2016), provide a new opportunity for model evaluation, particularly as observations are sustained and enhanced over the next decade.

Southern Ocean circulation, and heat and carbon uptake, are not only dependent on wind and buoyancy forcing, but also on isopycnal and diapycnal mixing, eddies, and topographic features. Mesoscale mixing is ubiquitous in the ocean, and plays a fundamental role in setting the overturning circulation, water-mass formation, and transport of tracers in the Southern Ocean. An accurate parameterization of mesoscale eddy mixing is a pressing challenge for the global ocean modeling community, and much work has been devoted to improving its representation in coarse-resolution models. For example, the eddy diffusivity has been related to the eddy kinetic energy derived through satellite altimetry. However, not only an estimate for the mean value is needed, but also its sensitivity to changes in forcing and interannual variability is crucial for properly representing mesoscale mixing processes and their effects on circulation and transport of tracers (e.g., Busecke and Abernathy, 2019). Mixing is critical for AABW formation, ice shelf and sea-ice melt, nutrient distribution, and other processes. The major Southern Ocean mixing mechanisms are winds, tides, interaction of currents and topography, and deep convection cells associated with polynyas. The influence of winds is limited to the upper ocean (Robertson et al., 1995) while the other mechanisms dominate deeper mixing. Tidal mixing plays a significant role in melting near the front of ice shelves (Robertson, 2013; Padman et al., 2018) and sea ice (Koentopp et al., 2005).

Presently, vertical mixing for all these mechanisms is parameterized in ocean and climate models. Some of the

parameterizations reproduce the wind-generated upper mixed-layer depth well, whereas others overmix the water column (Robertson and Hartlipp, 2017). Likewise, with a resolution of 1 km or finer, internal tides and tidal mixing can be replicated by some parameterizations (Robertson, 2006). However, there is room for improvement in the vertical mixing schemes and their parameterization in the global ocean and climate models. In an effort to address this mixing issue, national and international groups in the United States, China, France, Japan, Netherlands, and other nations have been formed and are collaborating. Progress in improving the vertical mixing would improve forecasts of future changes. Ice shelf-ocean interactions remain a challenge for observationalists and a source of errors and uncertainties in the production of bottom waters in models. Improvements will require a better representation of continental shelf ocean circulation, sea ice, winds, and higher resolution topography. All of which remain daunting tasks for the present generation of climate models.

Ecosystem Modeling Efforts

Ecosystem models are essential for integrating and contextualizing ecosystem observations, identifying how changes will affect ecosystems and the services they provide (Addison et al., 2017; Melbourne-Thomas et al., 2017), and for optimizing observing strategies (Constable et al., 2016). Ecosystem modeling efforts develop representations of the food web in relation to key biophysical drivers, and over the last decade have largely focused on sub-systems, such as open ocean, coastal and sea-ice areas, or particular regions (Hill et al., 2006; Murphy et al., 2012; Cordone et al., 2018; Marina et al., 2018a,b). Much of this work has been qualitative, with quantitative analyses of the structure of parts of the food web mostly limited to high data-density regions (e.g., WAP, Ross Sea, Potter Cove).

Common frameworks for ecosystem modeling include:

- (i) Population, growth, and habitat models for individual species (autecological models), focused on understanding how focal species respond to environmental conditions and external drivers such as harvest and bycatch (e.g., stock assessment models).
- (ii) Nutrient–phytoplankton–zooplankton–detritus models focused on understanding lower trophic level dynamics in response to physical drivers;
- (iii) Network models, representing linkages among components of ecosystems (synecological models) such as parts of the food web (functional groups and/or species), physical ecosystem components, and human activities.

International coordination of Southern Ocean ecosystem modeling is achieved through the Integrating Climate and Ecosystem Dynamics (ICED) subprogram of Integrating Marine Biosphere Research (IMBeR; Murphy et al., 2008). A long-standing goal of ICED is the development of “end-to-end” models that encompass the entire food web, coupled to key biological and physical forcings (Murphy et al., 2008). Simple end-to-end models using mass-balance approaches (Ecopath) have been implemented in West Antarctica (Hill et al., 2012; Ballerini et al., 2014; Gurney et al., 2014; Surma et al., 2014; Klein et al., 2018),

the Ross Sea (Pinkerton et al., 2010), and are in development for East Antarctica (McCormack et al., 2017), along with a more comprehensive end-to-end model in the “Atlantis” framework, which is targeted to inform management and policy (Fulton et al., 2011; Melbourne-Thomas et al., 2017).

Southern Ocean food-web models are currently oriented around krill (Ballerini et al., 2014; Gurney et al., 2014; Surma et al., 2014; Klein et al., 2018). These have been valuable in understanding the implications of climate change and changing patterns of krill fishing on krill and their major predators, yet are unlikely to represent non-krill dominated ecosystems. The sensitivity of krill dominance to structural uncertainty in these models has not been explored, but are potentially problematic (Hill et al., 2012). “Ensembles” or “toolboxes” of multiple structurally different ecosystem models will reduce this uncertainty and enhance understanding of patterns and drivers of ecosystem structure and function (Murphy et al., 2012, 2016; Gregor and Chan, 2014). Integrated modeling across multiple scales and dimensions (i.e., individual to global scales, and physical, ecological, and socio-ecological dimensions) will also be important (Melbourne-Thomas et al., 2017).

Ecosystem modeling capacity is currently limited by a lack of fit-for-purpose models and methods to evaluate the representativeness of models under development (i.e., model skill). This is due to difficulties in assembling data for difficult-to-observe parts of the ecosystem (section “Assessing Status and Trends of Key Southern Ocean Taxa”) and for trophic relations and rate parameters (section “Constraining Biological Energy Pathways”). Consolidating and comparing diets are a priority (Murphy et al., 2012) and efforts such as the SCAR Southern Ocean Diet and Energetics Database³⁷ improve the availability of trophic data, allowing comparisons of regional variation in food-web characteristics. Combining traditional dietary information from stomach contents with information from stable isotopes and dietary DNA will identify “missing links” in food-web models and thus reduce structural uncertainty (i.e., unknown and missed trophic links and/or important groups; Gregor and Chan, 2014). Additional priorities include improved understanding of the dependence of food-web structure and function on habitat structure and biogeochemical cycling through targeted process studies and data syntheses.

Essential Ocean Variables and Observing System Design

A core objective of SOOS is to ensure sustained delivery of the fundamental observations that meet the majority of stakeholder requirements. In the same way that the global network of meteorological stations provides end-users with a foundation of standardized observations around which to build specific requirements, SOOS will work with the broader Southern Ocean community to develop regionally defined, quantified sampling targets defining which observations are needed, where, how, and when. This will not only ensure base-level time series of key variables, but will support funders in identifying the observations that will deliver the greatest impact to the highest

number of end-users. In combination with parallel efforts within the international community (e.g., through the Global Ocean Observing System³⁸; GOOS), SOOS has identified candidate EOVs for the Southern Ocean³⁹, which are the most feasible (possible to observe in a sustained way) and highest impact (those variables that address the highest priority issues) variables that deliver observations to address the SOOS Science Themes. In the coming decade, the community must continue to prioritize candidate EOVs and develop the required documentation for determination of sampling requirements.

Ecosystem EOVs are the least developed in any observing system. Significant progress has been made in defining the process and criteria for determining eEOVs for the Southern Ocean (Constable et al., 2016). Sixty-four candidate eEOVs have been nominated from this process. They include variables for benthic species (11), pelagic and sea-ice taxa (17), marine mammals and birds (27), and direct human pressures (9). Nine of these are regarded as mature, and relate to fisheries catch and zooplankton from the SO-CPR Survey. The remainder are currently under review. Although specific to the Southern Ocean, these eEOVs have synergies with the GOOS biological EOVs⁴⁰ (Miloslavich et al., 2018), ensuring harmony in statements on global priorities.

The Southern Ocean Observing System has developed an Observing System Design Working Group to advance the knowledge and tools used in designing optimal observing systems. These tools, known as Observing System Simulation Experiments (OSSEs), are used to estimate the value of ocean observations, with respect to how well they constrain the goals of the observing system. Observing system design evaluation entails subsampling a realistic model solution and determining the ability to then reconstruct this model solution (e.g., Forget et al., 2008; Kurahashi-Nakamura et al., 2014; Kamenkovich et al., 2017). The realistic model solution being sampled is known as the “nature run.” The realism of this model run is the most important aspect of the endeavor, as it determines the partitioning between errors of commission, which arise from inability to reconstruct the nature run from the subsampling, versus errors of omission. These refer to phenomenon not in the nature run, and thus omitted from evaluation with regards to the observing system. For example, most models fail to capture the full spectrum of internal wave energy in the ocean, meaning that if these are used for the nature run, this source of variability is omitted with regards to assessment of observing system design.

Having a nature run with minimal omission errors allows accurate assessment of the observing system design and mapping method. It builds confidence in estimates of the observing system design and its skill in meeting the goals. Global ocean models are now being run with 2 km resolution in the Southern Ocean and appear to capture the internal wave spectrum (Rocha et al., 2016). A primary challenge with respect to observing system

³⁷<https://data.aad.gov.au/trophic/>

³⁸http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

³⁹<http://soos.aq/activities/system-design>

⁴⁰Figure showing links between SOOS and GOOS eEOVs, <http://soos.aq/activities/system-design>

design over the next decade is to validate these models. Do they fill in the spectrum for the correct reason? What physics (e.g., surface-gravity waves or ice shelves) are they omitting and what needs to be included? What aspects of ecosystem dynamics are omitted?

Tools exist to design and prioritize the observing system. These are primarily based on model statistics (e.g., Mazloff et al., 2018). By utilizing these tools, the observing system will provide estimates of quantities established by stakeholder needs at a minimal cost and with associated uncertainty estimates. However, adequate process studies are necessary to validate state-of-the-art numerical model statistics used in these OSSEs. Confidence in Southern Ocean science and policy relies on having simulations that capture all the biological, chemical, and physical dynamics of the region.

Priorities for Future Observational Technologies

Given the size, complexity, operational cost, and harsh conditions, a broad suite of technologies is required to observe the Southern Ocean. The biggest driver of technology development is the urgent need to address the spatio-temporal data gaps in traditional ship-based sampling, and the last decade has seen significant progress on this front. Augmenting ship-based observations with satellite-sensor technology, autonomous platforms, and fixed assets such as moorings, has made a step-change in our observational capabilities (Schofield and Kohut, 2018).

Autonomous underwater vehicles have experienced strong growth in Antarctic science applications over the last two decades, operating under ice shelves and sea ice to collect otherwise inaccessible ocean and ice data. The UK's National Oceanographic Centre's Autosub group was the first to conduct AUV missions beneath sea ice (Brierley et al., 2002, 2003; Hayes et al., 2007) and is exploring the cavities of major Antarctic ice shelves (Nicholls et al., 2006, 2008; McPhail, 2009; Jenkins et al., 2010; Graham et al., 2013). Other countries (Australia, Sweden, and Japan) are now developing their own polar AUV capabilities, with other nations certain to follow.

In situ sea-ice observations that are scalable to remote sensing and modeling products are a priority. New floe-scale measurements of sea-ice draft and morphology are now being delivered by the dual-hulled SeaBED-class of AUV that are reconfigured to face the bottom of the sea ice (Williams et al., 2015). New longer range AUVs will be able to address these observation gaps on a larger scale (100+ km). Better understanding of key processes such as the role of ice-wave interaction in sea-ice advance and retreat (Kohout et al., 2014, 2016), and the role of fast ice and polynyas in interactions with ice shelves (e.g., Massom et al., 2010, 2018; Silvano et al., 2018) will require coordinated *in situ* and autonomous observations (buoys and moorings) with high-resolution satellite-data products. Aerial electromagnetic induction techniques that measure sea-ice thickness will be important for validation of remote-sensing products (Price et al., 2015). Despite these new technologies, observing seasonal dynamics and snow thickness will still

require ice-mass balance buoys, which are rapidly evolving a range of new sensors (fluorometers, bio-optical sensors) (Maksym et al., 2012).

Profiling floats have revolutionized sampling of the Southern Ocean (coordinated through the global Argo program), but the coverage of 1 float per 3 degrees is well behind the global average, with large gaps particularly south of 60°S and for >2000 m depth everywhere. In the coming decade, we expect the under-ice domains to be addressed but technological challenges related to fixing positioning and communication under the ice will need to improve, for example, through expansion of sound sources such as RAFOS. Deployment of deep Argo floats will close the data gap for depths >2000 m, and new “bottom drifters” (Figure 7), currently being trialed by Sorbonne University and IFREMER through the WAPITI program (see footnote 9), will further support this.

Tagged marine animals, namely seals, have provided significant complementary datasets to the Argo program for temperature–salinity, and most recently fluorescence, from around the Antarctic margin and seasonal sea-ice zone. This technology has provided crucial winter and under-ice observations that could not be otherwise collected (Costa et al., 2010; Roquet et al., 2013; Heywood et al., 2016; Williams et al., 2016b; Treasure et al., 2017). Areas for improvement include sensor accuracy and rates, which have so far impacted data quality, as well as increasing sensor types for broader application, such as biogeochemical and acoustic sensors (Roquet et al., 2011; Frazer et al., 2018).

Underwater gliders now provide significant observations for the upper 1000 m at high spatio-temporal resolution and for multiple months at a time. They have been deployed over all parts of the Southern Ocean, including the ACC (Swart et al., 2015; Du Plessis et al., 2017; Viglione et al., 2018) and continental shelves (Kahl et al., 2010; Schofield et al., 2013; Thompson et al., 2014; Carvalho et al., 2016, 2017; Couto et al., 2017), as well as near ice shelves (Miles et al., 2015; Schofield et al., 2015; Naveira Garabato et al., 2017). They have a growing sensor suite capable of measuring nutrients, pH, acoustics, and CO₂. As battery technology and robustness of such platforms increase, autumn to winter observations will become ubiquitous (Du Plessis et al., 2019). Furthermore, autonomous surface vehicles (e.g., wind- and wave-powered and Lagrangian platforms) are also filling a growing need for surface-based observations. Recent studies assessing physical air-sea fluxes (Schmidt et al., 2017; Thomson and Girton, 2017) or gas fluxes, notably CO₂ (Monteiro et al., 2015), have demonstrated that surface vehicles are able to collect data for many months.

The use of UAS/drones for atmospheric (Cassano et al., 2010; Knuth et al., 2013), sea ice (Williams et al., 2016a), and ecological studies (Borowicz et al., 2018) is also expanding around Antarctica. They provide the ability to map at ecologically relevant scales and are proving effective tools to observe higher trophic levels. A growing suite of scientific sensors are becoming available for UAS applications, rapidly increasing the number of countries using these platforms. A major barrier for UAS is the significant regulatory issues involved. These technologies complement traditional satellite and airborne remote-sensing

approaches that continue to be the backbone of broad seasonal scale sampling of the Southern Ocean.

Advances in moored platforms have been less broadly cited, but promising developments include bottom landers, such as the cheap, soccer-ball sized, ice-resistant, anchor-weighted “T-pop” buoys deployed to depths of 6000 m. Dropped from a ship, ice, or helicopter, they measure temperature and pressure for several years before surfacing and relaying the data via satellite. T-pops were successfully deployed by Sweden in the Amundsen Sea in 2016. Further, the newly developed ApRES instruments (coordinated through the NECKLACE program) collect time series of melt rates from point locations and complement the satellite-derived maps of melt rates that are now becoming available.

In addition to new platforms, a wide range of physical, chemical, and biological sensors are rapidly maturing. Advances in bio-acoustic technologies – both on ships and other platforms – will be critical to resolving uncertainties around the abundance and biomass of key mid-trophic-level taxa (Handegard et al., 2012). Parallel development of observation models will be required to support use of complex data streams (e.g., Proud et al., 2018). Advances in technologies used to quantify biochemical tracers from biological samples will also be invaluable in resolving biological energy pathways and supporting the development of ecosystem models (Pethybridge et al., 2017).

Along with new technologies, observational coverage can be enhanced using existing technology through more efficient use of resources. Although industry-based shipping in the Southern Ocean is marginal, fishing and tourism are growing industries with regular trips and, in many cases, the capability and interest to support observational activities. Additionally, station resupply voyages rarely operate underway observations without specific research requests, which, if coordinated, could provide a step-wise enhancement of observational coverage. The installation of sensors such as flux towers, multibeam echo sounders, standardized camera systems, snow radar, and electromagnetic induction sensors are important systems that could be installed on all vessels to greatly enhance spatial coverage. The GOOS Ship Of Opportunity Program (SOOP)⁴¹ facilitates such coordination globally, but the Southern Ocean community is yet to take full advantage of these opportunities. Further, new initiatives (see SCOR Working Group 154: Integration of Plankton-Observing Sensor Systems to Existing Global Sampling Programs (P-OBS)⁴²; Lombard et al., 2019) are developing ways to integrate biological observing sensor systems into existing physical oceanographic networks, such as GO-SHIP and OceanSITES, to enhance biological observation coverage with minimal additional resourcing. Leveraging efforts in this way is critical to achieving multidisciplinary observational coverage. Another important consideration is the continued development of inexpensive systems capable of sustained broad-scale deployments (e.g., Expendable Bathythermograph (XBT), sea-ice mass balance buoys, ocean- and sea-ice drifters) by

ship or aircraft. Further, year-round coastal Antarctic stations have under-utilized potential for circumpolar field work stations to monitor seasonal and long-term evolution of, for instance, sea-ice algal biomass and production. Observing the scale and complexity of the Southern Ocean will require a full portfolio of these technologies.

Connecting and Delivering Southern Ocean Data

The international data-science landscape has changed significantly over the last decade, with the development of new data tools and an unprecedented increase in both the volume and diversity of data; presenting both opportunity and challenges. A particular challenge for SOOS is to link the science and data communities associated with National Antarctic Programs (NAPs) to the broader oceanographic community. The SOOS data system must leverage existing efforts, thus SOOS is working with other data initiatives to develop tools that bring together these efforts, to serve this thematically broad but regionally focused community.

Enhanced observations of the Southern Ocean will be of limited value if the data (*in situ*, satellite-derived, and model outputs) are not easily “Findable, Accessible, Interoperable, and Reusable” (the FAIR Principles; Wilkinson et al., 2016; Tanhua et al., 2019). Data complexity, lack of data- and metadata-exchange standards, and difficulty finding relevant extant datasets are major challenges for researchers (Lucas, 2017). Addressing these challenges is the core objective of the SOOS data strategy, and a “one size fits most” approach to data management will not solve these problems; therefore, we envisage several interlocking components.

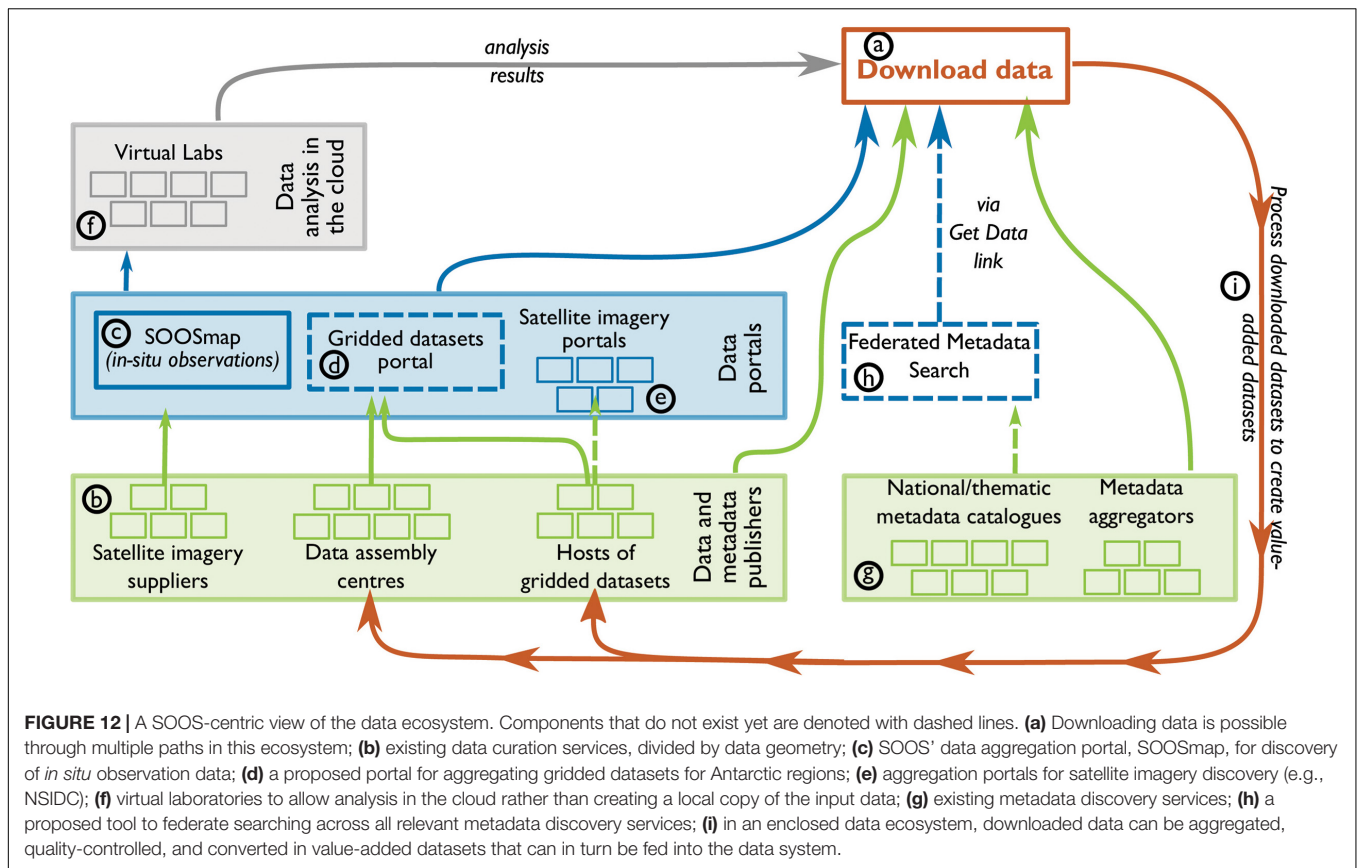
The SOOS data ecosystem (Figure 12) provides multiple pathways to access data (Figure 12a), based on the geometry of the datasets and the communities that produce them. A core focus for SOOS to date has been the development of SOOSmap by the European Marine and Observation Data Network Physics group (EMODnet Physics) (Figure 12c) to deliver standardized and aggregated *in situ* observational data in both real-time and delayed modes. A central task for SOOS this decade will be to populate SOOSmap with key observational datasets that allow researchers to explore temporal and spatial patterns in parameters. To create these datasets, SOOS is encouraging scientists and data managers to mine historical data to generate aggregations of similar datasets that have undergone standardized quality control. Examples of such projects include the aggregation of chlorophyll-a data from fast-ice cores (Meiners et al., 2018), the KRILLBASE database for krill and salp observations (Atkinson et al., 2017), and the SCAR Retrospective Analysis of Antarctic Tracking Data. Similarly, groups such as SCORs ECV-Ice group⁴³ are promoting the intercalibration of *in situ* measurement methods, a vital step for integrating observations from different research groups.

Southern Ocean Observing System is partnering with Antarctic data management organizations to deliver relevant gridded datasets (Figure 12d), and while satellite imagery is vital

⁴¹<http://www.wmo.int/pages/prog/amp/mmop/JCOMM/OPA/SOT/soop.html>

⁴²<https://scor-int.org/group/154/>

⁴³<https://scor-int.org/group/152/>



for SOOS, its data are globally managed (Figure 12e). These portals are likely to develop connections with cloud analytics services (Figure 12f).

Standardized datasets, such as those delivered through SOOSmap, require significant effort and for many data types the only practicable way to provide access is through comprehensive metadata discovery tools. At present, there are more than 70 metadata catalogs that contain SOOS-relevant data records (Figure 12g). Thus, SOOS and other data management initiatives are working to develop a federated metadata search tool for single-window searches of SOOS-relevant metadata repositories (Figure 12h) and exploring opportunities for structured schemas to improve metadata search (Beck et al., 2019).

This suite of tools will support the Southern Ocean community to add value to raw datasets (Figure 12i), producing aggregated datasets that can be republished through the data centers, iteratively improving the data available to the SOOS community.

All aspects of this data strategy require adequate and sustained funding, and given recent issues with sustained funding of data products, SOOS has identified core values for how community tools should be developed, including using free and open source software where available; not duplicating efforts; and creating a sense of community ownership so that the tools can survive changes in funding environments. Collectively, the SOOS ecosystem enables sharing and accessing data while being adaptable to the needs, varying levels of standardization, and

patterns of IT use among the disciplines that comprise SOOS. As the global data management community further develops tools to make data more FAIR, the mix of tools in the SOOS data vision will allow its community to adapt to these changes.

International Coordination and End-User Engagement

The success of SOOS will ultimately be determined by the delivery of sustained observations to end-users, which include scientists, policy makers, and industry. This requires significant efforts to ensure an integrated and coordinated approach.

Unique to the Southern Ocean, the Antarctic Treaty provides a framework within which the use of Antarctic resources and services can be monitored and managed. Because of this, all users of the Southern Ocean (south of 60°S) are obligated to record their activities and monitor their impact. This requires sustained observation of environmental variables and transfer of data into knowledge and statements of impact or change. This requirement has supported the development of coordinating bodies who manage specific aspects of program monitoring requirements.

Ecosystem-based management approaches to regulate fisheries activity, for example, are managed through CCAMLR. This requires a range of sustained environmental, biological, and ecosystem-level observations. CCAMLR takes an ecosystem approach to management, and this requires access to data sets that contribute to understanding the whole ecosystem, the

physical environment within which it sits, and the rates of change in both of these systems. Specific areas where accessible, sustained, and integrated decisions can contribute include the management of the marine protected areas, which have been established by CCAMLR. Additionally, the Antarctic Treaty System's "Committee for Environmental Protection" provides recommendations to manage the impact of other human activities in Antarctica, including climate change, and as such requires sustained observations of environmental conditions. It is expected to benefit from improved observations that enhance our understanding of environmental change, including the implications this will have for logistical and scientific operations.

The network of 53 NAPs has a broad remit to support strategic science, logistics, and their national commitments to Antarctic Treaty obligations. Further, their operations require observationally based services, such as sea ice and weather forecasts that are coordinated through programs such as the International Ice Chart Working Group (IICWG), and the World Meteorological Organization (WMO). Industry-based activities such as fisheries and tourism (coordinated through International Association of Antarctic Tourism Operators, IAATO) also require observationally based environmental information, and can additionally enhance opportunistic ship-based collection of data, as a strong statement of commitment to Treaty obligations toward environmental protection.

The influence of SOOS on policy is through the mechanisms described above for the Antarctic Treaty System, and also in terms of inputs to the Intergovernmental Panel for Climate Change (IPCC) assessment process. SOOS-supported datasets informed the last major assessment (AR5 in 2013) and are underpinning much of the Southern Ocean material in the ongoing Special Report on Oceans and Cryosphere in a Changing Climate (scheduled for release in 2019). Such data are also used to test and challenge climate projection models used by the IPCC and are critical to assessments of oceanic influence on the Antarctic Ice Sheet and hence global sea-level rise. The IPCC process includes direct connection with policy makers and outlining of response options, enabling the use and recognition of SOOS-supported observations.

Fundamentally for SOOS, the primary end-users are the scientists and research communities that collect and bring together the diverse observations to answer societies evolving questions on how the Southern Ocean is changing, and what the ramifications are for humanity. The Southern Ocean scientific community, through the NAPs, SCAR, SCOR, the World Climate Research Program (WCRP), and the IMBeR project, provides the scientific knowledge and recommendations that underpin the management and policy decisions.

Delivering the breadth of observations required by these end-users is an enormous task, and is greater than can be provided within each forum or by any one nation alone – a key driver for the development of SOOS in 2011. Over the last 7 years, SOOS has worked with all stakeholders to build networks and connections around the identified data priorities. With these structures now in place, the next decade sees a strong lean toward designing a network of regional systems that incorporate all overlapping end-user requirements where possible. This will not only facilitate

the delivery of data to end-users, but also enable funders to quantify and broaden their impact and up-take. Working with end-users and organizations such as the Committee of Managers of National Antarctic Programs (COMNAP), the SOOS Regional Working Groups will be central to developing and implementing these observing systems in an integrated and flexible way.

CONCLUSION AND RECOMMENDATIONS

Significant investment in data collection over the last decade has enhanced knowledge of Southern Ocean systems and their impact on the Earth system. Yet, the Southern Ocean remains poorly observed leading to uncertainty in estimates of future states of Southern Ocean processes and the consequences for the Earth system.

This community paper assesses decades of research and observational efforts in the Southern Ocean to provide forward-looking priorities that require sustained observations over the coming decade. Distilled into eight key issues, these are identified as the major data bottlenecks in addressing the SOOS Science Themes that have underpinned the focus of SOOS networks and efforts thus far. For Themes 1 and 2, the role of the Southern Ocean in the planet's heat and freshwater balance, and the stability of the Southern Ocean overturning circulation, respectively, observations of bottom water production processes are critical, and should be prioritized in the coming decade (Key Issue 1). Key Issue 2 on "reducing uncertainties in air-sea and air-sea-ice fluxes of heat, momentum, freshwater, and carbon" is a cross-cutting issue that delivers into each of the six Science Themes, and is fundamental in modeling efforts to project future states of Southern Ocean systems. Theme 3 on "The role of the ocean in the stability of the Antarctic Ice Sheet" is imperative to better constrain uncertainties in the contribution of the Antarctic Ice Sheet to future sea level. Key issue 3 supports this by prioritizing efforts to observe the contribution of oceanic heat to ice-shelf basal melt. The "future and consequences of Southern Ocean carbon uptake" is Theme 4, and fundamental to this are observations that enable constraining of the seasonal carbon cycle (Key issue 4). Theme 5 on "The future of Antarctic sea ice" is a broad challenge underpinned by two Key Issues "Integrating sea-ice satellite and *in situ* observations with modeling efforts to constrain circumpolar sea-ice variability" and "observing sea-ice thickness and volume." The final Theme 6, "Impacts of global change on Southern Ocean ecosystems" is so broad as to be difficult to define with respect to observational priorities. Now, two Key Issues have been defined "constraining biological energy pathways" and "Assessing status and trends of key Southern Ocean taxa." A focus of observational efforts on these Key Issues will thus deliver benefits across the SOOS Themes and directly to the networks and end-users of the data.

Further, the above disciplinary priorities share common needs for observation systems priorities:

- Enhanced observations of most variables from non-summer seasons are needed. Year-round use of autonomous vehicles year-round where possible,

deployment of sustained moorings, and other time-series platforms, as well as focused autumn/winter observational programs are needed to address this critical data gap.

- A strong relationship between implementation of new technologies and development of internationally agreed standards for collection, quality control, and management of the new data, delivered where possible in alignment with the FAIR data principals is a critical need. This requires appropriate funding, and will ensure that new data streams are high-quality, openly available, integrated data sets – following the example of Argo and other successful ocean observing programs.
- Related to this, standardization and aggregation of similar observations are vital. This requires concerted, long-term data management efforts to discover, quality control, standardize, and publish aggregated datasets for both historic and future observations.
- Requirements for the full suite of observations needed by the broad end-user community must be quantified and underpinned by robust observing system design efforts. The end-user community includes numerical modelers and scientists from other disciplines. The requirements need to be delivered across disciplinary barriers, through existing or new forums. In this way, the combined community can advocate for sustained efforts that deliver across user needs.
- Further, models should be better incorporated into the observing system design and evaluation. As the data-stream grows, these models can be used to semi-automate data quality control. Moreover, data assimilation can be exploited to extract maximum value from the observations and provide gridded products for baseline assessments of the Southern Ocean state.
- Remote-sensing data are vital for achieving observational coverage across large spatio-temporal scales for all disciplines. The Southern Ocean community must identify mechanisms to better articulate and advocate their requirements to Space Agencies.

Emerging direct human pressures will also require monitoring in the coming decade. Global issues such as organic pollutants, ocean plastics, and over-fishing are gaining attention. Although mechanisms exist for the reporting of pollutant and waste spills, plastics and fishing catch south of 60°S (e.g., through COMNAP, CEP, and CCAMLR), the impacts on the Antarctic ecosystems are not yet routinely observed and monitored. Some efforts are being made for single-species monitoring [e.g., Southern Ocean Persistent Organic Pollutants Program (SOPOPP)⁴⁴], and monitoring efforts for micro- and macro-plastics are gaining traction internationally. Future recommendations to SOOS for observing needs will come both directly from the stakeholder communities and through science organizations such as SCAR and SCOR. Another emerging issue is the impact of ocean acidification on the Antarctic ecosystem, which is encompassed in Science Theme 4, but is not yet addressed by SOOS. It is an increasing focus of international

research and this will stimulate the development of observational requirements. These emerging issues highlight the need for any observing system developed for the Southern Ocean to be flexible, and responsive to scientific advice from the broader community.

In the past decade, SOOS and the Southern Ocean community have made considerable progress toward designing a comprehensive and sustainable observing system by integrating existing efforts. In the next decade, the focus will turn to addressing the gaps in the system through a combination of technical innovation and greater coordination and sharing of data and logistics.

AUTHOR CONTRIBUTIONS

LN and EH: section “Abstract.” AC, MMM, and LN: sections “Impetus and Progress Toward Developing a Southern Ocean Observing System” and “The Vision.” LN: sections “A Decade of Progress,” “Drivers of the Future Development of SOOS,” and “Southern Ocean Observations: Future Priorities.” AM and JS: section “Themes 1 and 2: The Role of the Southern Ocean in the Planet’s Heat and Freshwater Balance; and the Stability of the Southern Ocean Overturning Circulation.” AW and RC: section “Theme 3: The Role of the Ocean in the Stability of the Antarctic Ice Sheet and Its Future Contribution to Sea-Level Rise.” SH and KH: section “Theme 4: The Future and Consequences of Southern Ocean Carbon Uptake.” PH, TM, RM, and BO: section “Theme 5: The Future of Antarctic Sea Ice.” DC and IS: section “Theme 6: Impacts of Global Change on Southern Ocean Ecosystems.” KK and AM: section “Observing Antarctic Bottom Water Production Processes.” SS and SG: section “Reducing Uncertainties in Air-Sea and Air-Sea-Ice Fluxes of Heat, Momentum, Freshwater, and Carbon.” KA and EvW: “Understanding the Contribution of Oceanic Heat to Ice-Shelf Basal Melt.” TM, RM, and PH: “Toward a Better Understanding of Processes Controlling Antarctic Sea-Ice Variability and Change.” IJS, RM, and PH: section “Observing Sea-Ice Thickness and Volume.” SM, SF, and ES: “Constraining the Seasonal Carbon Cycle.” RT: sections “Constraining Biological Energy Pathways,” “Assessing Status and Trends of Key Southern Ocean Taxa,” and “Southern Ocean Modelling Progress and Priorities.” RF: sections “Southern Ocean Modeling: Progress and Priorities,” “Required Ocean Modeling Efforts,” and “Ecosystem Modeling Efforts.” MM and LN: “Essential Ocean Variables and Observing System Design.” GW, OS, LN, PB, JB, RM, and SD: section “Priorities for Future Observational Technologies.” AC, SS, EH, MW, and LN: section “International Coordination and End-User Engagement.” LN, MW, EH, and PB: section “Conclusion and Recommendations.”

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⁴⁴<https://www.griffith.edu.au/griffith-sciences/southern-ocean-persistent-organic-pollutants-program/projects-and-collaboration>

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