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PERSPECTIVE

High-resolution satellite imagery meets the challenge of monitoring remote marine protected areas in the Antarctic and beyond

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Abstract

Remote, high-latitude oceans can prove challenging for the designation and implementation of marine protected areas (MPAs), partly due to issues in monitoring inaccessible localities and large spatial scales. A lack of protection combined with damage from growing human activities has contributed to the degradation of some of the Earth's richest marine biodiversity and highlights the urgent need to support improved marine conservation. High-resolution satellite imagery (VHR; 0.3–0.6 m spatial resolution) provides a much-needed tool for monitoring sentinel species in remote oceans, which would strengthen current and future MPA research and monitoring programs across the globe. This perspective specifies how recent advances in VHR studies have contributed to knowledge regarding occurrence, habitat suitability, and abundance of mesopredators in the Southern Ocean. We demonstrate how knowledge gained through VHR offers a cost-effective and easily accessible method for collecting previously unobtainable data to inform a representative network of Southern Ocean MPAs, and how the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) could utilize this technology. As VHR and automated detection algorithms continue to improve, we showcase a promising opportunity to use these methods to complement current research and monitoring efforts, thus strengthening MPA efforts in the Southern Ocean and beyond.

KEYWORDS
CCAMLR, crabeater seal, marine conservation, penguins, remote sensing, seabirds, Southern Ocean, Weddell seal

1 | INTRODUCTION

"The science we need for the ocean we want" is the catchphrase that now marks our transition into the United Nations Decade of Ocean Science and Sustainable Development (2021 to 2030—https://www.oceandecade.org/). Catalyzed by an increasing global awareness of the plight of our oceans, this initiative hopes to present a framework and opportunity for local, national, and international action toward sustainable and coordinated marine management that is informed by the frontiers of our knowledge. Over the past two decades numerous global targets called for the establishment of a globally representative network of marine protected areas (MPAs) (Gjerde et al., 2016), which are an increasingly popular and effective tool for maintaining marine ecosystem function and biodiversity (Lubchenco & Grorud-Colvert, 2015). However, at present, MPAs are heavily concentrated within national waters, under the jurisdiction of single coastal states. In the remaining ~60% of global ocean space governed under the 1982 United Nations Convention on the Law of the Sea (UNCLOS), MPAs are few and far between. Several reasons for this include the lack of an overarching legal mechanism for designating MPAs in high-seas areas (Gardiner, 2020) and challenges related to the coordination of conservation management in remote marine regions (Wilhelm et al., 2014). For too long, fragile ecosystems within international waters have been left vulnerable to the overexploitation of resources and the cumulative impacts of poorly managed human activities (including cumulative stressors from anthropogenic climate change). To address these regulatory shortfalls, the United Nations are negotiating a new ocean treaty that aims to improve the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction. This agreement will likely incorporate MPAs as an area-based management tool.

Designating MPAs alone, however, does not invariably lead to successful marine conservation (Edgar et al., 2014; Jentoft et al., 2011). Implementation of MPAs must be conducted with a management and policy framework that includes, among other key elements, a research and monitoring strategy, which enables managers, scientists, and other stakeholders to measure the conservation efficacy of the MPA over its lifespan. High-latitude oceans prove particularly challenging to undertake research and monitoring due (in part) to their remoteness and vast sizes (Wilhelm et al., 2014). Emerging remote sensing technologies offer potential solutions to these challenges, yet there is a lag in the explicit incorporation of these tools into monitoring plans for geographically remote MPAs.

The Southern Ocean (defined here as waters south of the Polar Front), provides a useful case for demonstrating how very high-resolution satellite imagery (VHR; 0.3–0.6 m spatial resolution) methods can significantly enhance MPA research and monitoring capabilities in remote regions. Representing ~10% of the world's total ocean space, it hosts some of the last intact marine ecosystems on Earth (Halpern et al., 2008). Marine resources in these vast international waters are managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)—a multinational regulatory body established under the Antarctic Treaty System. Despite CCAMLR's core objective to conserve Antarctic marine life, Southern Ocean ecosystems remain threatened by a rapidly changing climate and increasing human activities, particularly the expansion of commercial fisheries (Brooks et al., 2018). In line with global MPA targets, CCAMLR is working toward a representative network of MPAs, so far designating two high-seas MPAs successfully with three additional proposals pending. Yet, one sticking point for the adoption of Southern Ocean MPAs is persistent concerns over the cost and logistics of conducting consistent research and monitoring in such vast and remote regions (Brooks et al., 2019). Rugged conditions associated with field research in Antarctica have precluded, for example, the collection of broadly distributed or long-time series data for most Antarctic wildlife, making regular monitoring a challenge. This has led to significant knowledge gaps regarding important indicator species (i.e., those that serve as a measure of ecosystem health and provide insight to evaluating ecosystem change) such as seals (Otariidae and Phocidae) and penguins (Sphenisciformes), and particularly pack-ice obligates, like crabeater seals (*Lobodon carcinophagus*). VHR imagery provides an innovative tool toward gathering consistent population data of indicator species at spatial, and temporal scales and in locations previously impossible to acquire.

Here we propose the adoption of an emerging method that can be integrated within MPA policy frameworks: the monitoring of indicator species using VHR. We discuss its use combined with traditional surveys that could support Southern Ocean MPA research and monitoring efforts and demonstrate that this technology is low cost, easily accessible, and can possibly involve the public in the data collection process, aiding with capacity-building and science literacy among interested parties (LaRue et al., 2020). By using the Southern Ocean as a showcase for VHR capabilities, we further suggest that remote sensing and computer vision (e.g., Gonçalves et al., 2020) can be applied broadly to monitor species abundance in other similarly large-scale and remote areas.

2 | THE SOUTHERN OCEAN AND MPA POLICY

CCAMLR manages marine living resources in the Southern Ocean with a mandate for conserving the broader ecosystem. Currently, there are two primary commercial fisheries in the Southern Ocean: Antarctic krill (hereafter, krill; *Euphausia superba*), a keystone species in the Southern Ocean ecosystem, and toothfishes (*Dissostichus eleginoides and D. mawsoni)*. In the Ross Sea in particular, toothfish are critical intraguild predators, as they are simultaneously a top piscine predator and also prey for Type C killer whales (*Orcinus orca*) and Weddell seals (*Leptonychotes weddellii*) (Ainley et al., 2020). Indeed, reductions of toothfish could potentially cause Weddell seal populations to decrease by 10% per year (Salas et al., 2017). While CCAMLR's management for toothfish thus far has tended toward traditional single-species management despite criticism from Antarctic ecologists (Abrams et al., 2016), the Ross Sea region MPA—and all future Southern Ocean MPAs—provide an opportunity for true ecosystem-based management.

The Ross Sea region MPA has a suite of conservation objectives toward protecting the ecosystem and function of the region. These objectives include protecting the life history and ecosystem of Antarctic toothfish, as well as its predator the Weddell seal, and other species such as emperor (*Aptenodytes forsteri*) and Adélie penguins (*Pygoscelis adeliae*). Under CCAMLR's legal framework for the establishment of MPAs (Conservation Measure 91-04), all adopted MPAs must have a research and monitoring plan. Developed by the CCAMLR science community in 2017, the Ross Sea region MPA research and monitoring plan identifies numbers of Weddell seals, Antarctic toothfish, and numbers of nesting pairs of Adélie and Emperor penguins all as "indicators" that can provide insight into ecosystem health and thus a metric to measure MPA efficacy. While research activities in the Ross Sea have been underway for decades, the sheer scale of the MPA (>2 million km^2) and the high cost of field research make remote monitoring of indicator species through VHR methods a potential cost-effective, core element of research efforts. We suggest such remote monitoring could not only inform the CCAMLR MPA policy process—including designation of boundaries and assessments of effectiveness—but potentially provide guidance for similarly remote MPAs around the world.

3 | VHR IMAGING: A NEW TECHNOLOGY TO STUDY OCEAN ECOSYSTEMS

To monitor and evaluate the effectiveness of MPAs, a first step is to understand baseline populations of indicator species. Perhaps the most influential advancement via VHR to date has been the global censuses for several Antarctic penguin species. First, Fretwell et al. (2012) searched fast ice (sea ice "fastened" to the continent) in Antarctica using mostly QuickBird-02 (~0.6 m resolution) images during austral spring in 2009. They estimated ~238,000 breeding pairs of emperor penguins across 46 colonies, several of which were previously unknown to science. Shortly thereafter, Lynch and LaRue (2014) used QuickBird-02 and WorldView-2 (~0.5 m resolution) images during 2010–2013 to estimate ~3.8 million breeding pairs of Adélie penguins across 251 colonies—a >50% increase compared to estimates 20 years prior. Researchers added chinstrap penguins to the list of species with a global population estimate via integration of VHR imagery (Strycker et al., 2020), finding 375 colonies with approximately 3.42 million breeding pairs. Borowicz et al. (2018) confirmed the Danger Islands colony of Adélie penguins adding ~1.5 million breeding pairs to the previous baseline in Lynch and LaRue (2014). The speed at which VHR imagery has been tested, deployed, and adapted for new species in Antarctica is a hallmark of the technology, which lends credence to its potential utility in similarly remote areas of the ocean.

In addition to penguins, ice-obligate seals in the Southern Ocean are similarly detectable via VHR. Toward a first population estimate for Weddell seals, LaRue et al. (2020) discovered probable seal presence on only 0.55% of ~260,000 km^2 of available fast ice along the continental coast during November 2011. Differences among regions were apparent, notably the Ross Sea containing the highest density of seal presences. Wege et al. (2020) recruited >2200 volunteers to determine crabeater seal habitat in the Weddell Sea (currently proposed as an MPA), finding probability of crabeater seal presence was low (<4%) but machine learning models suggested that during breeding season, crabeater seals prefer ice floes over abyssal waters associated with their primary prey, krill, and areas of variable sea ice concentrations. Similarly, LaRue et al. (2019) found that the habitat preferences for Weddell seals (which are fast ice obligates) in the Ross Sea were focused on proximity to deep waters (>300 m ocean depth) close to shore and also highlighted a potential competitive relationship between the seals and sympatric penguins: Weddell seals in the Ross Sea seemingly prefer proximity to relatively small colonies of emperor penguins and are more likely to be found nearby Adélie penguins. Finally, Ainley et al. (2015) found an apparent decline in Weddell seals over >50 years in the western Ross Sea by comparing previous ground and aerial counts to VHR-derived estimates, suggesting the decline may be due to the toothfish fishery in the Ross Sea. These studies highlight the criticality of gaining context beyond a handful of site-specific studies for informing the efficacy of MPAs as a marine conservation tool in the Antarctic.

Integrating long-term field data with data gathered via VHR, along with machine learning techniques, has helped advance understanding of ecosystem function in the Southern Ocean. Santora et al. (2020) revisited geographic structuring of Antarctic penguins to find that intra- and interspecific competition plays a role in the distribution among penguin species, and Jenouvrier et al. (2020)

integrated dispersal parameters into population models for emperor penguins, after remote sensing-based observations suggested a lack of total philopatry in emperor penguins (LaRue et al., 2015). Comprehensive or large-scale data sets now exist for three penguin and two seal species (Fretwell et al., 2012; LaRue et al., 2020; Lynch & LaRue, 2014; Strycker et al., 2020; Wege et al., 2020). Researchers have also developed a neural network for detection of pack ice seals (Gonçalves et al., 2020), and artificial intelligence for whale (Borowicz et al., 2019; Cubaynes et al., 2019) and albatross detection (Bowler et al., 2020). Remote sensing techniques have contributed to the baseline data required to make significant conservation advances via monitoring species in the Southern Ocean.

4 | HOW VHR IMAGERY SUPPORTS SOUTHERN OCEAN MPA POLICY

Antarctic decision-makers and the research community have an opportunity to fine-tune state-of-the-art monitoring methods in the Southern Ocean and share the lessons learned, providing much-needed leadership and guidance on the international stage. So, what might a monitoring program focused on indicator species within the Southern Ocean and similarly remote MPAs look like? First of all, efforts will certainly include international collaboration (c.f. Gurarie et al., 2017). As an example, science teams could lead annual VHR searches of the Antarctic sea ice for Weddell and crabeater seals via online platforms (e.g., Maxar's Geohive; Figures 1 and 2), potentially involving volunteers. Crowd-sourcing projects may also lead to public appreciation and engagement participatory science that can lead to increased awareness of conservation problems (McKinley et al., 2017). Given the Antarctic is an international space, crowd-sourcing research effort provides a tremendous opportunity to learn and engage with this "remote commons." As an example, if previous pricing remains (Table 1), a tagging campaign (whereby volunteers help us label features on satellite imagery) completed each year on ~7600 km^2 of fast ice, which is the area searched in 2011 in the Ross Sea MPA (LaRue et al., 2019), could cost approximately $7600 USD in hosted imagery and take less than 3 months to complete. The most expensive component of the surveys will be the inevitable periodic groundtruthing surveys using alternative methods, at a cost orders of magnitude higher (e.g., Gurarie et al., 2017). Data analysis via a freely accessible code available on GitHub could be done inexpensively through automated processes that are completed as data become available. Reports and updates could be offered for inclusion at annual CCAMLR meetings and uploaded to the CCAMLR MPA Information Repository, which would in turn inform decadal and periodic reviews of Southern Ocean MPAs. Such data regarding population changes (numbers, spatial aggregations, or associations) could also help to inform potential revisions of the Ross Sea region MPA. VHR studies could be used in setting population baselines for the three MPAs currently under negotiation and inform their management once implemented. While specific scientific institutions and organizations at national and international levels and government agencies would need to take the lead on these projects, we have demonstrated that the research is well-established and cost effective.

As an example of applications in the Southern Ocean that are easily transferrable to other remote areas, workflows could be configured such that data acquired via VHR could constantly train neural networks for detecting Antarctic species through computer vision (as in Gonçalves et al., 2020 for crabeater seals and Borowicz et al., 2019 for cetaceans). For example, searching ~100,000 km^2 of fast ice Antarctic-wide for Weddell seals (~25,000 km^2) where seals have previously been present and ~75,000 km^2 where seal habitat is suitable but seals are absent, both in and outside of MPAs in the Southern Ocean, would ensure that we are not missing animals or that they are not relocating. For crabeater seals, we recommend searches focusing on areas with suitable habitat as per Wege et al. (2020) or in areas of ecological significance identified through multipredator tracking (Hindell et al., 2020). Similarly for Adélie and emperor penguins, given their stable colony locations (but see LaRue et al., 2015), we recommend analysis on images during peak chick-rearing in both cases (December–January and September–October, respectively). With an iterative process of searching and integrating into a neural network, an automated algorithm might be able to better predict crabeater seal habitat, dynamically estimate penguin population sizes, and thus hone CCAMLR's research strategy and population precision. This information could help to identify areas where indicator species appear highly sensitive to environmental stressors or change and inform decisions regarding the level of protection that may be required in specific areas. Furthermore, VHR-based population-level data could also inform risk assessments for the active fisheries, which require regular updates on the status of predator populations to understand the impacts of harvesting.

Consistent and strategic ground validation to ensure correct interpretation of remote sensing imagery will be critical in the near-term or until machine learning mechanisms (aforementioned) significantly improve (Gonçalves et al., 2020). Though the premise of our proposal is to use VHR to monitor and thereby avoid the very expensive, logistically complicated, and inconsistent ground surveys, it is critical to use verification methods to ensure that image interpretation is accurate. We envision that an Antarctic-wide

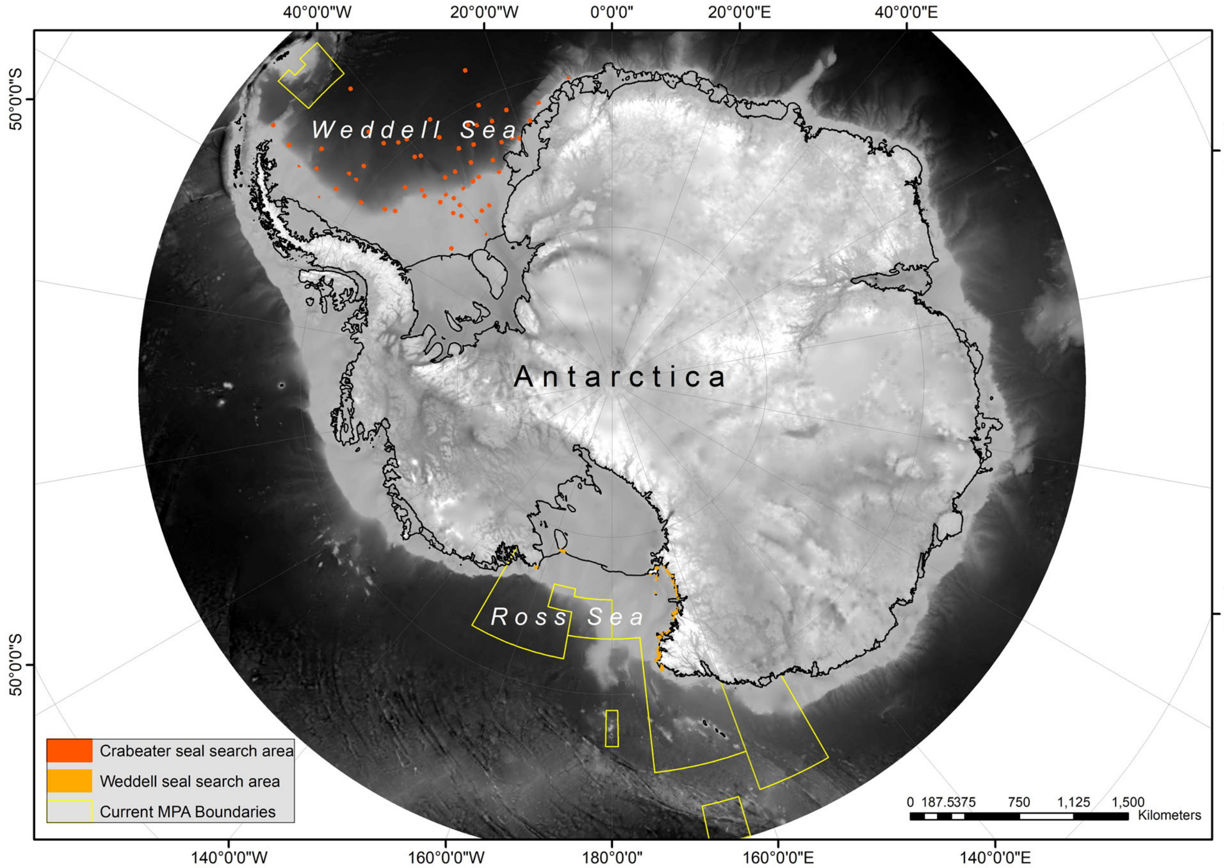

FIGURE 1 Possible search areas based on previous research (LaRue et al., 2019; Wege et al., 2020), to survey Weddell seals and crabeater seals via VHR imagery in the Ross Sea MPA and the Weddell Sea

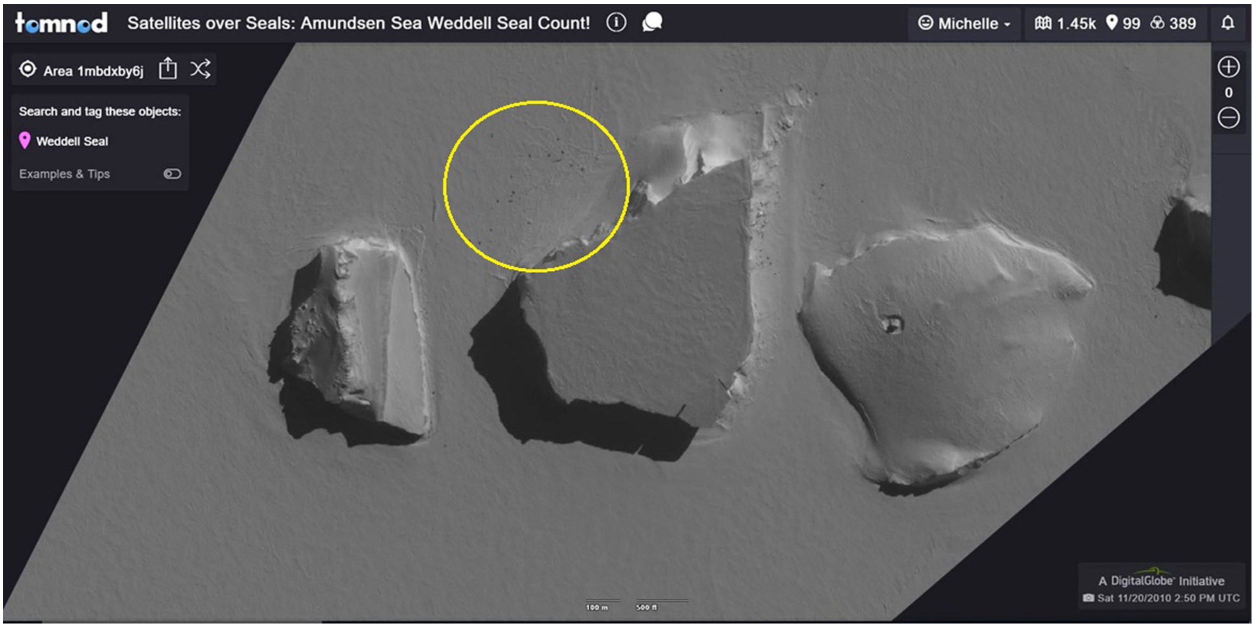

FIGURE 2 Example of Weddell seals on Tomnod crowd-sourcing campaign (high-resolution satellite imagery). The yellow circle on the image indicates a group of several Weddell seals, which can be seen as small black dots on the ice

TABLE 1 Citizen science campaigns to understand pack ice seal (Weddell seal and crabeater seal) presence and abundance in the Southern Ocean using the high-resolution satellite imagery and crowd-sourcing platform, Tomnod (now GeoHive, Maxar Technologies). Validation campaigns include a binary vote as to whether a seal was present and tagging campaigns include participants placing tags on top of features that are likely seals

Seal species	Campaign type	Location	# days	# participants	km^2	Price (USD)
Crabeater	Validation	Weddell Sea	120	2225	18,219	$16,000
Weddell	Validation	Amundsen/Bellingshausen	56	2615	21,508	$8603
Weddell	Validation	WAP/AstridOlaf/Weddell Sea	57	7540	38,732	$15,493
Weddell	Validation	Mawson, Davis/Adare	102	3158	100,494	$40,198
Weddell	Validation	Final campaign	45	1809	29,684	$11,874
Weddell	Tagging	WAPS	39	87	5665	$2266.
Weddell	Tagging	Ross Sea #2	24	74	10,668	$4267
Weddell	Tagging	Amundsen	8	35	1491	$596
Weddell	Tagging	East Antarctica #1	27	86	12,516	$5006
Weddell	Tagging	East Antarctica #2	13	51	9384	$3754
Weddell	Tagging	Queen Maud Land	36	231	21,075	$8430
Weddell	Tagging	Ross Sea #1	126	319,610	98,980	$39,592
		Total	*653*	*337,521*	*368,416*	*$156,079*

monitoring program, involving international collaboration (e.g., Antarctic Pack Ice Seals program; Gurarie et al., 2017), could not only advance our understanding of population trends for key indicator species in the Southern Ocean, but also engage the public in the scientific method, and promote trust in scientific institutions.

5 | GLOBAL RELEVANCE OF ANTARCTIC VHR LESSONS

Adopting VHR methods within Antarctic MPA research and monitoring programs would not only benefit conservation management in the Southern Ocean but also serve as an example of how to use these tools to support marine protection in similarly remote, international waters. Such leadership is especially pertinent to the forthcoming United Nations Treaty, which seeks a policy framework for designating MPAs in areas beyond national jurisdiction (Gardiner, 2020). Several studies beyond those dedicated to Antarctic ecosystems clearly demonstrate the feasibility of using VHR methods to detect species in other regions and inform marine conservation initiatives. For example, researchers have reported on the detection of, and deep-learning algorithms for, surveying baleen whales using VHR methods (Borowicz et al., 2019; Cubaynes et al., 2019). VHR images have also been used to detect and enumerate albatross (*Diomedea* spp.; Bowler et al., 2020), which are common fisheries by-catch. In the Russian Arctic, Platonov et al. (2013) found GeoEye images useful in detecting several species of marine mammals near Wrangel Island, which is already set aside for conservation. As the need for enhancing marine protection around the world grows, there is clearly a precedent that remotely sensed images can be integrated in monitoring several marine indicator species.

In the words of this decade, VHR methods are the science we need for the ocean we want. Current and future management authorities, MPA policies, and management plans can benefit greatly from the adoption of these monitoring technologies. Research groups across the planet are actively working to further methodologies for analyzing images, including artificial intelligence algorithms and better means to engage with, and analyze data from, community science programs. Remote sensing research and development institutions (e.g., NASA) are also rising to the challenge of monitoring biodiversity through remote sensing (e.g., Biodiversity Observation Network, https://geobon.org/). Investments to develop enhanced research and monitoring through VHR will help establish monitoring baselines as early as possible and better evaluate the rapid changes in polar ecosystems and other areas that are anticipated due to climate change.

VHR tools and methods are gaining reputation and have proven their worth in the icy, hostile, and vast ocean space surrounding Antarctica and in other such remote marine regions. The respective policy body for the Southern Ocean, CCAMLR, has also proven its merit by designating MPAs in some of the most treacherous and distant international waters on Earth. CCAMLR's mandate to use the best available science to underpin decisions regarding Southern Ocean ecosystems provides a strong foundation for the use of rapidly improving VHR technologies. Incorporating VHR methods into MPA research and monitoring efforts, as we argue here, will be a scalable and easy way for the research community to support the achievement of CCAMLR's core conservation objective and its commitment toward establishing a representative network of MPAs. Satellite imagery has also proven itself as a reliable method for collecting continuous data sets, even throughout periods of severe global disruption. Thus, we argue that VHR methods provide a key tool for marine conservation efforts across the world, both now and in the future.

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