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The vision for a Southern Ocean Observing System

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The Southern Ocean is fundamentally important to the Earth system, influencing global climate, biogeochemical and ecological cycles. Limited observations suggest the Southern Ocean is changing, yet chronic under-sampling makes the causes and consequences of such changes difficult to assess, and limits the effectiveness of any response. A Southern Ocean Observing System (SOOS) is thus being created, to facilitate integration of resources, to enhance data collection and access, and to guide the sustained development of strategic, multidisciplinary science in the Southern Ocean. Here we outline the long-term vision for this system, the gains inherent in its implementation, and how the international community can move towards achieving it.

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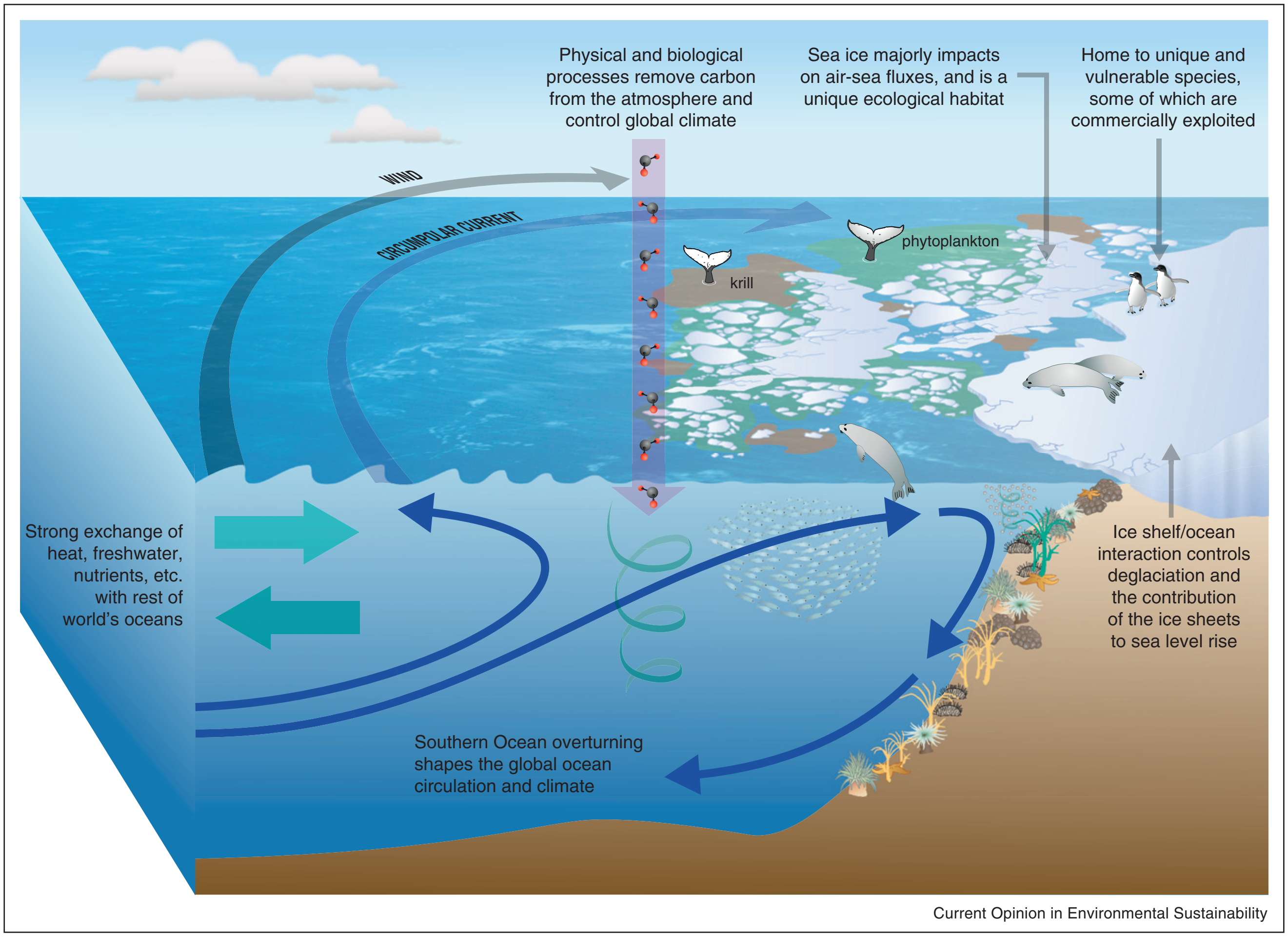
The need for a Southern Ocean Observing System

The Southern Ocean is the central connection between the major ocean basins, and between the upper and lower layers of the global ocean circulation [1,2]. It strongly influences global climate and planetary-scale biogeochemical cycles, accounting for up to half of the annual oceanic uptake of anthropogenic carbon from the atmosphere (e.g. [3–5]) and supplying nutrients that fertilise the majority of global ocean biological productivity north of 30° S [6]. Given the fundamental role that the Southern Ocean plays in the operation of the Earth system, recent observations suggesting large-scale changes are of significant concern. These changes include a circumpolar warming that exceeds the global average and which includes several 'hotspots' of extreme regional warming [7–10], and some rapid regional changes in sea ice and ice shelves; the latter of these has significant implications for global sea level [11–13]. Both upper and lower limbs of the Southern Ocean overturning have freshened, due to changes in the hydrological cycle and ice melt [10], and the rate at which the Southern Ocean can draw down anthropogenic carbon from the atmosphere has likely weakened [4,14]. Ecosystems are already being impacted by these changes (e.g. [15–17,18••,19]), and ocean acidification is likely to progress rapidly in the Southern Ocean in coming decades with strong implications for the productive food webs [20].

There is thus a critical need to observe and understand the Southern Ocean, in order to better determine its role in global environmental change, to increase our resilience to such change, and to ensure sustainable resource exploitation. However, the harsh conditions and remoteness of this area have led to it being the most under-sampled region of the global ocean (e.g. [21]). Implementation of a truly comprehensive Global Ocean Observing System (GOOS) requires this area to be observed more systematically. International coordination of the funding, planning and execution of data collection, as well as data handling, product development and dissemination are required. An overarching structure is needed to map activity onto the most pressing scientifically and societally important issues. Recognising this need, several international organisations (including the Scientific Committee on Oceanic Research, SCOR, and the Scientific Committee on Antarctic Research, SCAR) are pushing forward the development and implementation of a Southern Ocean Observing System (SOOS; www.soos.aq). The SOOS strategy [22••] identifies six challenges that are critical for SOOS to address (see also Figure 1):

(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 Southern Ocean in the stability of the Antarctic ice sheet and its future contribution to sea-level rise.

Figure 1



Schematic of the scientific and societal drivers that led to the development of SOOS.

(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.

During the initial planning phase of SOOS, significant attention was given to identifying the scientific platforms that are currently capable of collecting the measurements required to address each of the above challenges, and how best they might be used [22••]. This work is progressing, and particular attention is now being paid to producing quantitative targets concerning the time and space scales of observation required for each variable, to facilitate the production of an optimal, coherent and internally consistent observing system. Whilst this work is ongoing, it is already clear that significantly more data are required from the Southern Ocean than would result from the existing commitments and opportunities to gather such data. A marked increase in sustained data collection by the international community is required. Nonetheless, encouragement can be taken from the success of the International Polar Year 2007–2008 (IPY), during which a substantial upsurge in data collection occurred. Determining how to sustain, enhance and operationalise this level of effort, at a time of significant financial pressure for many nations, is guiding the approach to developing SOOS for both the near-term and longer-term futures.

The starting point for SOOS

Data collection from the Southern Ocean has traditionally been very labour intensive, and has relied heavily on scientific expeditions conducted from research ships. The advent of satellite oceanography in the 1970s represented a step-change in observing the Southern Ocean, as it did for the global ocean as a whole, and remotely sensed measurements of sea surface variables (temperature, colour, height, etc.) are now fundamental to our ability to detect and understand changes as they happen. Further, there have been recent advances with greater automation

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of *in situ* data collection, as exemplified by the Argo programme [10,23]. This initiative has deployed and maintained an array of robotic profiling floats that collect physical and some biogeochemical measurements from the upper 2000 m of the water column. For the open Southern Ocean (outside the sea ice zone), Argo has revolutionised our ability to monitor the ocean's changing interior properties over large scales, especially during the winter months. Whilst Argo floats are not intrinsically well-suited to the heavily ice-infested subpolar gyres, developments with ice-avoidance software and subsurface acoustic tracking has enabled some float programmes to be conducted in polar areas.

In addition to Argo, another technology development that has enabled significant increases in data collection has been the tagging of marine mammals with oceanographic sensors [24,25]. This was initially conducted as part of studies into the animals' behaviours and their interactions with the environment, though increasingly the temperature, salinity and other data that are gathered are proving important for oceanographic and climate-related studies. The mammals tagged have different paths through the ocean compared with the passive Argo floats, and are not subject to the same restrictions due to sea ice. Argo and the tagging of marine mammals are strongly complementary programmes in terms of the spatial and temporal sampling they enable. Such efforts have not lessened the need for ship-based sampling programmes however, due at least in part to the restricted number and type of variables that they can measure, and the fact that Argo does not yet measure the ocean below the 2000 m depth level.

In the Southern Ocean, the backbone of the ship-based sampling programme is the CLIVAR Repeat Carbon/Hydrography programme, which conducts large-scale sections on 5–10 year intervals throughout each of the major basins. The measurement suite includes numerous physical parameters, plus tracer measurements from which ocean acidification and the changing anthropogenic carbon content of the ocean can be quantified. A range of biogeochemical and some biological measurements are also made. This programme includes measurements of the deep ocean below the depth of Argo, but only in a temporally sparse manner. As such, the complementary efforts of many countries to monitor deep ocean circulation with moorings are important.

Other circumpolar initiatives to monitor the Southern Ocean that are currently underway include GACS, the Global Alliance of Continuous Plankton Recorder Surveys, an international programme to understand changes in plankton biodiversity across the globe, including throughout the Southern Ocean. A number of the ecosystem-related programmes relate to CCAMLR, the Commission for the Conservation of Antarctic Marine Living Resources, which seeks to develop understanding of the operation of the Southern Ocean ecosystem in the context of sustainable exploitation. Numerous other programmes exist, including the Southern Ocean tide gauge network, initiatives to measure sea ice and the ocean beneath the floating ice shelves, and diverse programmes to monitor different trophic levels and their interactions with each other and with the physical environment (see [22••] for full details). Many of these still rely heavily on *in situ* data collection from ships, but there is gathering momentum for automated data collection from ocean gliders [18••] and other autonomous underwater vehicles (e.g. [26•], etc.). Inevitably, many of these programmes are regionally focussed and/or specific to individual disciplines, though in combination they do constitute the foundations upon which a genuinely integrated Southern Ocean Observing System can be constructed.

Immediate priorities for SOOS

Despite the initiatives detailed above, there are significant observational gaps, and even the extra efforts from nations that are rapidly expanding their Southern Ocean scientific interests (e.g. Korea, China, India) are unlikely to alter this scarcity of data. The long-term solution is much greater automation of data collection, including the progressive transfer of measurements that currently require human intervention to technologies that can be operated remotely or completely autonomously. This transfer will require sensor and platform development, and SOOS will take a lead in promoting and specifying requirements for both of these over the next few years.

Earth-observing satellites will continue to be fundamental to our ability to monitor the Southern Ocean. A top priority for SOOS is the maintenance of the ongoing high-precision satellite altimetry missions (in full synergy with satellite gravity missions), plus continuations of scatterometer missions for wind stress, microwave and infrared instruments for sea surface temperature, and ocean colour and cryospheric satellites. For future missions, swath radar altimetry is required to resolve smaller-scale spatial features that are currently subsampled, but which are known to be critical in numerous Southern Ocean processes, and ice topography observations and freeboard measurements are required on a systematic, circumpolar basis.

In addition to enhanced data collection, a further approach to address the data shortage is much greater synergy between data and modelling efforts, where modelling can be exploited to increase the value/usefulness of the data. The initial planning of SOOS requires quantitative studies of the data coverage and resolution required for each of the challenges identified; Observing System Simulation Experiments (OSSEs) are a valuable tool in this context, and are being conducted. In the operational phase, ocean state estimations and reanalyses are becoming

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progressively more sophisticated (e.g. [27]), and have now reached the stage where they are capable of being used as routine tools for the execution of physical marine science. Atmospheric reanalyses achieved this state some time ago, whereas biogeochemical/biological models lag in development because of the extra complexity in the systems involved. Acquisition and rapid provision of sufficient ocean data of the correct type to keep these state estimates and reanalyses realistic will be a major use of SOOS, and the use of such state estimates for the production of key data products will be of great benefit to the SOOS user community. Over the coming years, as models become more sophisticated and data collection techniques develop, non-physical parameters will become included in such reanalyses and state estimates, for example biogeochemical properties. There is thus a need to understand and provide what these initiatives require, to link data gathering/dissemination with data assimilation as seamlessly as possible.

In this context, it is important to note that each of the six challenges outlined above will be progressed simultaneously, but it is inevitable that progress in some will be more rapid than in others. For example, challenges that rely heavily/exclusively on physical measurements are likely to see more rapid developments, since the infrastructure and data handling capabilities are more mature. Challenges that link to the ecosystem elements of SOOS, with the extra levels of complexity that are inherent in biological systems, are likely to require more initial planning and greater effort to develop. This work will initially include defining which ecosystem variables must be monitored as part of SOOS, and this requires interaction with parallel efforts being conducted to determine the Essential Ocean Variables (EOVs) of the biological components of GOOS. It is noted, however, that the Southern Ocean includes some unique elements, and it is unlikely that a simple adoption of the GOOS EOVs will be sufficient to address each of the challenges outlined above. Nonetheless, significant work is underway to determine the minimum requirements for sustained monitoring of the interdisciplinary ocean [28], and SOOS will draw on this effort. As SOOS develops, new variables will be progressively added to the system following the 'stages of readiness' concept elucidated by the Framework for Ocean Observations [29•], where each new variable has been determined to be needed in addressing one of the key challenges, or a new challenge that comes to the fore.

Not all aspects covered by SOOS will involve the measurement of variables that can be incorporated into reanalyses and state estimations in the foreseeable future, with obvious examples being higher predators, benthic communities, and so on. Biological observations are nonetheless equally vital components of SOOS, and the variables that are addressed via joint data gathering/assimilation programmes should be chosen so as to concurrently maximise the benefits delivered to scientists investigating all aspects of SOOS (e.g. by providing key data products that assist in understanding the spatio-temporal distributions of marine biota, and their interactions with the physical and biogeochemical environments).

A current high priority for SOOS is to develop and maintain a traditional data-centric cyberinfrastructure, with a data management system capable of accessing and providing data on a query basis, for example, a Southern Ocean data portal. This is especially important given the current lack of data sharing, both within and between nations. An operational prototype of such a portal, based on data infrastructure developed by the Australian Integrated Marine Observing System (IMOS) was launched recently (http://soos.aodn.org.au/soos/). Fully populating this portal will not be trivial and will require strong leveraging of existing data centres, but will have immediate scientific impact by providing seamless access to historical data alongside data from ongoing Southern Ocean activities.

In addition to rapidly developing a SOOS that is integrated, coherent and can address each of the scientific and societal challenges identified, it is vital that the system is designed in such a way that allows it to evolve and adapt, so that new technologies and systems can be developed and implemented, and new challenges met when they are recognised. It is also critical that the system connects with other sustained measurement programmes, such as GOOS at its northern boundary, and atmospheric and cryospheric observing systems that are important in determining boundary forcings for SOOS. To these ends, and with the development of SOOS now well underway, it is timely to clarify the steps required to ensure logical progression and coordination of activities, and hence ensure that the SOOS mission is realised.

The long-term vision

Models of the physical circulation and climate of the Southern Ocean are becoming increasingly more sophisticated, and it is now possible to conduct fully eddy-resolving integrations with coupled sea ice and active ice-shelf cavities. If sufficient data can be collected in an automated manner, such models could be run in assimilating mode in real time, using the data to continuously keep the output fields realistic. The value of the real-time collection and assimilation is that the simulations can be used with active cyberinfrastructure to control the autonomous observing instruments in an adaptive sampling approach. For example, in 20 years' time, a swarm of next-generation gliders could patrol the Southern Ocean, feeding data in real time to one or more data assimilation sites, and could receive automated instructions from those sites in order to keep the spatial

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data coverage optimised across the different variables being measured based on real-time model analyses. It is important to note here that optimisation of spatial coverage does not equate to roughly equal spacing geographically, but rather to best coverage of the spatio-temporal domain relevant to each of the heterogeneously distributed SOOS variables. Real-time modelling and assimilation can best describe this sampling as it evolves temporally. Real-time minimisation of model error fields by adaptive autonomous sampling would offer a step-change in optimal monitoring of the Southern Ocean.

It is important to note here that sensor developments will lead to a much greater range of variables being measured autonomously than can presently be measured, with a full suite of biogeochemical measurements (including carbonate system parameters) and numerous biological measurements (e.g. acoustic measurements of plankton density, physiological parameters to constrain rate processes, etc.) being made simultaneously with the more traditional physical measurements. Model developments will enable these variables to be factored into the automated control of the underwater platforms, enabling a truly integrated sustained observing system to be implemented. Over time, and as the system becomes more sophisticated, both measurement and model techniques for different variables will develop, and new variables will be tested and added to the process; the system is purposefully designed to be expandable and adaptable, not fixed.

This approach does not remove the need for ship-based science and other science that requires direct human activity, since there will always be a spectrum of measurements that cannot be obtained autonomously, and highest-quality measurements will always be required for calibration and validation purposes. Furthermore, measurement programmes conducted for process-oriented science will naturally be different in concept and execution to those conducted for sustained observational purposes, and the former will require more specifically targeted measurements than a SOOS could provide. Nonetheless, the system does offer scope to integrate human-generated measurements with autonomously generated ones, and will provide output fields of great use to process-oriented science and science on aspects of the Southern Ocean that are outside the direct scope of the cyberinfrastructure at the time.

The ocean model(s) that underpin such a cyberinfrastructure-based system will not capture all key processes, and it will be necessary to have very high-resolution embedded models in key regions (e.g. dense water formation regions, biological hotspots, regions of very rapid change, etc.). Such nested models would take the boundary conditions from a central overall Southern Ocean model, which would run at lower resolution. Additional nested assimilating models could be added progressively, as the system develops and more small-area systems become ready to deploy. The operation of the overall Southern Ocean model would be a key interface with GOOS, which could provide boundary conditions from its own systems to ensure compatability with SOOS outputs. A two-way interaction with GOOS and other monitoring systems for the atmosphere and cryosphere will be vital to the full implementation of SOOS.

To make this approach feasible, it is critical that the cyberinfrastructure developed by SOOS capitalises fully on the evolving capabilities in the computing and digital communities. SOOS will consist of a diverse distributed international community that will span observational/modelling scientists, operational governmental organisations and commercial entities, with increasing information available to the general public from SOOS programmes and systems. This diverse community has a wide range of data needs and computational sophistication. The development of this capability will be an iterative process to ensure the required flexibility to accommodate different national needs, whilst simultaneously providing a unified, system-wide infrastructure for the Southern Ocean.

From its beginnings as a functional data portal, the cyberinfrastructure for SOOS will need to transition to a fully capable system that will ensure end-to-end data preservation and access, provide a suite of visualisation tools, mature knowledge provenance tools and enable direct closed-loop interaction of models with the data acquisition programmes. These capabilities will feedback on the SOOS design by enabling ongoing OSSEs capable of defining and revising the target number and frequency of observations required, each of which will evolve over time as new challenges are identified, new technologies brought into SOOS, and new parameters being measured.

Over time, the output of the system will become a major resource for scientists and others working on Southern Ocean issues. It will be of great benefit in its own right, and will also enable forecast/prediction models to be run with optimal realistic starting conditions. Such a system is depicted schematically in Figure 2.

Achieving the vision

The above vision is many years away, and it behoves us to work towards it progressively, yet strategically. An estimated timescale for achieving the vision is approximately 20 years, based on the rates of progress with models, platforms and cyberinfrastructure techniques. There are also political dimensions — by necessity it would need to be a fully international system, with separate nations contributing hard assets to work under common control. This goal would require careful structuring to ensure that each nation saw tangible benefit from its involvement.

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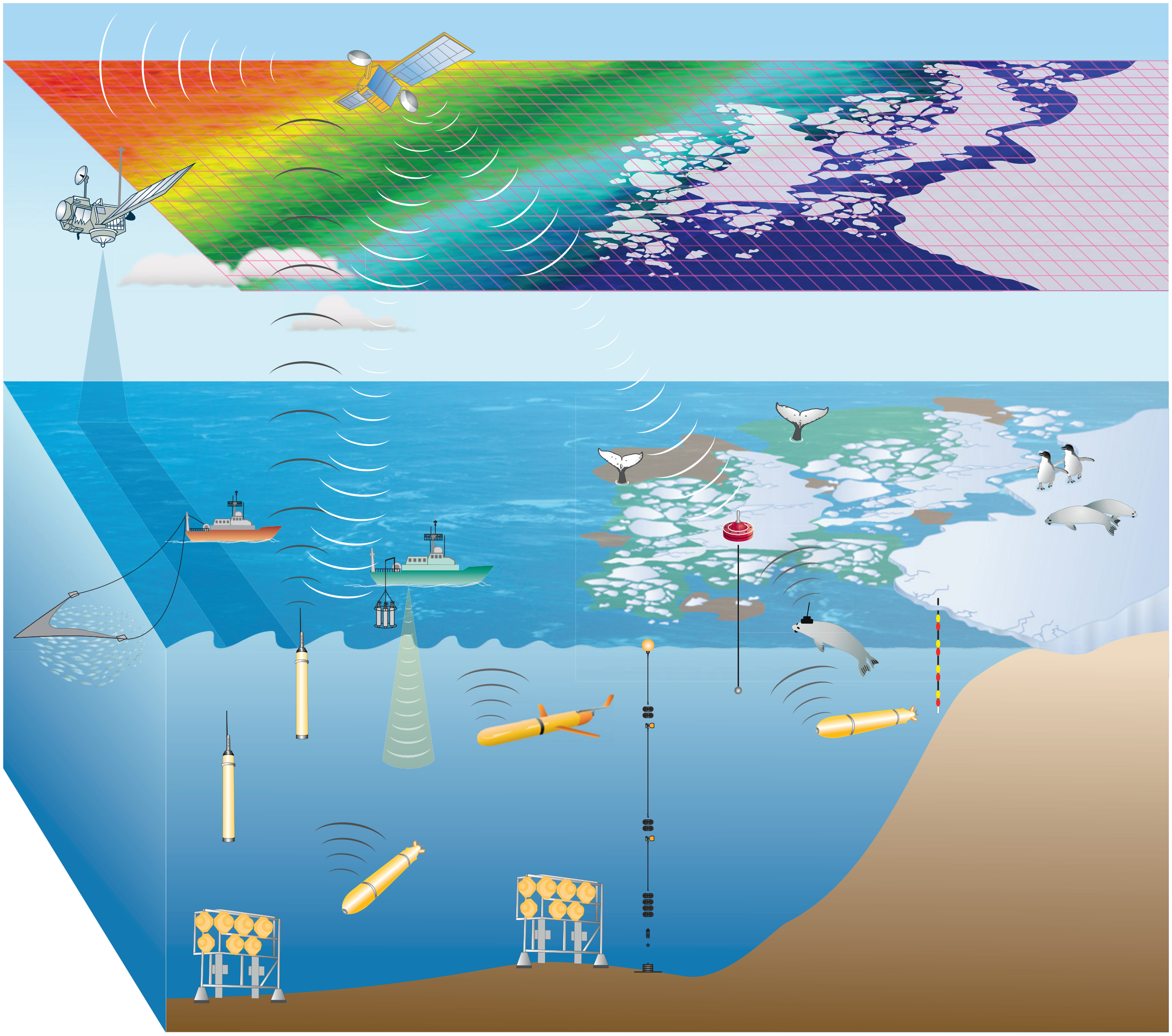
Figure 2



Schematic of a cyberinfrastructure-based vision for SOOS. Marine assets would include a mixture of both autonomous and non-autonomous platforms, but relying more heavily on the former over time. Combined with satellite remote sensing, the data would be relayed to ground stations in real time, where assimilating ocean models would produce near-real time state estimates of each of the parameters in the system. The error fields associated with these assimilating models would then be used to retask the autonomous platforms in real time, thus maximising the spatial–temporal coverage of each of the parameters being measured, without specific need for human intervention.

A key intermediate step would be a pilot study, to develop the cyberinfrastructure and automated control of ocean platforms, and to test the autonomous sensors and model performance in this system. Such a pilot study would most likely be a system focussed on a specific region of the Southern Ocean, with a high-resolution model assimilating data from a range of platforms (some autonomous, some not; some under direct cyberinfrastructure control, some not). The selected region of study should be an area where the existing data density is high, to minimise the initial expenditure needed, and where model efforts are already producing quasi-realistic results at high resolution. An estimated timescale to implement such a pilot study is 10 years. Before this intermediate step, the SOOS community and its stakeholders would need to decide which area it wanted to chose for a pilot study, to select the most appropriate variables/models/platforms for the trial, and to acquire funding from one or

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more nations at a sufficient level to conduct the work. Costs will be significant, but developments in marine cyberinfrastructure are already underway, and sensor and model performance and scope are being improved continuously. It is hoped that work to fully plan and secure funding for such a pilot study might be achieved within the next three to five years.

Closing thoughts

SOOS is currently defined around six key challenges that are perceived as the most compelling contemporary issues that require sustained observations of the Southern Ocean. In a couple of decades' time, it is highly likely that new issues will have emerged and will require community effort to address. SOOS needs to be a system that is adaptable, as well as optimisable, cost-effective, regionally scalable and progressively more automated. The ability to incorporate new measurements and techniques in the coming years is vital, not only to reflect sensor development, but also to reflect evolving need. By constructing such a system, SOOS will be able to serve the scientific and societal needs for sustained observations of the Southern Ocean for the foreseeable future.

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