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Antarctic Affairs is the academic magazine of the Antarctic and Southern Ocean Coalition (ASOC) and Agenda Antártica, which aims to publish and disseminate the most prominent and influential research in relation to Antarctica. The journal publishes articles, reviews and official documents in English and Spanish. The purpose of this publication is also to stimulate research that contributes to environmental protection of Antarctica and the Southern Ocean.

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The Antarctic and Southern Ocean Coalition (ASOC) was founded in 1978 by five environmental organizations in the US, UK, Australia and New Zealand, promoting a World Park vision for protecting Antarctica and the Southern Ocean. ASOC has worked since 1978 to ensure that the Antarctic Continent, its surrounding islands and the great Southern Ocean survive as the world's last unspoiled wilderness, a global commons for the heritage of future generations. ASOC is an invited observer to the meetings of the Antarctic Treaty and CCAMLR. The Secretariat of the ASOC, which includes 21 organizations in 11 countries, is based in Washington, D.C. For more information about ASOC, visit: www.asoc.org

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MESSAGE FROM THE MANAGING EDITOR

Dear readers,

It is a true pleasure to present the eleventh volume of the *Journal of Antarctic Affairs*, in a global context marked by accelerated environmental transformations, growing geopolitical tensions, and renewed international attention to the future of the oceans and polar regions. In this scenario, Antarctica continues to occupy a central place in both cutting-edge scientific research and debates on environmental governance, biodiversity conservation, and international cooperation.

As climate change redefines the physical, biological, and social balances of the white continent and the Southern Ocean, it becomes increasingly urgent to understand not only its ecological dynamics but also the institutional, legal, and political frameworks that guide its protection. In this new volume, *Antarctic Affairs* reaffirms its commitment to disseminating excellent research that contributes to scientific knowledge, strengthens the Antarctic Treaty System, and informs evidence-based public policy.

This edition opens with an article by Matt Spencer, Claire Christian, Holly Curry, and Mary Liesegang that analyzes the emerging challenges to the conservation of the Southern Ocean amid accelerated climate change. Through a detailed examination of the mandate of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), negotiations on marine protected areas, and the 30x30 global framework, the authors offer a political and scientific analysis of the obstacles and opportunities for consolidating an effective marine protection network in one of the planet's most pristine and fragile ecosystems.

Next, Virginia Gascón, Nina Gallo, Rodolfo Werner, and Juan Lucci examine the emerging regime on microplastic pollution in Antarctica, based on recent discussions at the Antarctic Treaty Consultative Meetings. Through an institutional analysis that connects the evolution of global environmental law to the specific challenges of the Antarctic Treaty System, the authors offer a critical perspective on regulatory gaps and opportunities for multilateral cooperation to address this issue.

The third article, by Nicolás Antonio Napolitano, Francisco Massot, Cecilia Quiroga, Walter Mac Cormack, and José Luis López, delves into polar microbiology and the study of Antarctic bacteriophages. Through genomic and functional research on extremophile bacteria, the authors explore virus-bacteria coevolution in polar environments and its biotechnological potential, opening new perspectives for applications in health, industry, and bioremediation.

This volume concludes with the work of Francyne Elias-Piera, Juliana Souza-Kasprzyk, Elaine Alves dos Santos, Cristiane Fonseca Caetano da Silva, Sandra Freiburger-Affonso, and Sílvia Dotta, who analyze Antarctic science education and outreach through webinars in the Global South. Their case study in Brazil demonstrates how digital tools can broaden access to polar knowledge, reduce territorial gaps, and strengthen scientific culture in societies geographically distant from Antarctica.

Finally, I would like to express my gratitude to the authors for the quality and commitment of their contributions, as well as to the translators, reviewers, and members of the Editorial Board, whose

MESSAGE FROM THE MANAGING EDITOR

work has been essential in making this edition possible. We are confident that the perspectives presented in this volume will enrich the academic and political debate on the present and future of Antarctica and contribute to building an international community increasingly committed to its protection.

Juan José Lucci

ASOC PROLOGUE

Antarctica and the Southern Ocean are today at the center of some of the most relevant environmental and geopolitical discussions on the planet. In the context of increasing human pressures and accelerating climate change, the region faces challenges that test the ability of the international community to uphold the mandate of peace, science, and cooperation that underpins the Antarctic Treaty System.

There are several priority issues on which Antarctic Affairs has focused in previous editions, and which continue to define the state of Antarctic conservation and shape its future in the coming decades.

First, the prolonged stagnation in the establishment of new Marine Protected Areas reveals the tension between scientific evidence and the political dynamics of consensus within CCAMLR. The proposals to establish MPAs in East Antarctica, the Weddell Sea, and Domain 1 (Antarctic Peninsula) have strong scientific foundations and broad support from Members, yet objections from a few States have prevented progress in protecting particularly vulnerable ecosystems.

Another key issue is the sustainable management of the Antarctic krill fishery, a resource essential to the ecological fabric of the Southern Ocean and subject to an expanding fishery, both in volume and spatial concentration. Environmental variability and increasing fishing pressure underscore the need to strengthen a precautionary and ecosystem-based approach.

The accelerated impact of climate change represents another major concern. The loss of ice shelves, the decline of sea ice, and shifts in oceanographic patterns are affecting seabird populations and altering species distributions, even facilitating the arrival of organisms from more temperate regions. Translating this knowledge into effective conservation policies remains one of today's greatest challenges.

Adding to these concerns is the growing evidence of microplastic contamination in the region. Synthetic fibers have been detected in seawater, sediments, snow and even marine organisms, reminding us that no ecosystem, no matter how remote, is isolated from global pressures.

In this context, education and outreach emerge as fundamental pillars for strengthening collective awareness of the need to conserve Antarctica and the Southern Ocean. Promoting public understanding of their fragility, climatic importance, and the threats they face is essential to fostering an informed and committed citizenry. Education—in this sense—is key to inspiring new generations of professionals, decision-makers, and citizens.

In this volume, Antarctic Affairs seeks to continue contributing to the understanding of the many issues affecting the Southern Ocean and Antarctica, facilitating the debate that will support the development of appropriate conservation policies.

Dr. Rodolfo Werner*
Editor

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PROTECTING A CHANGING SOUTHERN OCEAN

Matt Spencer, Claire Christian, Holly Curry and Mary Liesegang

ABSTRACT

Antarctica remains one of Earth's most pristine regions, yet growing scientific evidence indicates a paradigm shift in its oceanic and atmospheric conditions. The resilience of the Southern Ocean, once considered robust against global climate pressures, is weakening. This article examines the urgent need for enhanced protection through the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the establishment of a representative system of marine protected areas (MPAs). Drawing from recent assessments, including the 2023 Marine Ecosystem Assessment for the Southern Ocean (MEASO), this analysis highlights the accelerating environmental changes, governance challenges, and the need to move protection of Antarctica in line with other international frameworks, such as the Convention on Biological Diversity's 30x30 target. Recommendations are presented to reiterate CCAMLR's conservation mandate through the immediate implementation of pending MPA proposals, development of a Domain 9 MPA, and refining nationally determined MPAs in the Southern Ocean to mitigate against climate change.

KEYWORDS

Southern Ocean, CCAMLR, marine protected areas, climate change, Antarctic governance.

INTRODUCTION

Antarctica resides in the global imagination as a realm of unparalleled beauty and one of the last bastions of environmental purity. However, emerging research signals a paradigm shift in Antarctica’s oceanic and atmospheric systems: the continent’s long-standing resilience in the face of climate change is showing signs of decline. Once perceived as remote and unchangeable, the Antarctic is now increasingly recognized as a frontline region for global climate disruption (Constable et al., 2023). The management of fishing activities and the protection of the Southern Ocean fall under the remit of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Founded in 1982 under the Antarctic Treaty System (ATS), CCAMLR’s central tenet is the application of an ecosystem-based precautionary approach to fisheries management and the conservation of Antarctic marine living resources. This approach recognizes that exploitation should not proceed without sufficient scientific understanding of its potential ecological consequences.

In 2009, CCAMLR committed to establishing a representative system of marine protected areas (MPAs) by 2012. Yet more than a decade later, progress remains stalled. Urgent implementation of these MPAs is now critical, as scientific evidence demonstrates escalating changes affecting the Southern Ocean, ranging from sea ice loss to ecosystem shifts impacting krill, penguins, and whales (Siegert et al., 2023).

Time is not on the side of the Southern Ocean. As the ecological transformations accelerate, CCAMLR must act as the guardian of Antarctic marine life it was designed to be. The Antarctic and Southern Ocean Coalition (ASOC) therefore calls upon CCAMLR Members to act collaboratively for the collective benefit of the Antarctic and uphold the precautionary principle that is central to the Convention.

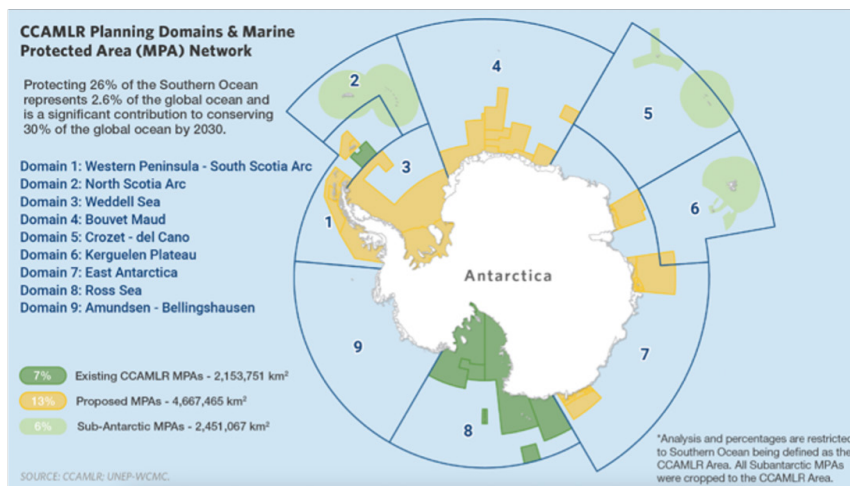


Figure 1. Proposed and implemented protected areas in the Southern Ocean. Credit: Michael Wissner, The Pew Charitable Trusts.

THREATS TO THE SOUTHERN OCEAN

The Southern Ocean is a reservoir of biodiversity, supporting complex food webs from phytoplankton to apex predators. Yet, it also carries a history of intense exploitation. The first major threat emerged when seal hunting began around 1790, rapidly decimating populations of species such as the Antarctic fur seal (*Arctocephalus gazella*).

Throughout the 19th and 20th centuries, extraction expanded to include whales and fish. Distant-water trawlers from multiple nations dismantled marine ecosystems, driving species such as marbled rockcod (*Notothenia rossii*) to near collapse, with populations that have yet to recover fully. This historical depletion created a legacy of ecological imbalance that continues to shape the region's resilience today (Brooks et al., 2020).

In recent decades, the dominant threats have shifted from overfishing to anthropogenic climate change. The Marine Ecosystem Assessment for the Southern Ocean (MEASO) underscores that “substantial ecosystem changes are occurring now and could occur in the future over periods of only a few years or decades as a result of rapid environmental shifts, extreme events, or the crossing of system thresholds to alternative states” (Constable et al., 2023).

These “thresholds” reflect tipping points that, once crossed, can irreversibly alter ecosystem structure and function. Extreme events such as marine heatwaves, ice shelf collapse, and unprecedented temperature anomalies are now increasing in frequency. For example, the Antarctic continent recently experienced temperature deviations more than 30°C above seasonal norms, a phenomenon unmatched elsewhere on Earth (Siegert et al., 2023).

These climatic disruptions interact with human activities such as industrial krill fishing and expanding tourism. Fishing pressure can undermine krill availability for predators like penguins and seals, while tourism growth introduces invasive species and pollution risks. Collectively, these pressures compound the ecological stressors driven by global warming and ocean acidification.

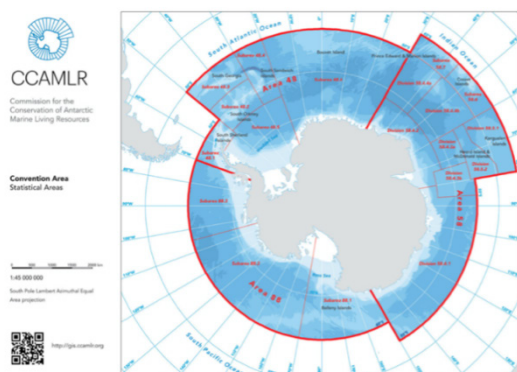


Figure 2. A figure showing CCAMLR’s management boundary. Source: CCAMLR 2024a.

THE ROLE AND MANDATE OF CCAMLR

The Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) was established as part of the Antarctic Treaty System to address growing concerns over unregulated exploitation, especially the expansion of the krill fishery in the late 1970s (Trathan, 2023). CCAMLR, the Commission established to implement the Convention, was conceived not merely as a fisheries management body, but as a pioneering approach to ecosystem-based governance.

Article II of the CAMLR Convention unambiguously defines conservation as its paramount objective, explicitly requiring that rational use not compromise ecosystem integrity. This legal framing distinguishes CCAMLR from most regional fisheries management organizations (RFMOs), which typically balance conservation with exploitation objectives.

Despite this ambitious design, CCAMLR's consensus-based decision-making process, once lauded as a model of Cold War-era cooperation, has become a double-edged sword. While consensus fosters inclusivity, it also allows any Member to veto progress. This procedural rigidity has repeatedly hindered adoption of new MPAs, particularly since 2016 (Miller & Slicer, 2014).

MARINE PROTECTED AREAS: CONCEPT AND BENEFITS

Marine protected areas (MPAs) are foundational instruments for marine biodiversity conservation. They vary in design and management purposes, but their core purpose is to safeguard ecosystem processes, preserve species habitats, and enhance resilience to disturbance.

Scientific research consistently demonstrates that large, well-designed MPAs with strict protection, particularly no-take zones, produce substantial ecological benefits. These include increases in biomass, species diversity, and genetic variation, which in turn bolster ecosystem resilience against climate-induced shocks (Chavez-Molina et al., 2023).

Moreover, MPAs generate spillover effects, whereby populations within protected zones replenish adjacent fished areas. This phenomenon illustrates that conservation and rationale use can be complementary rather than mutually exclusive (Ashford et al., 2022).

CURRENT CCAMLR NEGOTIATIONS ON MARINE PROTECTED AREAS (2012–2024)

CCAMLR's deliberations on MPAs span more than a decade. In 2009, CCAMLR formally endorsed the development of a representative system of MPAs and agreed to a framework for establishment (CM 91-04) in 2011. Early successes included the 2009 South Orkney Islands MPA, the world's first high seas MPA, and the 2016 Ross Sea Region MPA. However, since 2016, the Commission has failed to agree on any new designations, despite strong scientific consensus supporting additional MPAs in East Antarctica, the Weddell Sea, and the Antarctic Peninsula (Domain 1).

Between 2017 and 2022, successive CCAMLR meetings reaffirmed support for these proposals but failed to reach consensus. Political divisions, primarily between conservation-oriented and resource-extraction-oriented Members, have repeatedly impeded progress (Brooks et al., 2020; Pew Charitable Trusts, 2023). The Scientific Committee (SC-CAMLR) consistently validated the science underpinning the proposals, yet the Commission's requirement for unanimity has proven a formidable procedural obstacle.

The 2023 annual meeting (CCAMLR-42) again placed MPA establishment at the top of the agenda (ASOC, 2023a). Discussions focused on refining the East Antarctica (EAMPA), Weddell Sea (WSMPA Phase 1), and Domain 1 (D1MPA) proposals. Although Members acknowledged the urgent need for action in the face of accelerating climate impacts, negotiations concluded without agreement. Several Members cited geopolitical tensions and differing views on zoning and fishery access as reasons for deferral (ASOC, 2023b).

In 2024, a mid-year symposium co-convened by the United States and the Republic of Korea sought to harmonize the Domain 1 MPA's boundaries with updated krill fishing management strategies. Despite productive exchanges, the October 2024 Hobart meeting once again ended without MPA designation (ASOC, 2024). Moreover, the Commission failed to renew Conservation Measure 51-07, a protective measure that distributed krill catch to prevent local depletion, raising further concerns about ecosystem resilience.

Observers noted that while scientific data are ample, with the Domain 1 MPA proposal including 150 data layers, political inertia persists. To many stakeholders, the inability to advance MPA designations, despite compelling evidence, represents a crisis of credibility for CCAMLR's precautionary mandate.

ANTARCTICA AND THE GLOBAL 30X30 FRAMEWORK

Recent international commitments have reinvigorated global attention to marine conservation. In December 2022, the Convention on Biological Diversity (CBD) adopted the Kunming-Montreal Global Biodiversity Framework (GBF), pledging to protect 30% of Earth's land and ocean areas by 2030.

Given that the Southern Ocean constitutes roughly 10% of the global ocean, CCAMLR's progress, or lack thereof, will substantially determine the feasibility of achieving the 30x30 target. The Southern Ocean's ecological significance extends far beyond its boundaries; it regulates global carbon cycles, drives thermohaline circulation, and supports migratory species that connect hemispheres.

CCAMLR's leadership in implementing MPAs represents not only a regional obligation, but also a global responsibility. The Antarctic region's inclusion within the 30x30 vision would symbolize multilateral environmental cooperation at its most ambitious scale (Chavez-Molina et al., 2023).

A NETWORK OF MPAS IN THE SOUTHERN OCEAN

Despite the recent stalemate, CCAMLR has a history of conservation milestones. The adoption of the South Orkney Islands Southern Shelf MPA in 2009 and the Ross Sea Region MPA in 2016 established precedents for high-seas protection under multilateral governance. However, only 13% of the Southern Ocean is currently designated as MPAs, and a mere 5% falls under strict no-take status (Brooks et al., 2020).

Four large MPA proposals remain pending, each scientifically vetted, with two gaining endorsement from the Scientific Committee to CCAMLR (SC-CAMLR):

- Domain 1 MPA (460,000 km²): Encompasses critical habitats for emperor penguins and foraging areas for humpback whales. It also protects nursery and early life stage zones for krill, a keystone species (proposed 2017).
- East Antarctica MPA (970,000 km²): Hosts extensive vulnerable marine ecosystem (VME) indicator species such as sponges and cold-water corals (proposed 2012).
- Weddell Sea MPA Phase 1 (2.2 million km²): Supports a third of known emperor penguins, half the world's Antarctic petrels, and benthic ecosystems comparable in complexity to tropical coral reefs (proposed 2018).
- Weddell Sea MPA Phase 2 (780,000 km²): Covers biologically significant areas like the Maude Rise, among the planet's most pristine environments (proposed 2023).

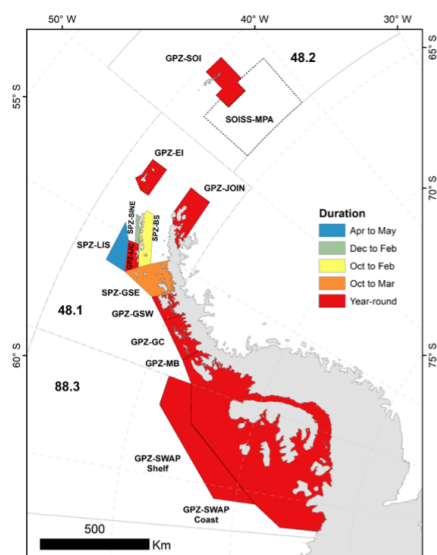


Figure 3. *The Domain 1 MPA: General protection zones and seasonal protection zones with colors representing the periods of closure. Source CCAMLR 2024b*

PROTECTING A CHANGING SOUTHERN OCEAN

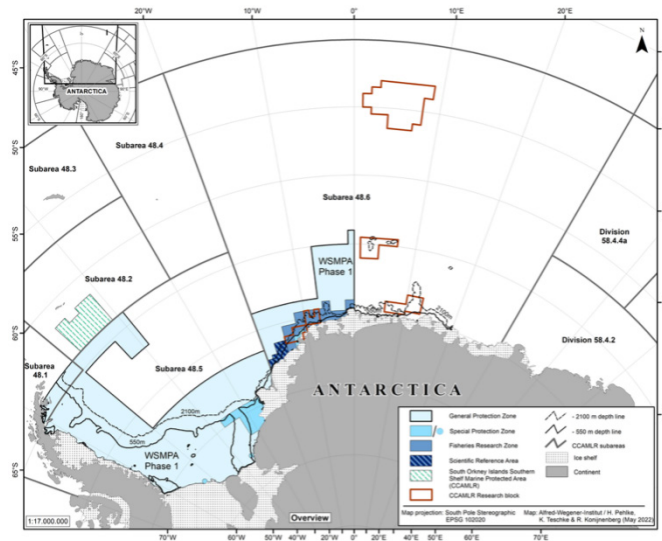


Figure 4. Proposed Weddell Sea MPA (WSMMA) Phase 1 (in blue). Source: Alfred Wegener Institute Weddell Sea MPA proposal status 2023.

Each of these proposals represents years of cooperative scientific effort and negotiation. Their adoption would advance CCAMLR toward a truly representative MPA network, aligning its mandate with the CBD's 30x30 framework and the broader objectives of the United Nations Decade of Ocean Science. When adopted, combined with existing protections, 26% of the Southern Ocean and 2.6% of the global ocean would be protected, a critical step towards 30x30 ambition.

DOMAIN 9: THE MISSING LINK

Among CCAMLR's planning domains, Domain 9, the Amundsen-Bellinghousen Sea, is the least studied and most neglected in terms of proposed protection. The absence of an MPA proposal in this region leaves a significant gap in CCAMLR's commitment to representativeness.

Scientific studies have identified Domain 9 as home to productive polynyas, cold-water corals, seamounts, and hydrothermal vents, particularly near Peter I Island (Adams et al., 2021). Establishing an MPA here would complete the geographic coverage envisaged under CCAMLR's 2011 framework and protect one of the last intact marine ecosystems on Earth.

NATIONALLY DETERMINED MPAS

The Southern Ocean has a number of notable islands outside of Antarctica's immediate vicinity and beyond CCAMLR jurisdiction, albeit still part of the Southern Ocean because they are shaped

by the Antarctic Circumpolar Current (ACC). These sub-Antarctic islands - which are overseas territories administered by Australia, France, Norway, South Africa, and the United Kingdom - host extraordinary biodiversity, including millions of penguins, vast seal colonies, and migratory seabirds (Brooks et al., 2019). It is important to note, however, that CCAMLR does not recognize territorial claims and some Members formally dispute such claims.

Currently, seven MPAs exist in the Southern Ocean, five of them surrounding these sub-Antarctic islands are nationally determined. Collectively, they account for nearly half of all MPA coverage in the region. It is apparent then that the contribution of individual Members towards the protection of the Southern Ocean has and will continue to be crucial in light of a changing climate. The enhanced protection around sub-Antarctic islands also serves to highlight the inadequacy of CCAMLR's own efforts to implement protective measures, and represents a gap that must urgently be closed.

Expanding and enhancing the protection of sub-Antarctic islands is essential for building climate resilience. As environmental shifts intensify, national MPA reviews must consider dynamic management approaches—adjusting boundaries and enhancing protection in response to changing conditions (ASOC, 2023c).

RECOMMENDATIONS

CCAMLR was once heralded as a model of multilateral conservation, yet its credibility now depends on renewed action. Implementing a representative network of MPAs across the Southern Ocean would restore confidence in its governance and signal that Antarctic protection remains a global priority.

-Recommendation I: Implement Pending MPA Proposals

The Antarctic Peninsula (Domain 1), Weddell Sea Phase 1, East Antarctica, and Weddell Sea Phase 2 MPA proposals are based on robust science and are ready for adoption, pending the political will. ASOC calls on all Members to uphold the precautionary principle, follow the advice of best available science and adopt these proposals without further delay.

-Recommendation II: Develop a Domain 9 MPA

CCAMLR must begin formal consideration of a Domain 9 MPA to close the gap in the commitment to a representative network of MPAs. Although CCAMLR has yet to begin the formal process of developing a Domain 9 MPA proposal, a suite of information is already available from scientific surveys and from members of the science community who have researched the region and whose findings should be utilized.

-Recommendation III: Review Nationally Determined MPAs for Climate Resilience

Given the pace of ecological change, ASOC recommends systematic review of all nationally determined MPAs to ensure they remain effective under new environmental conditions. Specific

recommendations include:

- Australia: to further expand the marine reserve boundaries within the Heard and McDonald Islands Exclusive Economic Zone (EEZ), ahead of its statutory review in 2034, to incorporate key areas such as undersea canyons, biodiverse seamounts and the Williams Ridge.
- Norway: to immediately expand the reserve around Bouvet Island to 200 nm and in doing so create an International Union for Conservation of Nature (IUCN) Category 1 MPA to protect key oceanographic features and the local ecosystem.
- South Africa: to review the Prince Edward Islands MPA and implement enhanced conservation measures. In its current design only 5.5% of the EEZ prohibits all human activity, with key sites such as seamounts falling outside of highly protected areas.
- France: to revisit its marine spatial planning for Crozet Islands, which remains largely open to human activities, such as fishing, to ensure France commits to safeguarding 30% of its marine environment in the Terres Australes et Antarctiques Françaises (TAAF) region through protected areas by 2030.
- South Georgia and South Sandwich Islands (UK): to continue the formal MPA review every five years, or more frequently if data is suggesting urgent action is needed.

Together, these actions would lay the foundation for an adaptive, climate-resilient conservation network in the Southern Ocean, bringing the world a critical step closer to achieving global ocean conservation goals.

CONCLUSIONS

The fate of the Southern Ocean reflects the broader crossroads facing global environmental governance. CCAMLR's ability, or failure, to act will determine whether the region remains a sanctuary for biodiversity or becomes another casualty of political paralysis.

By fulfilling its commitments—adopting pending MPAs, developing a Domain 9 MPA proposal, and ensuring adaptive management—CCAMLR can reclaim its leading role in international conservation. Protecting the Southern Ocean is not only vital for Antarctic species and ecosystems, but also for maintaining planetary stability. The time for action is now.

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and enhance ecosystem connectivity and function.

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THE ATCM AND THE EMERGING REGIME ON MICROPLASTIC POLLUTION IN ANTARCTICA: A REVIEW OF CHALLENGES AND OPPORTUNITIES

Virginia Gascón, Nina Gallo, Rodolfo Werner and Juan Lucci

ABSTRACT

Plastic pollution is one of the most pressing environmental challenges of our time, affecting ecosystems and communities worldwide. Not even the remote and relatively untouched Antarctic region is immune to this threat, with growing evidence of widespread microplastic contamination and accumulation in Antarctic environments—from coastal seawater and snow to the digestive systems of marine organisms and seabirds. Addressing this issue is not only vital for the health of Antarctic ecosystems but also for the global fight against marine plastic pollution. The Antarctic Treaty Consultative Meeting (ATCM) has a critical role to play in spearheading international efforts to prevent and mitigate plastic waste in this fragile region. While research and monitoring efforts are growing, however, policy actions remain fragmented and underdeveloped. This article provides an analysis of the latest developments at the ATCM level, highlighting key challenges, opportunities and recommendations in light of global negotiations for a Global Plastics Treaty. By linking Antarctic initiatives to broader global frameworks, the ATCM can contribute meaningfully to a more comprehensive and effective global response to plastic pollution.

KEYWORDS

Microplastics, ATCM, Antarctica, Southern Ocean, Global Plastic Treaty

INTRODUCTION

The proliferation of plastics represents one of the most pervasive forms of anthropogenic pollution. Global plastics production exceeds 400 million tonnes annually, with an estimated 11 million tonnes entering the oceans each year (OECD, 2022; Pew Charitable Trusts, 2020). Once in the environment, plastics fragment into smaller particles—microplastics (<5 mm) and nanoplastics (<1 µm)—that persist for centuries and interact with biological systems. Comprising particles made of synthetic polymers, microplastics were first identified in the 1960s and subsequently described in the 1960s (GESAMP, 2015), and have since been detected in the ocean, atmosphere and the digestive tracts and faeces of living organisms. Primary microplastics come from a range of marine and terrestrial sources, including wastewater, which may contain microplastic fibres and fragments from synthetic fabrics in laundry water and microbeads from personal hygiene products. Secondary microplastics originate from the breakdown of larger macroplastic items, such as abandoned, lost, or discarded fishing gear (ALDFG), marine plastic pellets (nurdles), ropes, paints and antifouling systems (Yang et al., 2021). The Antarctic, long thought to be protected by geographic isolation and legal safeguards, is not immune to this trend with microplastics having been identified in the Southern Ocean, Antarctic snow, sediments and wildlife (Aves et al., 2022; González-Aravena et al., 2024; Isobe et al., 2017)¹. Their presence in such a remote environment illustrates the transboundary nature of plastic pollution.

This article aims to analyse how the Antarctic Treaty System (ATS) and, in particular, the Antarctic Treaty Consultative Meeting (ATCM) have responded to the growing evidence of microplastic contamination in the region. By analysing the evolution of scientific evidence, policy debates and institutional responses, the paper seeks to identify the main governance gaps, challenges and opportunities for strengthening Antarctic environmental protection within the broader context of global plastic governance. The analysis is based on a qualitative review of scientific literature and policy documents, including ATCM Resolutions, CCAMLR Conservation Measures, and records from ATCM 46 and 47 (Kochi, 2024; Milan, 2025). Through this combined assessment, the paper traces how knowledge generated by Antarctic research is informing policy discussions and explores how the ATCM can serve as a bridge between regional conservation initiatives and future global frameworks.

This paper is structured as follows: Section 2 reviews the most significant scientific literature regarding sources, transport mechanisms and ecological impacts of microplastics in Antarctica, situating these findings within the broader context of polar contamination. Section 3 expands the analysis to global governance efforts addressing plastic pollution, including recent negotiations towards a UN Global Plastics Treaty. Section 4 examines the existing regulatory framework under the ATS, followed by an assessment of the evolving role of the ATCM in shaping policy action on plastic pollution. Section 5 identifies the main challenges and opportunities for strengthening the Antarctic response to plastic pollution and presents policy recommendations. The paper concludes by discussing how the ATS can take a leading role in advancing global environmental governance in the age of plastics.

LITERATURE OVERVIEW: MICROPLASTIC POLLUTION IN ANTARCTICA

Microplastic contamination in Antarctica arises from both local and distant anthropogenic sources. The main local contributors include research stations, tourism and fishing operations, while long-range transport via atmospheric and oceanic currents introduces additional inputs (Cunningham et al., 2022; Isobe et al., 2017; Napper & Thompson, 2016; Primpke et al., 2024). Early research on Antarctic plastic debris, predating the focus on microplastics, documented/registered macroplastic accumulation on beaches and fishing gear losses as early as the 1980s (Barnes et al., 2009; Gregory, 1989). These foundational studies established how human activity at research stations and in fisheries introduced synthetic materials to the region.

Recent evidence shows that microplastics are widespread across Antarctic environments and ecosystems, with their presence having been detected in coastal seawater near the Antarctic Peninsula (Lacerda et al., 2019), in snow samples from Ross Island (Aves et al., 2022), and in sediments of Terra Nova Bay (Munari et al., 2017) and near Rothera Research Station (Reed et al., 2018). Comparable contamination levels have been reported in the Southern Ocean and Ross Sea, with some concentrations approaching those of highly polluted coastal regions in other areas of the world (Switzerland, 2024). A growing body of research also documents atmospheric deposition, confirming that microplastics are transported via precipitation, including snow (Allen et al., 2021; Illuminati et al., 2024). Indeed, Illuminati et al. (2024) measured an average daily atmospheric flux of -1.7 ± 1.1 particles $m^{-2} d^{-1}$, dominated by polypropylene, polyethylene and polycarbonate fragments, demonstrating that both local and long-range inputs contribute to Antarctic contamination. Likewise, Kelly et al. (2020) identified fourteen polymer types in land-fast sea-ice cores from East Antarctica, highlighting sea ice as a significant sink and secondary source of plastic debris.

The transport and deposition mechanisms of these pollutants are diverse. Microplastics reach the continent via atmospheric circulation, drifting ice and ocean currents, while local wastewater, packaging waste and ALDFG intensify contamination near human installations (Allen et al., 2021; Obbard et al., 2018; Primpke et al., 2024). Studies increasingly emphasise the coupling of these pathways: Jones-Williams et al. (2023) showed that even inland regions of Antarctica exhibit a microplastic footprint dominated by $< 50 \mu m$ polyamide particles, implying the combined effect of long-range atmospheric transport and local emissions. Similarly, Zhang et al. (2022) found that microplastic distribution in the Southern Ocean reflects both southward transport from lower latitudes and local Antarctic sources.

The ecological presence and biological uptake of microplastics are now well-established and have been identified in the digestive tracts and faeces of penguins, krill, fish and benthic filter feeders, revealing trophic transfer within Antarctic food webs (Dawson et al., 2018; Fragão et al., 2021; Zhu et al., 2023). Bessa et al. (2019) found microplastic fibres in approximately 20 % of Gentoo penguin faecal samples at Bird and Signy Islands, while a more recent study by Fragão et al. (2021) detected microplastics and other anthropogenic particles in three penguin species. More recently, Bhattacharjee et al. (2024) identified microplastics in penguin internal organs, highlighting a previously unrecognised exposure pathway, while a study synthesising data from the late 1980s to 2023 found that 97 % of sampled Antarctic birds contained at least

one microplastic fragment or fibre (Taurozzi & Scalizi, 2024).

Zhu et al. (2023) detected microplastic ingestion in four Antarctic fish species and contamination of Antarctic krill (*Euphausia superba*), highlighting the entry of synthetic particles at the base of the Southern Ocean food chain. Microplastics can also be ingested by planktonic suspension and filter feeders such as krill, which are particularly vulnerable due to their feeding strategies (Dawson et al., 2018). This vulnerability is further intensified by sea-ice dynamics that enhance the uptake of microplastics by algae and krill (Rota et al., 2022). Once ingested, these particles can exert toxicological effects on keystone species, influencing entire ecosystems through bioaccumulation and biomagnification (Waller et al., 2017). Moreover, microplastics may act as vectors for pathogenic bacteria (Caruso et al., 2022) and can degrade into nanoplastics (< 1 µm). The unique environmental conditions of the Southern Ocean—low temperatures, intense UV radiation and strong turbulence—likely accelerate the fragmentation of larger plastics into micro- and nanoplastics, increasing their ecological risks (SCAR, 2023). Laboratory evidence shows that krill digestion can actively fragment microplastics into nanoplastics (Dawson et al., 2018), enhancing their bioavailability and capacity to cross biological barriers. The interplay between sea-ice dynamics, microbial colonisation and mechanical abrasion thus creates a continuous cycle of fragmentation that transforms macroplastics into microplastics and ultimately into nanoplastics permeating the Antarctic food web.

González-Aravena et al. (2024) further found microplastics in *Laternula elliptica* clams around King George Island, and microplastics have also been detected in Antarctic sediments and deep-sea environments, revealing that remote benthic ecosystems are not exempt from human pollution. Cunningham et al. (2020) recorded microplastics in 93% of deep-sea sediment samples from the Antarctic Peninsula, South Georgia and South Sandwich Islands, suggesting that these sediments act as long-term sinks.

Taken together, existing research shows that microplastic particles are present in the Antarctic environment and biota, in some cases in high concentrations (Leistenschneider et al., 2024). Pellegrino et al. (2025) stress that Antarctica's isolation does not protect it from microplastic contamination across marine, freshwater and terrestrial systems, as was once thought, with microplastics originating from both local and long-range anthropogenic sources. Moreover, De-la-Torre et al. (2025) add that accumulation of macro-, micro-, and nano-plastics is increasingly constraining the health and resilience of Antarctic benthic and pelagic communities.

GLOBAL GOVERNANCE FOR PLASTIC POLLUTION

Plastic pollution has evolved from a localised waste-management concern into a global governance challenge that transcends borders, ecosystems and jurisdictions. Its durability, mobility and ubiquity ensure that even the most remote environments are affected by its accumulation and degradation products. Yet, despite its global scale, international responses have long remained fragmented, often limited to voluntary initiatives or sector-specific regulations, with little coordination between production, trade and waste management. Addressing this crisis requires not only improving recycling but also developing a comprehensive regulatory framework capable of governing the entire

life cycle of plastics. The search for such coherence has prompted renewed diplomatic attention and intergovernmental negotiations aimed at elevating plastic pollution to the same level of urgency as climate change and biodiversity loss.

Academic literature has increasingly examined the structural weaknesses that undermine global plastic governance. Da Costa et al. (2020) observed that although the number of laws, regulatory initiatives and soft-law guidelines addressing plastic and microplastic pollution has grown worldwide, these instruments remain disjointed, lacking effective enforcement mechanisms and scientific grounding. Similarly, Knoblauch et al. (2021) synthesised forty-five policy studies and found that most national and international frameworks are piecemeal, struggling to address the systemic drivers of plastic production, consumption and waste. Their complementary research on policy capacities and institutional constraints highlights persistent fragmentation across sectors and governance levels, limiting the effectiveness of existing instruments. Nagtzaam et al, (2023) traced the historical evolution of plastics regulation and demonstrate that, despite mounting urgency, international initiatives remain insufficient and poorly coordinated. Collectively, this body of literature indicates that the principal challenge of plastic governance lies not merely in the creation of new instruments but in achieving institutional coherence, scientific alignment and enforceable obligations capable of confronting the transboundary and systemic nature of plastic pollution.

Recent diplomatic initiatives have begun to address these long-standing weaknesses in the global governance of plastic pollution. In November 2021, the International Maritime Organisation's (IMO) Marine Environment Protection Committee (MEPC) adopted its Strategy to Address Marine Plastic Litter from Ships. This initiative represents the first coordinated global effort within the maritime sector to prevent plastic waste discharges from vessels. Its overarching objective is to achieve "zero plastic waste discharges to sea from ships by 2025" (IMO, 2021). The strategy focuses on three complementary pillars: improving waste management practices onboard ships, strengthening port reception facilities and enhancing monitoring and enforcement mechanisms under MARPOL Annex V. By emphasising the life-cycle management of shipborne plastics—including fishing gear, packaging materials and operational waste—the IMO strategy seeks to reduce both intentional and accidental discharges. It also promotes technological innovation, such as biodegradable materials and retrieval systems for lost gear, and elevates plastic pollution to a core element of maritime environmental governance, influencing regional port authorities and industry compliance standards.

Building on this momentum, the United Nations Environment Assembly (UNEA) took a decisive step in March 2022 by adopting Resolution 5/14, which mandates the negotiation of an international legally binding instrument (ILBI) in the form of a Global Plastics Treaty by the end of 2024. This Resolution marked a turning point in multilateral environmental diplomacy, recognising plastic pollution as a planetary crisis requiring a comprehensive response across the entire plastic life cycle—from production and product design to waste management and remediation. To implement the Resolution, UNEA established an Intergovernmental Negotiating Committee (INC) tasked with drafting the treaty text, supported by a Secretariat and technical working groups. The treaty's core objectives include eliminating problematic and avoidable plastics, curbing the release of microplastics, fostering circular economy principles and promoting technology transfer and capacity building for developing countries.

The fifth negotiating session (INC-5.1), held in Busan, South Korea, in November 2024, represented a crucial milestone in the Global Plastics Treaty process, consolidating diverse national positions into a preliminary framework. Despite this progress, however, negotiations concluded without consensus, revealing persistent division among member states. The draft treaty proposed ambitious measures—including global product design standards, a phased ban on harmful polymers and chemicals, and limits on plastic production—but progress was blocked by a small number of countries opposing binding production caps and global restrictions. Consequently, key decisions were postponed to INC-5.2, held in Geneva, Switzerland in 2025, which again ended without agreement. INC-5.3 is scheduled to be held in Geneva, Switzerland, in February 2026; however, this meeting will not involve further negotiation on substance, and the future of the proposed treaty is uncertain.

Despite the inability of parties to reach an agreement at this time, these negotiations have nevertheless reshaped the global discourse on plastics, aligning it more closely with governance models developed for climate and biodiversity regimes, and underscoring a growing recognition of plastic pollution as a planetary crisis demanding coordinated, science-based action.

REGULATION OF PLASTIC POLLUTION UNDER THE ANTARCTIC TREATY SYSTEM

The ATS constitutes the overarching governance framework for all human activities south of 60° South latitude. Established through the 1959 Antarctic Treaty, it provides the legal and institutional basis for maintaining Antarctica as a zone dedicated to peace and science. The ATS encompasses several interlinked instruments, including the Protocol on Environmental Protection to the Antarctic Treaty (commonly known as the Madrid Protocol), the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), the Convention for the Conservation of Antarctic Seals (CCAS) and the Treaty itself. Collectively, these instruments seek to establish a cooperative regime aimed at protecting Antarctic environments and ecosystems. In practice, however, fragmentation and limited monitoring and enforcement capacity pose challenges for the effective management of emerging pollutants such as microplastics and nanoplastics, which cross jurisdictional and sectoral boundaries.

The Madrid Protocol provides the basis of environmental governance in Antarctica. As a legally binding agreement, it commits Parties to the “comprehensive protection of the Antarctic environment and dependent and associated ecosystems”, designating the continent as a “natural reserve, devoted to peace and science” (Art. 2). The Protocol contains several provisions of direct relevance to plastic pollution.

- Annex I on Environmental Impact Assessment (EIA) requires Parties to undertake EIAs for all activities conducted within the Antarctic Treaty area, including the adoption of mitigation measures to minimise environmental impacts.
- Annex III on Waste Disposal and Management mandates the removal of plastic wastes from the Antarctic Treaty area (Art. 2).
- Annex IV on Marine Pollution includes specific prohibitions:
 - The disposal from ships into the sea of all plastics, including synthetic ropes, fishing nets and plastic garbage bags (Art. 5[1]); and
 - The discharge of untreated wastewater from vessels within twelve nautical miles of the coast (Art. 6[1a])².

National Antarctic Programs (NAPs), coordinated under the Council of Managers of Antarctic Programs (COMNAP), have also taken steps to mitigate plastic pollution within their operational scope. The COMNAP Environmental Protection Expert Group has issued a series of recommendations discouraging unnecessary plastic use in the Treaty area, including voluntary bans on personal care products containing microplastics, and strategies to minimise the release of textile-derived microfibrils from laundry and wastewater systems. These measures illustrate an emerging awareness among operational stakeholders of the need to integrate pollution prevention into daily logistical activities. However, they remain largely voluntary and fragmented due to the absence of a binding, ATS-wide framework supported by systematic monitoring, technological innovation and clear compliance and enforcement mechanisms³.

Similarly, CCAMLR has addressed aspects of plastic pollution, particularly those arising from fishing activities. Through Conservation Measure 26-01, vessels are required to report lost or abandoned fishing gear, a primary source of marine debris in the Southern Ocean. Yet, the scope of this measure remains narrow, focusing mainly on gear loss reporting rather than prevention or retrieval, and its enforcement is inconsistent across fleets and jurisdictions (CCAMLR, 2023). Expanding the measure to include mandatory retrieval programmes, gear-tracking systems, or financial disincentives for non-compliance could significantly enhance its effectiveness in mitigating marine-based plastic inputs.

When taken together, the existing provisions under the Madrid Protocol, CCAMLR and COMNAP could, in principle, provide a robust normative foundation for plastic waste prevention. In practice, however, their implementation remains uneven. Many NAPs face logistical and infrastructural challenges in managing waste at remote research stations, compounded by extreme environmental conditions and the reliance on ship-based controls under MARPOL Annex V (IMO, 2021). Moreover, the Madrid Protocol—negotiated before the recognition of microplastics and nanoplastics as a global threat—lacks specific provisions addressing these pollutants. It contains no binding requirements for filtration systems, airborne dispersal mitigation, or the management of secondary microplastic sources, such as synthetic textiles or polymer coatings. This regulatory lag has left the ATS struggling to adapt to emerging forms of pollution whose scientific understanding and transboundary impacts exceed the scope of its original design.

As Zhang et al. (2020) note, while the ATS has increasingly focused on locally generated plastic waste (from research stations, vessels and tourism operations) it remains poorly equipped to address plastics transported into the region via oceanic or atmospheric pathways. This gap exposes a broader governance dilemma: the ATS can regulate human activity within the Treaty area but holds no authority over global or extra-regional sources. Its reliance on voluntary measures, soft-law instruments and limited compliance monitoring reflects structural challenges that also affect other international environmental regimes confronted with transboundary pollutants.

Beyond intergovernmental mechanisms, private-sector and programme-level initiatives are beginning to complement the formal regulatory framework. Some commercial fishing and tourism operators have adopted voluntary measures to reduce plastic discharges; for example, some fishing vessels have trialled laundry filtration systems to capture microplastic fibres (ASOC & COLTO, 2018). Meanwhile, the International Association of Antarctic Tour Operators (IAATO) has incorporated

plastic reduction measures into its field operations manual, aligning them with the CCAMLR Marine Debris Form and ATCM Resolution 5 (2019), while developing new visitor guidelines to reduce single-use waste⁴.

Plastic pollution and the ATCM

The ATCM is the principal decision-making forum under the ATS, bringing together Treaty Parties, expert organisations and observers to discuss the protection and management of the Antarctic environment. While not a regulatory body *stricto sensu*, the ATCM provides the political and normative platform through which Decisions, hortatory Resolutions and legally binding Measures are proposed, negotiated and adopted. Measures become legally binding once adopted by all Consultative Parties and implemented through national legislation, while non-binding Resolutions provide guidance for national policies. As new environmental pressures emerge, the ATCM has become a key forum for framing Antarctic responses to global challenges such as climate change and, more recently, plastic pollution.

Growing scientific evidence of plastic contamination in the Southern Ocean has drawn the ATCM's attention to this issue. A working paper submitted to the ATCM by the United Kingdom in 2019 (see UK, 2019) identified marine plastic pollution as “a major global conservation issue”, noting that the Antarctic may be particularly vulnerable to microplastic pollution due to patterns of surface circulation across the Southern Ocean, which may transport surface-floating plastics from northern latitudes into polar waters, and high levels of UV radiation, which accelerate the breakdown of macroplastics into microplastics.

In response to this paper, the ATCM adopted Resolution 5 (2019) on Reducing Plastic Pollution in Antarctica and the Southern Ocean. The Resolution recommends reductions in the use of personal care products containing microplastic beads, and information exchanges between Parties on minimising microplastics in wastewater. The Resolution also invites the Scientific Committee on Antarctic Research (SCAR) to report on new information about the presence and risks of plastic pollution, calling for greater monitoring of plastic pollution in Antarctica. Finally, it recommends that the issue of microplastic release be considered in connection with any possible future revisions of Annexes III and IV to the Protocol on Environmental Protection.

Since 2019, the ATCM's engagement with plastic pollution has expanded significantly, reflecting a growing alignment between scientific evidence and policy deliberation. Against this evolving backdrop, the 46th ATCM, which convened in Kochi, India from 20 to 30 May 2024, represented a defining moment in the Antarctic dialogue on plastic pollution. The following section examines in greater depth the key findings, proposals and debates that shaped these discussions.

Microplastics at the 46th ATCM

The 46th ATCM took place amid heightened global attention to environmental governance in Antarctica, with discussions encompassing climate change, waste management, biodiversity conservation and marine protected areas. Among these themes, microplastic pollution emerged as

one of the most prominent and unifying issues, reflecting both the growing scientific recognition of its pervasiveness, and the evolving engagement of the ATS with global pollution challenges.

Building on earlier commitments, in particularly Resolution 5 (2019), the 2024 meeting provided the most extensive and detailed exchange to date on plastic contamination in the Antarctic region. A total of eight information papers (IPs) formed the scientific foundation of these discussions, complemented by a draft Resolution on Ending Plastic Pollution introduced by the Netherlands (ATCM 46-CEP 26, 2024)⁵. Collectively, these contributions signalled a maturation of the policy debate, shifting from preliminary awareness towards the design of potential institutional responses within the ATS framework.

One of the key contributions came from Switzerland, summarising research on microplastic pollution in the Weddell Sea and Dronning Maud Land (WSDML), a remote area with minimal human activity. The multi-year study conducted by the Alfred Wegener Institute, the Royal Netherlands Institute for Sea Research and Utrecht University found that small microplastics (11 µm–500 µm) constituted 98% of plastic particles identified, with concentrations comparable to heavily impacted regions such as the Norwegian and Chinese coasts. Microplastics were also identified in snow, sediments, sea ice and organisms including fish, seals and penguins—demonstrating their extensive presence in the food web. The paper emphasises the need for multidisciplinary research to better understand microplastic interactions with environmental variables, trace their origins and transport pathways, and develop effective mitigation and conservation strategies.

In its IP, Belarus presented the first findings on microplastic contamination in the soils and freshwater systems of East Antarctica, a region historically understudied compared to the marine ecosystems of West Antarctica. The research revealed unexpectedly high concentrations of microplastics in freshwater samples from Thala Hills, highlighting the urgency of continued research and international collaboration. Peru contributed a comprehensive literature review on plastic pollution in Antarctica, identifying persistent methodological gaps, particularly the absence of standardised sampling and analysis protocols, and recommending the implementation of quality control mechanisms in waste management, along with assessments of pollution originating from scientific bases and human activities.

Argentina reported on the Nuclear Technology for Controlling Plastic Pollution (NUTEC) Plastics Initiative, a collaborative project carried out at Carlini Base and aboard the ARA Almirante Irizar in cooperation with the International Atomic Energy Agency (IAEA). The initiative emphasised the need to harmonise microplastic monitoring methodologies and offered Argentina's technical expertise to other Parties interested in adopting comparable approaches.

The Antarctic and Southern Ocean Coalition (ASOC) urged stronger measures to combat plastic pollution within the Antarctic Treaty Area. ASOC highlighted the ecological risks associated with microplastics, including ingestion by krill, bioaccumulation across trophic levels and potential ecosystem-wide impacts, and identified local operations such as research stations, tourism and fishing activities as major contributors. The paper recommended developing a regional action plan, reviewing existing management provisions under the Environmental Protocol, and supporting global initiatives aimed at reducing plastic production and use.

Together, these papers stressed the urgency of addressing microplastic pollution through standardisation, collaboration and stronger international measures. In response, the CEP reviewed the draft Resolution on ending plastic pollution proposed by the Netherlands, which expressed concern over the increasing presence of plastics in Antarctic ecosystems and their associated environmental risks. Although the Committee did not reach consensus, it forwarded the draft to the ATCM for further consideration. However, despite broad support for the initiative, formal adoption was ultimately hindered by procedural and jurisdictional disagreements. Several Parties contended that ongoing negotiations towards a UN Global Plastics Treaty rendered new Antarctic-specific measures premature, while others viewed regional action as a necessary complement to global efforts. The subsequent plenary discussions reflected this tension between environmental ambition and diplomatic caution, a recurring feature of AT'S decision-making. Many Parties expressed appreciation to the Netherlands for elevating the issue, but procedural objections persisted, particularly concerning compliance with submission protocols and the translation of documents into all official languages. It was also noted that the ATCM should await technical guidance from global fora with specialised expertise on plastics. To advance the process, several Parties proposed mandating the CEP to provide technical, scientific and environmental advice on plastic pollution, ensuring that future deliberations are informed by consolidated evidence and aligned with evolving international frameworks.

Overall, the deliberations at ATCM-46 revealed both progress and constraint: while there is growing scientific consensus on the pervasiveness and ecological risks of microplastics, the institutional caution and procedural rigidity that characterise Antarctic environmental governance continue to limit the speed and scope of collective action.

Microplastics at the 47th ATCM

Microplastic pollution remained a topic of significant discussion the following year at the 47th ATCM held in Milan, Italy between June 23 and July 3, 2025, with two working papers (WPs) and eight IPs submitted on the topic.

An Argentinian IP presented the initial findings of the Argentine Antarctic Programme's NUTEC Plastics Initiative, highlighting their adoption of a standardised methodology of sample analysis and the use of specialised equipment as prescribed by the IAEA. Switzerland and Germany submitted an IP presenting the final results and conclusions of their comprehensive microplastic research in the WSDML region between 2017 and 2025, reiterating the "high abundance" of microplastics in the region, advising a precautionary approach to policy and operations in respect of microplastics, and offering several mitigation strategies to address local sources. Ecuador submitted an IP presenting national initiative, including microplastic monitoring, toxicological studies and capacity building, while an IP submitted by Brazil reported on microplastics research undertaken by the Brazilian Antarctic Program (PROANTAR) and a new partnership with the NUTEC Plastics Initiative and the IAEA. The United Kingdom submitted a Working Paper addressing plastic pollution arising from field operations, specifically the degradation of polyester flags used for marking safe routes in Antarctica.

SCAR submitted two IPs concerning microplastic pollution. The first presented the conclusions of a long-term study of deep-sea sediment-dwelling organisms, which found that a third of sampled

organisms had ingested microplastic and other anthropogenic debris every year between 1986 and 2016, noting that the level of contamination was similar to that found in the Arctic, despite the significantly lower population. The second reviewed policy responses to plastic pollution under the ATS, concluding that “further actions on assessment, monitoring and mitigation are now needed to comprehensively address the issue of plastic pollution in the Antarctic Treaty area”. In collaboration with twelve Parties, SCAR also submitted an IP to report on a workshop entitled “Monitoring Chemical Pollution in Antarctica – Tackling future Challenges together”. Workshop attendees, which included expert researchers and environmental stakeholders, identified an “urgent need for increased coordination” to improve monitoring and analysis of pollutants including microplastics, and to inform the development of policies. Most of the above papers highlighted the importance of introducing standardised, comparable methodologies and protocols for sampling and analysis, as well as implementing long-term, systematic monitoring programmes to inform policy.

Finally, the Netherlands presented their WP proposing that the ATCM adopt a Resolution “Towards ending plastic pollution in the Antarctic Treaty Area”. The Meeting agreed, adopting Resolution 5 (2025), which calls on Parties to, inter alia, share information on best practices for addressing plastic pollution, strengthen research and monitoring efforts, and engage in international discussions on plastic pollution.

CHALLENGES, OPPORTUNITIES AND POLICY RECOMMENDATIONS

Challenges

While considerable progress has been made in identifying the sources, pathways and ecological impacts of microplastics in the Antarctic environment, the capacity of the ATS to address this issue effectively remains limited. The complexity arises not only from the logistical and physical characteristics of the region but also from institutional fragmentation and uneven scientific data. Nonetheless, these same constraints reveal strategic opportunities to strengthen Antarctic environmental governance, deepen scientific collaboration and position the ATS as a leading actor in global plastic governance.

A primary challenge lies in the persistent data gaps and lack of standardised monitoring protocols across Parties. As such, despite growing awareness, microplastic research in Antarctica remains spatially and temporally fragmented, making it difficult to establish long-term baselines or detect regional trends. Sampling methodologies vary widely, and most studies are concentrated around research stations and tourist routes, leaving vast areas of the continent and surrounding ocean unexplored. Without harmonised procedures—something SCAR’s Plastic Action Group has repeatedly emphasised—data comparability remains weak, constraining both scientific understanding and policy coherence.

A second challenge, as noted above, concerns the fragmented governance landscape of the ATS. Responsibilities related to plastic pollution are dispersed among multiple institutions, including the ATCM, the CEP, COMNAP and CCAMLR. Although these bodies share a common commitment to environmental protection, there is limited cross-referencing of policies or data exchange mechanisms between them. This absence of an integrated framework has led to duplicated efforts, inconsistent

monitoring and policy gaps—particularly between land-based and marine-focused initiatives.

Logistical constraints further compound the problem. Waste management and retrieval in the Antarctic are extremely costly and technically challenging due to remoteness, harsh weather conditions and seasonal access limitations. Even well-intentioned waste reduction measures encounter barriers in transportation, storage and disposal. As a result, operational activities such as research, tourism and fishing continue to generate plastic waste, including lost gear and packaging materials, some of which escape containment and enter local ecosystems.

The difficulty of monitoring and enforcing compliance also undermines the effectiveness of existing regulations. Moreover, emerging forms of pollution—such as microplastics, nanoplastics and airborne plastic particles—fall outside the scope of current regulatory frameworks, revealing the need for adaptive governance capable of addressing evolving environmental challenges.

Category	Key Issues / Actions	Description / Explanation	Relevant Actors / Sources
Scientific & Data Challenges	Data gaps and inconsistent methodologies	Lack of standardised monitoring protocols across Parties limits comparability and long-term assessments; most studies focus on accessible areas near stations.	SCAR Plastic Action Group (2023); ATCM Parties
Institutional Fragmentation	Weak coordination among ATS bodies	Overlapping mandates of ATCM, CCAMLR and CEP result in policy gaps and limited cross-referencing of measures.	ATCM, CEP, CCAMLR
Operational Constraints	Logistical and financial barriers to waste management	Harsh conditions and high transport costs hinder retrieval and disposal of waste; local operations continue to generate plastic leakage.	Research programs, COMNAB, IAATO
Enforcement Limitations	Voluntary compliance and limited inspections	Most provisions are non-binding; few mechanisms for enforcement or systematic compliance monitoring.	Treaty Parties, ATCM inspectors

Table 1. *Key challenges in addressing microplastic pollution under the ATS*

Opportunities

Despite these obstacles, several opportunities do exist to transform the Antarctic response into a model of proactive, science-based environmental management.

THE ATCM AND THE EMERGING REGIME ON MICROPLASTIC POLLUTION IN ANTARCTICA:
A REVIEW OF CHALLENGES AND OPPORTUNITIES

The ATCM Resolution 5 (2019) and Resolution 5 (2025) represent important steps towards acknowledging and addressing the threat of microplastic pollution in Antarctica. It is important to note, however, that these documents were drafted in the context of constructive negotiations towards an ILBI to address plastic pollution, which were ongoing at the time. The collapse of these negotiations at INC-5.2 (2025) has resulted in a regulatory void in respect of plastic pollution.

The ATS is well-positioned to introduce region-specific regulations that will fill the gap left by the paused Global Plastics Treaty. There is widespread agreement amongst Parties that plastic pollution in the Antarctic needs to be addressed: the ATCM 47 “reiterated the importance of addressing plastics pollution in the Antarctic Treaty area” (ATCM 47 Final Report (304)), and many Parties have indicated their support for the implementation of standardised research methodologies and protocols, and systematised monitoring.

Standardisation and collaboration can be achieved through the development of systematic monitoring protocols and harmonised reporting systems under the leadership of SCAR and COMNAP. Such efforts would enhance data consistency and facilitate the integration of Antarctic findings into global plastics assessments.

Innovation also plays a critical role in the process. Emerging technologies, including on-site wastewater filtration, biodegradable material substitution and circular supply chains for remote operations, can substantially reduce plastic leakage. Research stations could serve as experimental sites for piloting sustainable logistics systems and closed-loop material cycles. In addition, promoting collaboration between scientific, logistical and commercial actors—such as SCAR, COMNAP and IAATO—can ensure that operational sustainability translates into measurable environmental outcomes.

Institutional leadership is another area offering an important opportunity. The establishment of an ATS Task Force on Plastic Pollution would provide a formal mechanism for coordinating policy, monitoring data and facilitating dialogue between the ATCM, CCAMLR and other relevant

Key Issues / Actions	Description / Explanation	Relevant Actors / Sources
Standardisation and collaboration	Develop harmonised monitoring protocols and shared reporting frameworks under SCAR and COMNAP guidance.	SCAR, COMNAP, CEP National programmes,
Innovation and best practice	Implement circular logistics, wastewater filtration and biodegradable materials in Antarctic stations and vessels.	COMNAP
Institutional leadership	Establish an ATS Task Force on Plastic Pollution to coordinate data, policy and engagement with global processes.	ATCM, CCAMLR, CEP

Table 2. *Strategic opportunities to strengthen the Antarctic response to plastic pollution*

organisations. This Task Force could prepare joint recommendations, oversee the implementation of Resolutions and participate in international fora on plastics as appropriate, ensuring that Antarctic priorities are represented in global policy discussions.

Policy recommendations

In practical terms, addressing these challenges requires a comprehensive set of policy actions. The ATS should adopt an overarching Action Plan on Plastic Pollution encompassing macro-, micro-, and nanoplastics, covering both land-based and vessel-based sources. This plan should assign clear responsibilities to relevant institutions and actors, ensuring accountability and coordination. Standardised monitoring and reporting obligations, guided by SCAR’s Plastic Action Group, would help generate consistent datasets and enable long-term trend analysis.

Enhanced cooperation between the ATCM and CCAMLR is also crucial. Developing joint measures on marine debris management and ALDFG, supported by retrieval incentives and sanctions for non-compliance, could bridge the divide between terrestrial and marine governance. Integrating plastic management into Environmental Impact Assessments (Annex I of the Environmental Protocol) would further institutionalise preventive measures, including mandatory wastewater filtration systems and microplastic risk assessments for all new facilities and vessels operating in the region.

Finally, broader awareness and behavioural change must complement technical and institutional reforms. Education and outreach initiatives targeting researchers, logistics operators and tourists

Key Issues / Actions	Description / Explanation	Relevant Actors / Sources
ATS Action Plan on Plastic Pollution	Adopt a comprehensive plan covering macro-, micro-, and nanoplastics from land- and vessel-based sources.	ATCM Secretariat
Standardised monitoring and reporting	Establish guidelines for comparable data collection and trend analysis through SCAR coordination.	SCAR, COMNAP
CCAMLR Conservation Measures	Introduce retrieval incentives and penalties for gear loss; coordinate marine debris monitoring.	CCAMLR, ATCM
Integration into EIAs	Require filtration and microplastic risk assessments in all Environmental Impact Assessments (Annex I).	CEP, national programs
Education and awareness	Promote sustainable logistics and reduce single-use plastics through operator and tourist engagement.	IAATO, COMNAP, research institutions

Table 3. Policy recommendations for addressing plastic pollution in Antarctica

can promote the reduction of single-use plastics, sustainable material choices and a culture of environmental responsibility within Antarctic operations. Linking these initiatives to global movements—such as UNEP’s Clean Seas campaign or IMO’s Marine Plastic Litter Strategy—would amplify their visibility and impact.

Taken together, these measures can form a roadmap for transforming the ATS response to microplastic pollution from reactive and piecemeal to proactive and adaptive, through an approach capable of addressing the multifaceted challenges of plastic pollution. Through standardisation, innovation and institutional cooperation, Antarctica could serve not only as a sentinel for global environmental change but also as a testing ground for governance solutions that advance planetary stewardship in the age of plastics.

CONCLUSIONS

Plastic pollution constitutes a growing and complex risk to Antarctic and Southern Ocean ecosystems, operating through poorly understood pathways of ingestion, bioaccumulation, transformation and biomagnification of micro- and nanoplastics. Evidence reviewed in this article demonstrates that no Antarctic ecosystem—whether marine, terrestrial, or atmospheric—remains unaffected. Yet despite clear scientific signals, policy responses under the ATS continue to lag behind the scale and urgency of the challenge. In order to address and tackle this emerging threat, it requires both scientific consolidation and institutional innovation. A such, standardised methodologies for monitoring, sampling and analysis must be prioritised to generate comparable data and establish robust baselines to inform policy. However, the absence of full datasets should not be used as grounds for inaction. In line with the precautionary principle, early preventive and adaptive measures are warranted to avoid irreversible ecological impacts.

At the policy level, the ATCM should play a catalytic role by developing a comprehensive ATS Action Plan on Plastic Pollution, encompassing macro-, micro-, and nanoplastics from both land- and vessel-based sources. This plan should clearly delineate institutional responsibilities among the ATCM, CCAMLR, COMNAP and SCAR; establish mechanisms for data sharing and capacity building; and promote the deployment of technologies such as filtration systems, biodegradable materials and circular logistics within Antarctic operations.

Enhanced international coordination is equally important. Aligning Antarctic policies with global initiatives such as the IMO Strategy to Address Marine Plastic Litter from Ships will help ensure policy coherence and strengthen Antarctica’s contribution to global plastic governance. By engaging proactively with these frameworks, the ATS could position itself as a model for science-based regional cooperation in addressing transboundary pollutants. Ultimately, the Antarctic response to plastic pollution must evolve from a reactive posture to become a proactive, integrated and adaptive governance model. To do so this will entail bridging the divide between scientific research and policy implementation, reinforcing compliance and monitoring mechanisms, and fostering behavioural change among operators, researchers and visitors. By doing so, the ATS can not only safeguard one of the planet’s last great wildernesses but also afford a valuable precedent for global environmental governance in the age of plastics.

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EDNOTES

1. An IP presented by SCAR to the 45th ATCM summarised available information on the occurrence of macroplastics (> 5 mm), microplastics (1 µm-5 mm) and nanoplastics (< 1 µm) in Antarctica (SCAR, 2023).

2. Parties are not compelled to treat wastewater released from their scientific research station, beyond maceration (Annex III; Article 5, 1b).

3. An educational poster with suggestions on how National Antarctic Programs can reduce plastic pollution is available at: <https://static1.squarespace.com/static/61073506e9b0073c7eaaf464/t/613fe40109a713366b37b86a/1631577091358/COMNAP-Understanding-sources-of-plastics-in-the-Antarctic-Treaty-Area.pdf>

3. IAATO guidelines can be consulted here: <https://iaato.org/wp-content/uploads/2020/04/Reducing-waste-visitor-guidelines.pdf>

5. IPs were submitted by Belarus (IP 2), Argentina (IP 15), Switzerland (IP 44), India (IP 58), Peru (IP 148), Uruguay (IP 170), and the Antarctic and Southern Coalition (IP 140). Although Chile's paper (IP 23) focuses on conservation challenges of Fildes Peninsula in general, it does mention plastic pollution as one of the threats affecting the area. Quotations for all these IPs are provided in the references section of this article.

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ANTARCTIC BACTERIOPHAGES: THEIR ECOLOGICAL ROLE AND BIOTECHNOLOGICAL POTENTIAL

Nicolas Antonio Napolitano, Francisco Massot, Cecilia Quiroga,
Walter Mac Cormack, and José Luis López

ABSTRACT

Abstract

*Viruses that infect bacteria (bacteriophages or phages) are the most abundant biological entities in the biosphere. Phages play a central role in shaping microbial communities and regulating global biogeochemical cycles. Two major biological cycles characterize phages: the lytic and the lysogenic cycles. This study focuses on the lysogenic cycle, in which phages integrate into the bacterial genome. The study of bacterium–phage systems in Antarctic environments is of particular interest due to the extreme environmental conditions under which these interactions occur. Antarctic bacteria isolated from different habitats were investigated to characterize their lysogenic viruses. *Bizionia argentinensis*, *Rhodococcus* spp. strain ADH, and *Agreia* spp. were characterized both *in silico* and *in vitro* for the presence of integrated phages (prophages). These prophages harbor a genetic repertoire that may play a central role in host–environment interactions. In addition, some prophage-derived genes (including endolysins, enzymes that lyse bacterial cell walls) have potential biotechnological applications. In particular, enzymes adapted to function at low temperatures could be exploited for industrial use.*

KEY WORDS

Evolution; Bacteriophages, Lysogeny; Genes of interest, Biotechnology, Antarctica, Antarctic Treaty, Antarctic Environmental Protection, Antarctic Tourism

INTRODUCTION

Antarctica represents one of the most extreme and least explored ecosystems on Earth, characterized by unique environmental conditions that pose constant challenges to life. In this hostile environment, microbial communities play critical roles in global biogeochemical cycles and in maintaining ecosystem functioning. Among these microorganisms, bacteriophages emerge as key regulators of microbial dynamics, exerting a decisive influence on the structure of bacterial communities and on the flow of matter and energy.

What are bacteriophages and what are their main biological characteristics?

Bacteriophages, or simply phages, are viruses that infect bacteria. Like any virus, they depend on the cellular machinery of their host to reproduce. They are considered the most diverse and abundant biological entities in the biosphere (Suttle 2007; Anderson et al. 2011; Paez-Espino et al. 2016; Carroll et al. 2018). It is estimated that there are around 10^{31} bacteriophage particles in nature, and approximately 10^{23} phage infections occur every second worldwide (Weitz and Wilhelm 2012). This highlights not only the magnitude of their population but also their dynamics and relevance in various fields. Bacteriophages play a crucial role in several processes: a) Global ecology: they regulate microbial populations and affect carbon and nutrient flows in ecosystems; b) Microbial evolution: they promote the diversification of microorganisms and facilitate horizontal gene transfer; c) Scientific research: They have been key tools in molecular biology and in the study of cells at the molecular level; d) Healthcare system: They are being investigated as alternatives for the control of antibiotic-resistant bacterial infections (Weitz and Wilhelm 2012; Jamal et al. 2019; Kim et al. 2020). Bacteriophages are classified according to the type of genome they possess, which can be either DNA (deoxyribonucleic acid) or RNA (ribonucleic acid). Most bacteriophages have double-stranded DNA (dsDNA). However, there are also phages with single-stranded DNA (ssDNA), single-stranded RNA (ssRNA), or double-stranded RNA (dsRNA). They exhibit a wide variety of shapes and structures. Most lack a lipid envelope, although some have an additional lipid layer. In terms of shape, we find tailless phages and phages with head-tail structures, which are the most common. These latter ones can have long, contractile tails, long, non-contractile tails, or short, non-contractile tails. (Figure 1).

One of the most fascinating findings from comparative studies of bacteriophage genomes is their mosaic nature (Gauthier and Hatfull 2024), meaning they have DNA segments from different origins in their genome. This phenomenon is mainly explained by horizontal gene transfer, where bacteriophages share their genetic material with other organisms, resulting in genomes with a unique mix of genes and contributing significantly to their evolution and diversity (Hatfull and Hendrix, 2011).

Bacteriophage life cycles

Bacteriophages have two main strategies for multiplying: the lytic cycle and the lysogenic cycle (Mavrich and Hatfull 2017). In the lytic cycle, the phage infects the bacterium and uses its cellular machinery to replicate its own genome and produce new viral particles. At the end of this process, the bacterial cell ruptures (lysis), releasing the new phages that can infect other evolutionarily related bacteria. This cycle is characteristic of virulent phages, which cause lysis and kill the host cell. In

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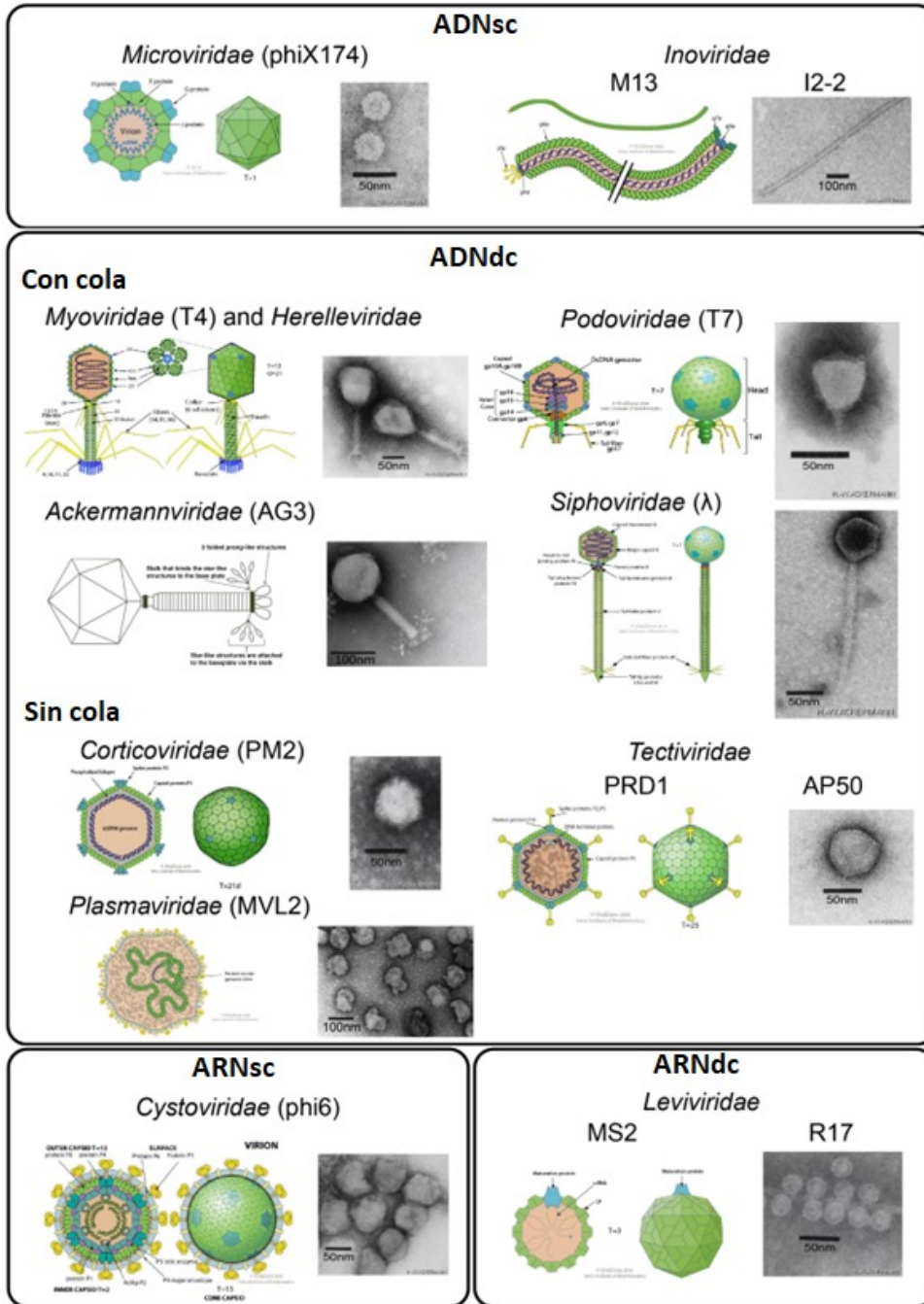


Figure 1. Classification of bacteriophages based on genome type and morphology. The bar indicates the size scale (Dion et al. 2020).

the lysogenic cycle, after infection, the phage genome integrates into the bacterial DNA. In its form integrated into the bacterial chromosome, the phage is identified as a prophage. At this stage, the viral genome can be transmitted vertically (from parent cells to daughter cells) to subsequent generations of the bacterium. Under certain environmental conditions, which can stress the bacterial cell, the prophage can be activated, detach from the bacterial genome, and restart the lytic cycle. This process is known as induction and marks the beginning of the lytic cycle. Phages that can alternate between both cycles are called temperate phages. Lysogeny is a process in which the bacteriophage genome integrates into the host bacterium's genome, allowing their coexistence without destroying the bacterial cell. This state offers significant advantages for both the virus and the bacterium. On the one hand, the phage ensures its survival under adverse conditions, such as when there is a low density of susceptible bacteria, and guarantees its propagation through vertical replication along with the bacterial DNA. On the other hand, the bacterium can benefit from lysogenic conversion, acquiring new characteristics derived from the prophage genes. These can include genes that encode toxins, such as the cholera toxin of *Vibrio cholerae*, the diphtheria toxin of *Corynebacterium diphtheriae*, or the Shiga toxin of *Escherichia coli* O157:H7 (all examples of great clinical and pathological significance). Furthermore, prophage genes can confer antibiotic resistance or modify bacterial structures, such as the cell wall or surface proteins, making the bacteria less detectable by the immune system of humans or animals during an infection or more resistant to other phages. They function as a reservoir of mobile genes, facilitating their horizontal transfer and promoting microbial evolution.

Bacterial defense systems against bacteriophage infection

Bacteria have developed a variety of defense systems to protect themselves from bacteriophage infection, including physical, chemical, and genetic mechanisms. These systems represent a kind of “evolutionary arms race” between bacteria and phages. The main bacterial defense mechanisms are described below: a) physical barriers such as the modification of surface receptors; b) innate immune systems such as the DNA Restriction and Modification system or the Toxin-Antitoxin system; c) adaptive immune systems such as the CRISPR-Cas system; d) abortive defense systems such as the Abi system (Wang et al. 2010; Makarova et al. 2011; Shi et al. 2020; Payne et al. 2021; Tesson et al. 2024).

Although bacteria have multiple defense mechanisms to protect themselves from bacteriophages, these viruses sometimes manage to inject their genetic material into them. This occurs thanks to the ability of phages to evolve and adapt, developing strategies that allow them to evade or neutralize these defenses.

EXPLORING ANTARCTIC BACTERIOPHAGES

Methodological approach

The Virology area of the Microbiology group at the Argentine Antarctic Institute (IAA) conducts research on virus-host coevolution mechanisms in bacteriophage-bacteria systems, with special emphasis on the study of prophages integrated into the genome of Antarctic bacteria isolated from extreme environments (soil, continental and marine waters). Our project has the following main objectives: (1) the genomic and functional characterization of these viral elements, with particular

attention to their role in the adaptive and evolutionary processes of their bacterial hosts; and (2) the evaluation of their biotechnological potential. Complementarily, through comparative genomic analyses, we investigate the molecular mechanisms involved in the acquisition of mobile genetic elements, the patterns of prophage integration, and bacterial defense systems against viral infections (Figure 1).

Lysogenic state in *Bizionia argentinensis*

Bizionia argentinensis JUB59, is a psychrotolerant bacterium (tolerates growth at low temperatures) isolated from the surface marine waters of Potter Cove, Carlini Base, Argentine Antarctica (Bercovich et al. 2008) (Figure 2).

This bacterium contains a prophage that parasitizes it. It was isolated and fully sequenced in Argentina



Figure 2. Geographic location where the studies were carried out, Argentine Antarctica, Potter Cove, Carlini Base.

as part of the White Genome Project, a public-private interinstitutional project involving the Argentine Antarctic Institute and the National Antarctic Directorate (genetic database access code: AFXZ01000000). Within this project, different proteins of unknown function were expressed and structurally characterized. Among them, the crystal structure of C24, a structural protein genetically homologous to the tail fiber of a phage, was characterized. Through induction with Mitomycin C, it was demonstrated that the C24 protein was a structural protein of an inducible prophage (Pellizza et al. 2020) (Figure 4).

Bioinformatic analysis of the defense systems present in *B. argentinensis* allowed the identification of several innate immunity systems (Restriction and Modification, retron, pycar, and DMS). Furthermore, in silico studies identified a potential endolysin with peptidase activity, which we have named EndoBap (Endolysin of *Bizionia argentinensis* prophage). Functional and structural analysis of this lysis system will not only expand our basic knowledge of these mechanisms but will also open

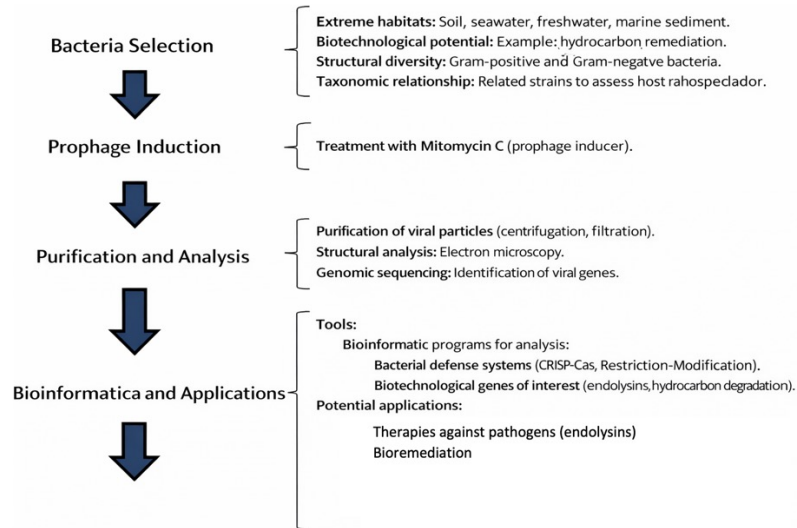


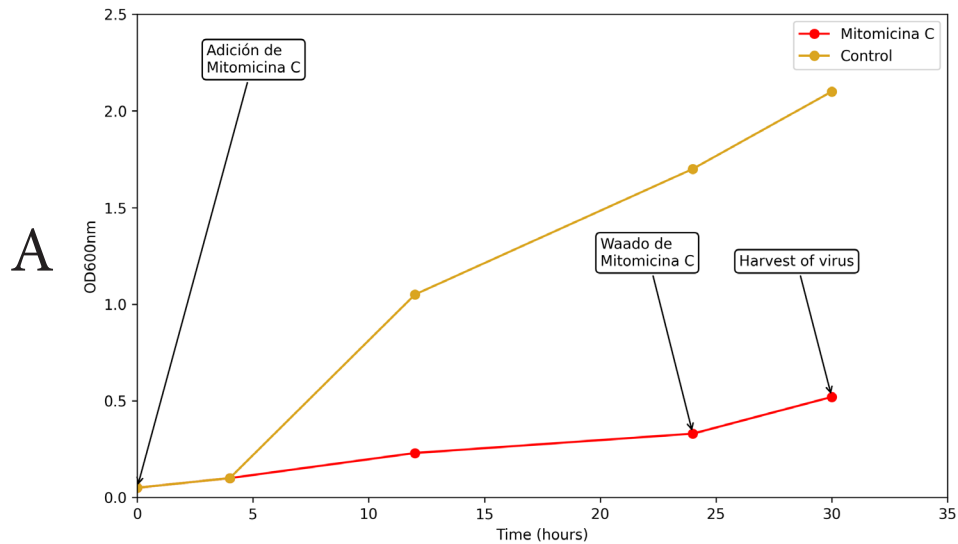
Figure 3. Methodology of study of the virology area of the Argentine Antarctic Institute (IAA).

Lysogenic state in *Rhodococcus* sp. strain ADH

Rhodococcus sp. strain ADH is a psychrotolerant hydrocarbon-degrading bacterium isolated from soil near Carlini Base, Antarctica, contaminated with petroleum-derived fuels (Ruberto et al. 2005). Induction with Mitomycin C demonstrated the presence of an inducible prophage in the bacterium. The bacterial genome was sequenced (accession number). Analysis of the defense systems present in the bacterium identified several innate immune systems (Restriction and Modification, Wadjet, and DISARM), an adaptive immune system (CRISPR-Cas type IVB), and an abortive defense system (Abi). (Figure 4).

Lysogenic state in Antarctic endophytic bacteria

The endophytic bacteria *Agreia* sp. CGGE2_1 and *Agreia* sp. CGGE2_18, which inhabit the rhizosphere of *Deschampsia antarctica*, an emblematic Antarctic plant, were also studied for the identification of prophages. Their respective genomes were sequenced, and the presence of prophages and defense systems (accession numbers) was determined. In *Agreia* sp. CGGE2_1, a prophage was detected after induction with Mitomycin C; while in *Agreia* sp. CGGE2_18, another prophage, also induced by this method, belonging to the Vilmaviridae family, was identified. Furthermore, both bacteria exhibited various defense systems. In *Agreia* sp. CGGE2_1, the innate immune systems DMS, retron, and Restriction and Modification were identified; while in *Agreia* sp. CGGE2_18 detected dXTPase, Restriction Modification and retron (Figure 6A and 6B).



B

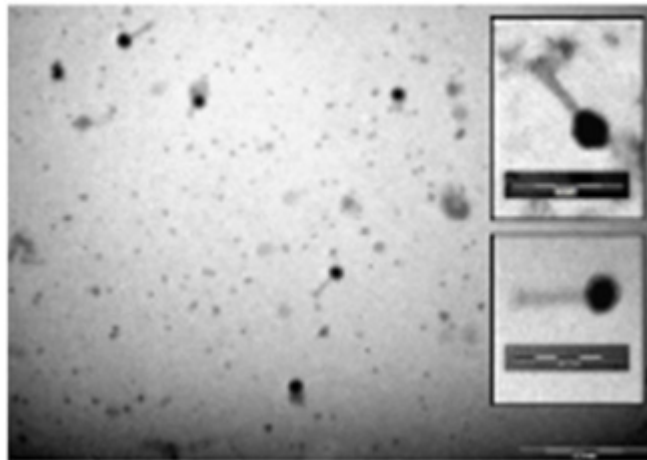


Figure 4. A) Induction of a *Bizionia argentinensis* JUB59 culture. Bacterial cultures in liquid medium were performed in parallel with and without treatment with Mitomicin C. The OD600nm is a measure of light beam interference and directly measures the turbidity of the culture (turbidity is directly proportional to the number of bacteria in the culture). The decrease in culture turbidity (lower OD600nm, Figure 4A) constituted a preliminary indication of bacterial rupture by the action of released phages. B) Electron microscope image obtained by negative staining with phosphotungstic acid of the phage concentrate from the cultures treated with Mitomicin C. The electron microscope image constitutes strong evidence of prophage induction from the bacterial genome.

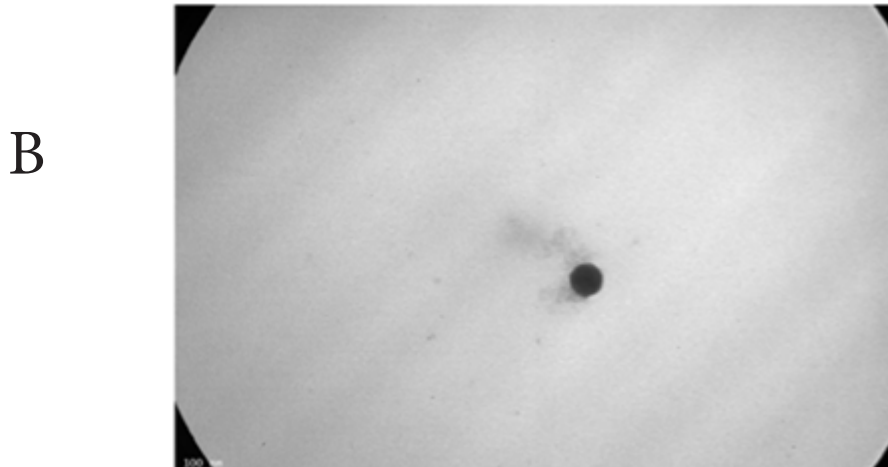
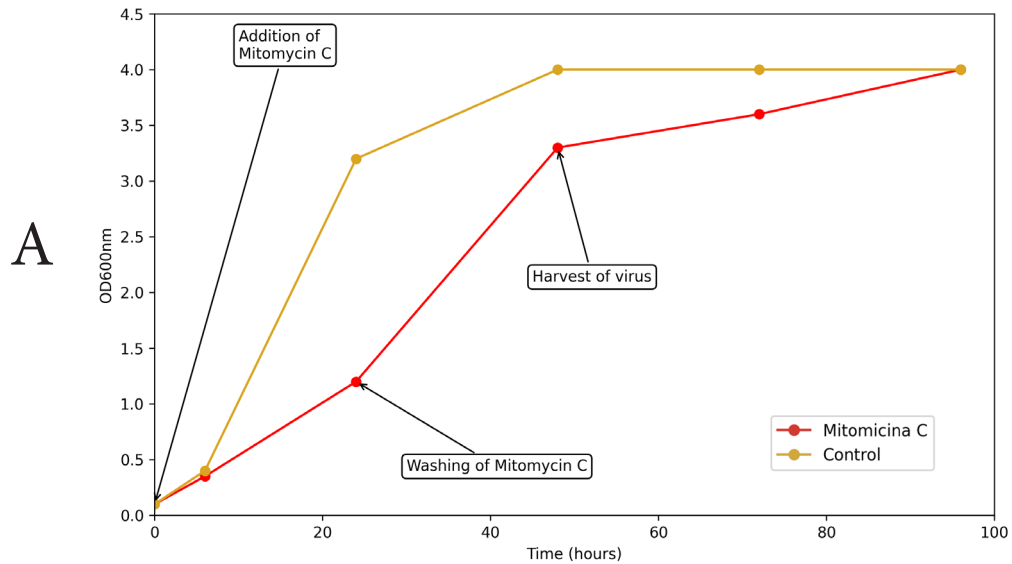


Figure 5. *A) Induction of a Rhodococcus sp. ADH strain culture. Bacterial cultures in liquid medium were performed in parallel with and without treatment with Mitomycin C. The OD600nm is a measure of light beam interference and directly measures the turbidity of the culture (turbidity is directly proportional to the number of bacteria in the culture). The decrease in culture turbidity (lower OD600nm, Figures 5A and 5B) constituted a preliminary indication of bacterial rupture by the action of released phages (compare the red curve versus the yellow curve). B) Electron microscope image obtained by negative staining with phosphotungstic acid of the phage concentrate from the cultures treated with Mitomycin C. The electron microscope image constitutes strong evidence of prophage induction from the bacterial genome.*

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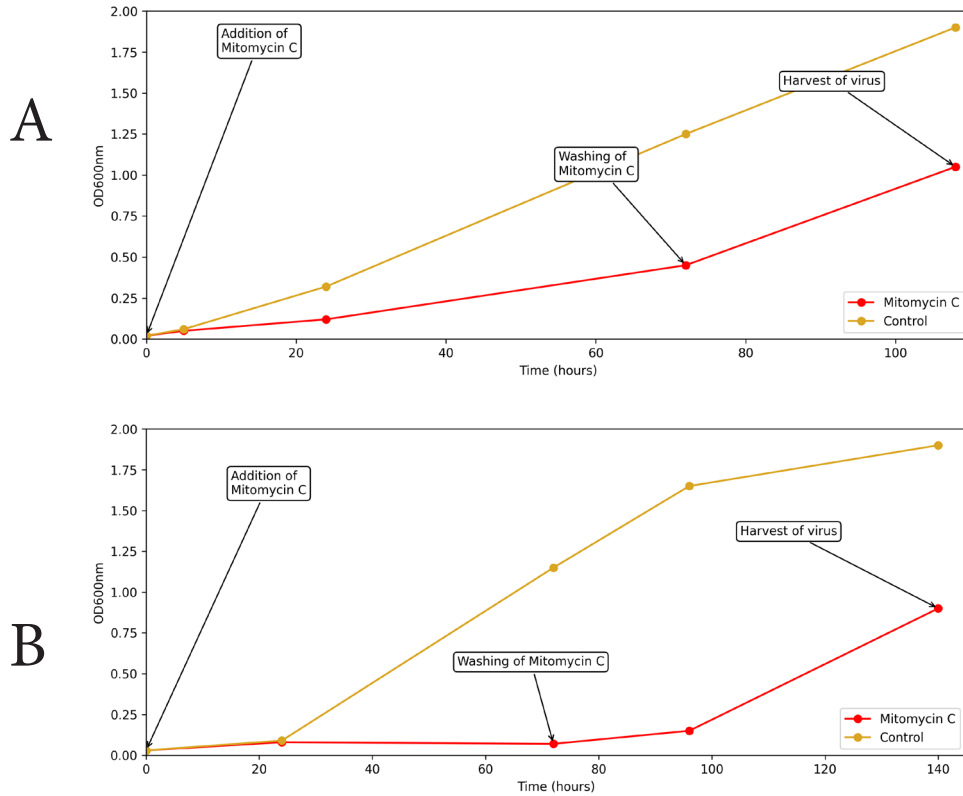


Figure 6. A) Induction of *Agreia* sp. cultures CGGE2_1 B) Induction of *Agreia* sp. CGGE2_18. Bacterial cultures in liquid medium were performed in parallel with and without treatment with Mitomycin C. The OD600nm is a measure of light beam interference and directly measures the turbidity of the culture (turbidity is directly proportional to the number of bacteria in the culture). The decrease in culture turbidity (lower OD600nm, Figures 6A and 6B) constituted a preliminary indication of bacterial rupture by the action of released phages (compare the red curve versus the yellow curve). The electron microscope image provides strong evidence of prophage induction from the bacterial genome.

Detailed bioinformatic analysis of the prophage genetic content revealed that approximately 25% of the genes were related to structural and viral replication functions (viral hit in the pie chart). The remaining 75% (non-viral hit) were auxiliary metabolic genes that could modulate host metabolism. This suggests that prophages can have a significant impact on bacterial cell physiology. The encoded proteins would have functions including protein binding, nucleic acid (DNA and RNA) binding, and the presence of transmembrane domains (DomTM). These transmembrane domains, when located at the amino-terminal end of the protein, constitute a molecular signal that allows secretion outside the cell (Figures 7A and 7B). These extracellular proteins encoded by the viral genome exit the lysogenic bacterium and impact plant root physiology.

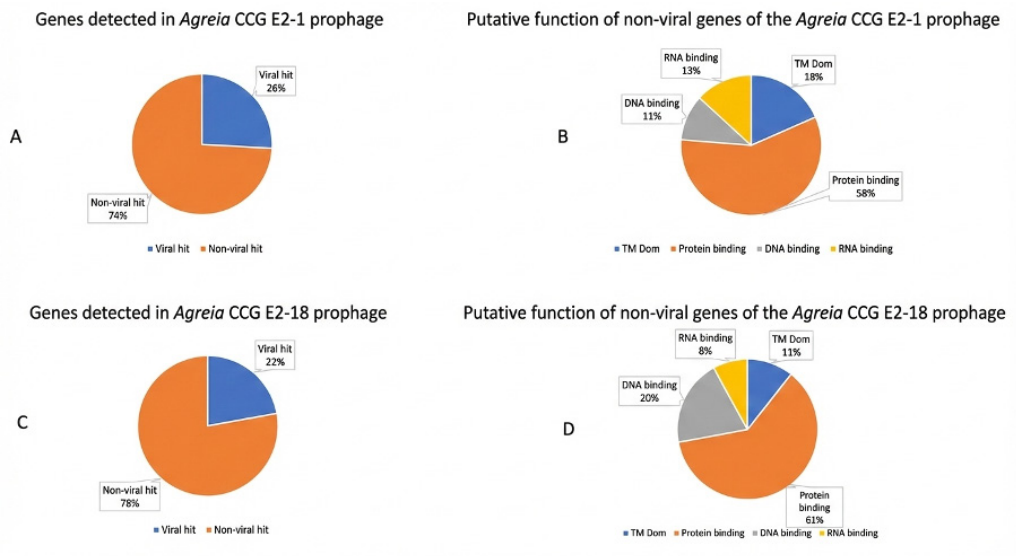


Figure 7. A) Genes present in the prophage of *Agreia* sp. CGGE2_1. B) Putative function of non-viral genes present in the prophage of *Agreia* sp. CGGE2_1. C) Genes present in the prophage of *Agreia* sp. CGGE2_18. D) Putative function of non-viral genes present in the prophage of *Agreia* sp. CGGE2_18.

CONCLUSIONS

The results of these studies provide preliminary evidence on the coevolution between prophages and Antarctic bacteria, their adaptation to extreme environments, and their biotechnological potential. The bacteria studied, from diverse Antarctic habitats, reveal how prophages not only play a crucial role in the evolution of their hosts but also in the diversification of their defense strategies. Analysis of the defense systems of Antarctic bacteria shows a remarkable variety of innate, acquired, and abortive immune systems, which protect them against viral invasion.

The identified genes, such as the EndoBap endolysin from *B. argentinensis*, represent promising biotechnological tools with specific applications in cold environments. This finding is contextualized within the growing industrial use of bacteriophage systems, where endolysins such as CF-301 (Exebacase) are used against MRSA, and formulations such as ListShield™ and SalmoFresh® are employed in the control of *Listeria* spp. and *Salmonella* spp. in the food industry. Endolysins and proteases derived from prophages have potential applications in combating pathogenic bacteria and in industrial processes, especially in sectors where low-temperature stability is crucial.

The discovery that approximately 75% of the prophage genes identified in *Agreia* sp. CGGE2_1 and *Agreia* sp. CGGE2_18 correspond to auxiliary metabolic genes suggests that these could modulate essential cellular processes in the host, impacting its physiology and adaptive capacity. The most

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common predicted functions, such as binding to proteins, DNA, and RNA, suggest that prophages can act as modulators of gene expression (proteins that bind to DNA and RNA), cellular metabolism (proteins that bind to other proteins), molecular transport, or cell signaling. The identification of these protein domains reinforces the hypothesis that lysogeny modulates coevolution between viruses and bacteria.

This study not only expands our understanding of the biology of prophages and their hosts in extreme environments but also highlights the value of these microorganisms as biotechnological resources. Taken together, the results not only underscore the genetic and functional biodiversity of Antarctic microorganisms but also their relevance as a model for understanding evolution in extreme environments and as a source of innovative solutions to global challenges. These include:

- 1) The use of Antarctic prophages as a promising alternative against the rise of antibiotic resistance—declared by the WHO as one of the greatest threats to health.
- 2) The development of bioremediation strategies adapted to cold ecosystems to address climate change and environmental pollution.
- 3) New methods of natural food preservation and more sustainable industrial processes that benefit global food security.

Finally, these findings are highly relevant within the framework of the Antarctic Treaty System. First, they corroborate Antarctica's status as a natural laboratory for cutting-edge scientific research, as established in Article II of the Antarctic Treaty. Second, they demonstrate how Antarctic studies can be translated into technological applications with global reach, in accordance with the environmental protection principles set forth in the Madrid Protocol.

AUTHOR CONTRIBUTIONS

NAN and JLL performed the experimental work and data analysis. All five authors contributed to manuscript writing and editing. NAN is the corresponding author.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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EDUCATION AND OUTREACH OF ANTARCTIC SCIENCE BY WEBINARS

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ABSTRACT

The Brazilian National Committee of the Association of Polar Early Career Scientists (APECS-Brazil) developed a series of monthly webinars between December 2018 and April 2020 as a strategy to promote Antarctic science outreach across Brazil. All authors were part of the APECS-Brazil executive board during this period and actively contributed to these initiatives. This study evaluates how these webinars helped communicate Antarctic science to diverse audiences in a geographically large and socially unequal country. We analyzed three dimensions: reach (geographic and demographic diversity), accessibility (participation despite structural limitations), and heterogeneity (diversity of scientific themes). Our results show that the webinars reached all Brazilian states and attracted mostly students, teachers, and early-career professionals. Participation was highest in states with existing polar research groups, while limited digital access affected engagement in remote areas. Despite these challenges, webinars proved to be an effective and low-cost tool to disseminate polar science, engage new audiences, and inspire interest in global environmental issues. This case study highlights the importance of digital outreach tools in promoting science communication in the Global South, especially when supported by inclusive practices and institutional networks. The APECS-Brazil experience offers valuable insights for future programs seeking to expand access to polar knowledge through scalable online strategies.

KEYWORDS

Antarctic research, computer-mediated communication, scientific outreach, web-based seminars, online engagement

INTRODUCTION

Over the last decades, the field of information science and communication technologies has been growing considerably (Qiang & Pitt 2004), and new tools for online educational resources have been developed (Cook & Grant-Davis 2005). Along with this, the broader access to digital technology (e.g., smartphones, computers, tablets, among others) by the general public has leveraged the power of these digital communication tools.

Such technological development has provided researchers with a large range of new possibilities to advertise their findings and interact with students and enthusiasts of the subject, for example, through social media. It also allowed the development of a new relationship between science and society and a review of teaching methodologies used for so long.

To take the most out of the experience, webinars can be conducted in two ways, synchronous or asynchronous. In asynchronous communication, the so-called communication agent and the participants have the freedom to be in different locations as well at any given moment (any place, any time). In synchronous communication, these agents and the participants can still be anywhere, but will all be connected simultaneously (any place, real-time). Synchronicity and interaction are great advantages during online events, as it allows the group to interact in real-time regardless of the number of participants.

Choosing the type of communication wisely is vital for the event to flow smoothly with high engagement. The interaction between the participants can add to the content and bring great insights to the class or webinar. On the other hand, demanding everyone to take part in the event at a specific time can decrease the enrollments due to lack of availability or even due to different time zones. Such an issue can be mitigated by a simple recording of the online event.

Taking advantage of all technological resources possible provides dynamic synchronous communication and online interaction between researchers and a public interested in their experiences (Rich et al. 2011). They are then accomplished through a virtual platform that allows simultaneous participation of students and researchers (Pan & Sullivan 2005) and can be used for disseminating information in real-time and with immediate feedback from the public (Rich et al. 2011). Webinars allow interaction between teachers and students and interaction among the students themselves (Lobel et al. 2002), i.e., students can simultaneously communicate with each other, using the tools available, such as chat rooms (Mihai, 2014).

Webinars can generate a more globally connected community, approaching the audience and researchers because they are time effective. Due to their intrinsic online existence, there is no need for people to travel (Rich et al. 2011). According to Hamstra et al. (2011), the association of webinars and blogging technology can offer numerous benefits to students. By the drastic reduction of expenses with traveling, commuting, and lodging, universities and institutes can integrate speakers and participants in an “in-person like” format comparable to the traditional in-person presentations. All that without compromising content and interaction. That is not only because of the affordability but also because webinars offer the possibility of attending the session in each person’s home or workplace (Wang & Hsu 2008).

Nonetheless, to perform webinars in full potential and efficiency, some conditions must be considered: the work of a dedicated organizing committee or team, the establishment of a clear webinar subject, the selection of an appropriate online platform to be used, the proper disclosure of the event, and the participation of experienced speakers (Parija & Shanmuganathan 2019).

Although the webinar concept was first introduced in 1998 by Eric R. Korb (2000), and has increased ever since, there is a limited number of studies on scientific outreach (e.g., Wang & Hsu 2008, Zhang et al. 2006, Nagy et al. 2006, Dotta et al. 2014, Gupta & Sengupta 2021).

Considering virtual lecturing advantages, the Brazilian Committee of the Association of Polar Early Career Scientists (APECS-Brazil) has been promoting an affordable teaching-learning environment on Antarctic Sciences and exchange experiences between researchers, educators, and the public interested in the theme.

APECS is an international and transdisciplinary organization with national committees in more than 30 countries (APECS, 2021). APECS-Brazil started its polar scientific dissemination activities in 2008. Currently, it is one of the most prominent national committees of APECS performing many diverse scientific, education and outreach activities on polar science, especially Antarctic Science, for students and teachers of the most diverse levels of education. Through the experience of APECS-Brazil, this paper aims to discuss the efficacy of alternatives and approaches for Antarctic science to communicate to the public in general. For this purpose, we focused on a specific technologic media, the webinars.

The novelty of this study lies not in the use of webinars itself, which are now a common tool for educational outreach, but in the thematic focus: Antarctic science. In a tropical country like Brazil, far removed geographically and culturally from polar regions, Antarctic topics are often overlooked or absent from educational settings. This research seeks to understand how such distant and complex themes can reach, engage, and inspire diverse audiences when communicated through accessible digital means.

In this context, we defined three analytical categories: (1) reach, referring to the geographic and demographic diversity of subscribers; (2) accessibility, understood as the actual attendance and participation in webinars despite structural limitations; and (3) heterogeneity, which evaluates the diversity of scientific topics presented. These categories help us frame a broader question: what are the potentials and limits of webinars as a tool for Antarctic science communication in Brazil?

This paper draws on the case study of monthly webinars held by APECS-Brazil between December 2018 and April 2020. By evaluating audience profiles, participation rates, and content variety, we reflect on how this digital strategy contributed to raising awareness and interest in Antarctic science, while also identifying points that need to be strengthened for broader engagement in the future.

MATERIAL AND METHODS

Scientific-educational webinars were organized monthly by APECS-Brazil from December 2018 to April 2020 using the GoBrunch platform (gobrunch.com), totaling sixteen events. GoBrunch is a

free webinar platform that simulates a physical environment, allowing users to choose their virtual seat in the audience (Supplementary Material - Figure S1). Most recorded webinars (those with signed consent forms) are available on the APECS-Brazil YouTube Channel (<http://www.youtube.com/APECSBRASIL>).

Each webinar featured a speaker—mainly from the APECS-Brazil council—who presented research or outreach activities related to Antarctic topics. Themes included biology, women in Antarctica, palynology, mineral dust, governance, archaeology, science education, and more (Supplementary Material - Table S1). Meetings lasted approximately one hour, with 15 minutes allocated for audience questions (held in the afternoon, GMT -3). Webinars were advertised via APECS-Brazil's Facebook (/APECSBrasil), Instagram (/apecs_brasil), and email. Participation required prior registration through Google Forms (Supplementary Material - Figure S2), available up to three weeks before the event.

The registration form collected open-ended data such as name, age, region, occupation, and institutional affiliation. This information was compiled and analyzed quantitatively to characterize both the “reached audience” (registrants) and the “engaged audience” (attendees). Post-event feedback surveys (Supplementary Material - Figure S3) were sent to all participants, and certificates were provided.

Three analytical categories guided our approach:

1. Reach: defined as the breadth and diversity of those reached (by geography, age, and occupation), based on registration forms and visualized using R (R Core Team 2015; Wickham 2007, 2009; Neuwirth 2014). A map of Brazilian state-level distribution was generated using QGIS (version 3.14.15).
2. Accessibility: defined as the gap between registrants and participants, analyzed by comparing lists and feedback on potential technical barriers (e.g., internet, platform interface).
3. Heterogeneity: defined as the diversity of scientific disciplines addressed in the webinars, categorized through content analysis of the topics presented (Supplementary Table S1).

To contextualize regional differences in participation, we cross-referenced participant origin with the presence of polar research groups per state using data from the CNPq (2021), CAPES (2021), INCT-APA (2021), and INCT-Criosfera (2021). This helped assess how proximity to research centers might influence engagement with Antarctic science webinars.

This exploratory, descriptive study offers a first step in evaluating how accessible online science communication formats can broaden interest in Antarctic topics across Brazil.

RESULTS

In terms of reach, a total of 1,231 individuals registered for the webinars. Among them, 1,204 (97.8%) were from Brazil, covering all 26 states and the Federal District (Figure 1). The states with the highest representation were Rio Grande do Sul (265), Rio de Janeiro (230), and São Paulo (227),

which also host the majority of Brazil's polar research groups. Participants also came from 13 other countries, including Italy, Peru, and South Korea.

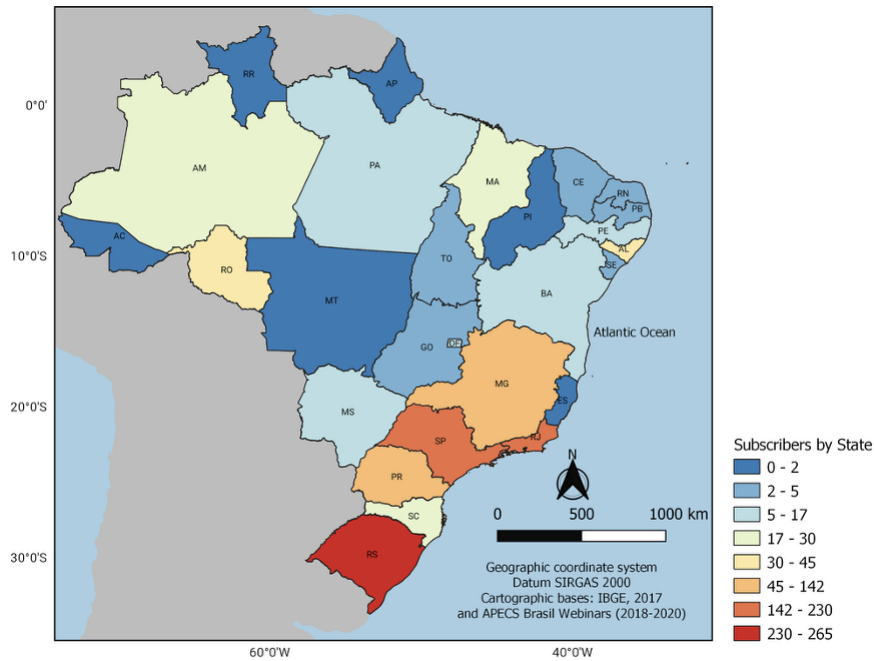


Figure 1. Distribution of APECS-Brazil webinars subscribers (12/2018 - 04/2020) in Brazil by state.

The age of registrants ranged from 14 to 68 years, with the majority (over 61%) between 21 and 35 years old (Figure 2). Their occupations included students (48.4%), teachers (18.2%), and biologists (14.7%) (Figure 3; Supplementary Table S2). These results suggest a strong interest from both educational professionals and individuals in training.

Regarding accessibility, of the 1,231 registrants, 516 attended at least one webinar. Attendance per session ranged from 14 to 136 people (Figure 4). March 2020 had the lowest participation, likely due to the onset of the COVID-19 pandemic and social uncertainty, while April 2020 had the highest turnout, potentially reflecting increased interest in digital events during early lockdown. About 24% of participants attended more than one session, with 42% of them joining four or more webinars. Figure 4. The number of subscribers and participants over the months on APECS-Brazil webinars.

Feedback from 80 participants indicated that nearly 60% found the GoBrunch platform easy to use and were satisfied or very satisfied with the event format. Over 90% stated they would participate again and recommend the webinars to others (Supplementary Figure S4).

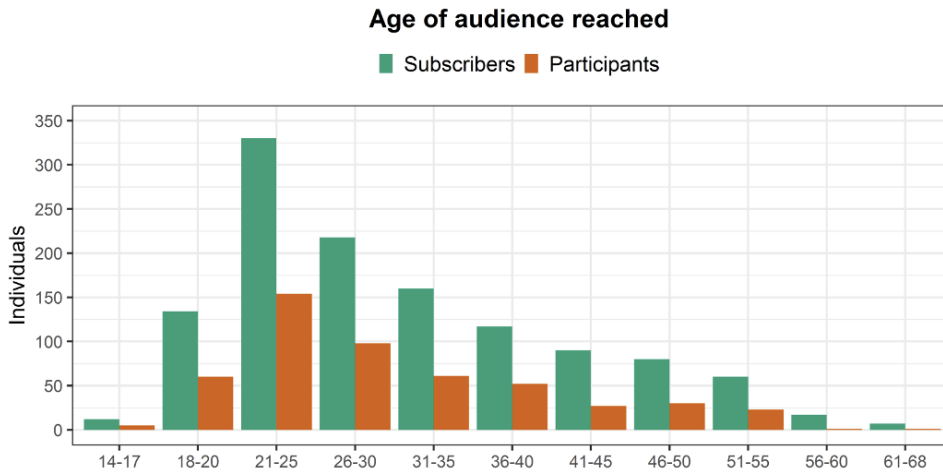


Figure 2. *The number of subscribers and participants in APECS-Brazil webinars per age class.*

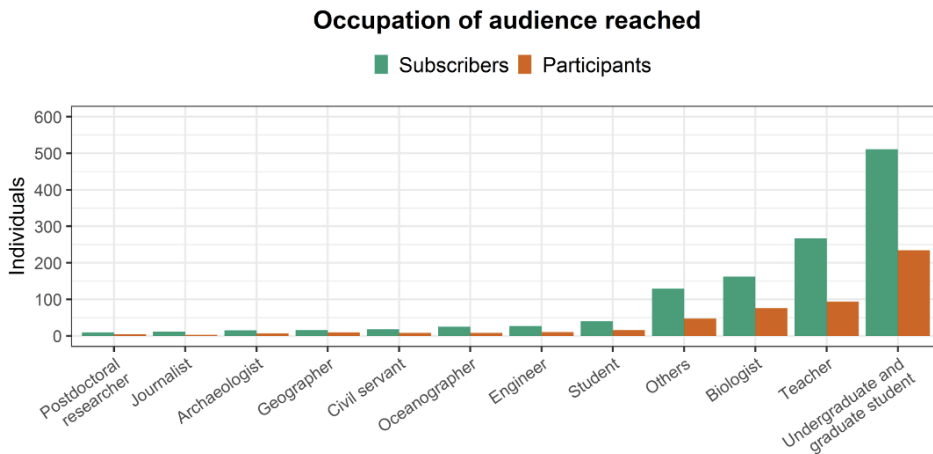


Figure 3. *The number of subscribers and participants in APECS-Brazil webinars per their reported occupation.*



Figure 4. The number of subscribers and participants over the months on APECS-Brazil webinars.

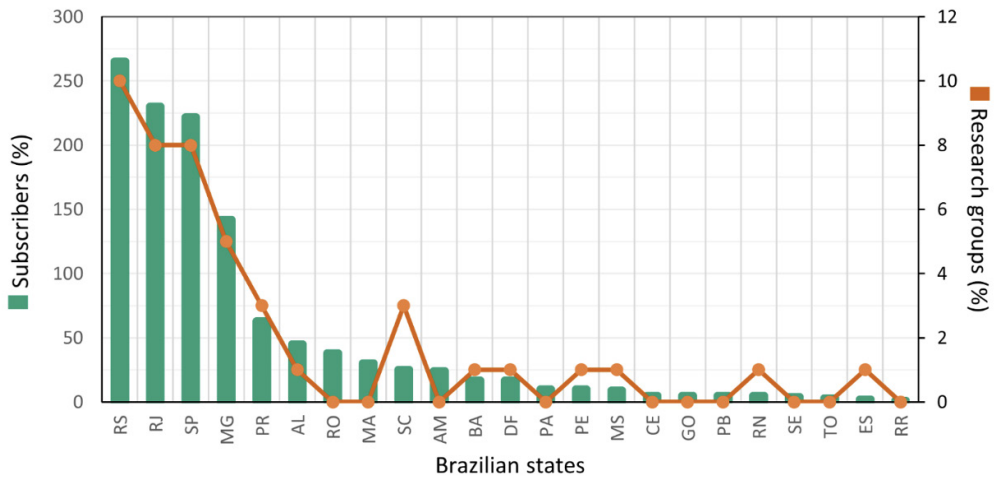


Figure 5. Comparison between the percentage of the subscribers residing in Brazil and polar research groups in Brazil per state.

In terms of heterogeneity, the webinars covered a wide range of Antarctic topics, although biological sciences were the most frequently addressed (Supplementary Table S1). Other fields such as governance, archaeology, education, and climate science were also included, indicating an effort to diversify content and attract various audience interests.

A spatial comparison between webinar participants and the geographic distribution of Brazilian polar research groups (Figure 5) revealed a correlation: states with established polar research institutions had higher registration and attendance rates. Conversely, states with limited academic infrastructure or internet access showed lower engagement, suggesting ongoing challenges in equitable outreach.

DISCUSSION

Considering the results shown above, several conclusions can be drawn regarding the reach, accessibility, and heterogeneity of the Antarctic-themed webinars organized by APECS-Brazil. The geographical trend observed—higher participation from individuals in southern and southeastern Brazil—may be related to the concentration of polar research groups in states such as Rio Grande do Sul, Rio de Janeiro, São Paulo, and Minas Gerais. These regions also have higher digital infrastructure and stronger engagement from APECS-Brazil members, which likely contributed to increased awareness and participation in the webinars.

In contrast, states with little or no polar research infrastructure, particularly in northern and northeastern Brazil, showed limited engagement. This can be attributed to multiple factors, including a lack of exposure to Antarctic science in schools and limited internet connectivity in remote and rural areas. Brazil is a continental country with deep social and regional inequalities, and despite technological advances, internet access remains inconsistent across its territory. Many homes and schools in less developed regions still struggle with basic digital access, which affects the capacity of individuals to attend and benefit from virtual events like webinars.

When analyzing the participant profile, a high number of students and teachers—especially from elementary and undergraduate levels—stood out. Many of these individuals had previously participated in APECS-Brazil activities, such as International Polar Week (IPW), a program that connects polar researchers with schools and universities. This suggests that continuity and presence in educational networks are key factors in fostering long-term interest in Antarctic science. As shown in Xavier et al. (2018, 2019), initiatives such as IPW are effective in introducing complex polar topics to younger audiences and laying the groundwork for more in-depth participation, such as through webinars.

The predominance of students aged 21 to 25 years old likely reflects their search for extracurricular opportunities that enhance academic and professional profiles. It also indicates that the dissemination strategy—centered on social media—successfully reached this demographic. Teachers, on the other hand, showed a willingness to expand their knowledge and participate in a broader educational network. Given the lack of Antarctic-related content in Brazilian curricula (Caramello et al. 2017), webinars and similar initiatives fill an essential gap in science education, offering resources and

training to educators eager to innovate in the classroom (Dotta et al. 2018).

Despite these positive outcomes, the data reveal that the reach of APECS-Brazil webinars was still geographically limited, mostly restricted to areas with stronger institutional ties and better infrastructure. Although webinars can break physical barriers, their effectiveness is still conditioned by digital access. In this regard, our findings are consistent with recent literature on digital education in Brazil, which stresses the persistent challenge of digital exclusion. According to Cardoso et al. (2023), inclusive digital educational programs must simplify access and account for technological limitations faced by marginalized populations.

As for accessibility, the persistent gap between subscribers and participants suggests recurring barriers, such as internet instability, time conflicts, or unfamiliarity with digital platforms. This issue could be mitigated by offering more flexible formats (e.g., asynchronous access to recordings), clearer communication, and reminder systems. Additionally, participant feedback—though largely positive—was limited in quantity. To enhance future assessments, feedback collection could be linked to certificate delivery and forms should be simplified and visually optimized, as suggested by Gegenfurtner & Ebner (2019).

A notable point in this study is the diversity of disciplines addressed in the webinars, although biological sciences were the most represented. While this reflects the predominant research areas among APECS-Brazil members, it also suggests a need to further diversify the content in future editions. The inclusion of social sciences, governance, education, and climate studies proved to be effective in attracting different audiences. This aligns with results from other initiatives, such as the NASA-Rio partnership, where web-based climate education reached broader audiences by connecting global themes to local realities (NASA Applied Sciences, 2021).

Additionally, the success of initiatives like the LAEH webinar series in Pernambuco illustrates how this format fosters strong academic networks and helps decentralize access to scientific debates (Silva & Oliveira 2021). Furthermore, webinars have also been successfully used as tools for combating misinformation and promoting science literacy during the COVID-19 pandemic, as seen in projects by Souza et al. (2023), reinforcing the strategic value of digital communication in science outreach. The rise in participation observed in April 2020 coincides with the beginning of COVID-19 lockdowns in Brazil. While this peak may reflect greater availability due to social isolation, it also reveals how APECS-Brazil was ahead of its time: its webinar program was already fully operational before the pandemic, highlighting the committee's innovative approach to digital outreach. This distinguishes our study from others focused only on post-2020 digital education, offering valuable insights from a pre-pandemic baseline.

In summary, this study demonstrates that webinars, when strategically designed and supported by existing educational initiatives, can effectively bridge the gap between polar science and the Brazilian public. However, structural challenges—such as regional inequality, digital access, and content diversity—must be addressed to maximize their potential. The integration of global experiences and literature reinforces the relevance and scalability of this model, particularly for countries with vast territories and social disparities like Brazil.

CONCLUSIONS

This study presents the experience of APECS-Brazil in organizing monthly webinars as a strategic tool for Antarctic science communication and outreach. The results confirm that, despite infrastructural and regional limitations, webinars can effectively bridge the gap between polar science and a wide and diverse audience across Brazil. By analyzing three core aspects—reach, accessibility, and heterogeneity—we were able to evaluate the strengths and limitations of this communication format. Our findings show that webinars attracted considerable participation, especially from students and teachers eager to explore new scientific content outside of standard school curricula. The strong engagement from regions with established polar research institutions also suggests that previous institutional ties and educational presence play a critical role in outreach success. Nonetheless, the lower participation from underserved regions reinforces the need for integrated strategies that combine digital events with local educational initiatives, especially in areas where internet access is still precarious.

Webinars, as demonstrated in this study, can amplify access to Antarctic themes, promote scientific literacy, and inspire new generations of learners and educators to engage with polar science. However, for this tool to reach its full potential, continuous efforts are needed to improve digital inclusion, diversify content beyond dominant scientific disciplines, and simplify participation and feedback mechanisms.

The APECS-Brazil experience, developed before and during the early days of the COVID-19 pandemic, exemplifies how early investment in digital science communication can be leveraged in times of crisis and beyond. As Brazil and other countries continue to expand their use of online educational technologies, lessons learned from this initiative may guide future outreach programs, especially in contexts marked by geographic and social inequalities.

Ultimately, the case of Antarctic science webinars in Brazil reinforces the idea that digital communication—when combined with strategic outreach planning, strong institutional engagement, and inclusive practices—can serve as a powerful, scalable model for science dissemination, particularly in the Global South.

AUTHOR CONTRIBUTIONS

FEP and JSK proposed and drafted the subscription form. FEP, JSK, CFCS, and MJC organized and mediated the webinars. EAS organized the results and made the map. SD collaborated with the discussion on education and outreach and drafted about these topics. All authors were responsible for data compilation and analysis and contributed equally to writing the final version of the manuscript.

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DISCLAIMER

The authors declare no conflict of interest. The views expressed in this article are those of the authors and do not necessarily reflect the official position of the institutions they are affiliated with. The authors declare no financial or personal conflicts of interest that could have influenced the content or interpretation of this study.

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Event Registration Form

- 1** Email Address
Your answer _____
- 2** Full Name
Your answer _____
- 3** Institution / Organization
Your answer _____
- 4** Occupation
Your answer _____
- 5** Age
Your answer _____
- 6** City
Your answer _____
- 7** State / Region
Your answer _____
- 8** Country
Your answer _____



Post-Event Survey Questionnaire

1 Full Name
 Your answer _____

2 How satisfied are you with the...

	Very dissatisfied	Somewhat dissatisfied	Somewhat satisfied	Very satisfied
Event	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Webinar theme	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Meeting time	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Time duration	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

3 How likely are you to attend a similar event in the future?

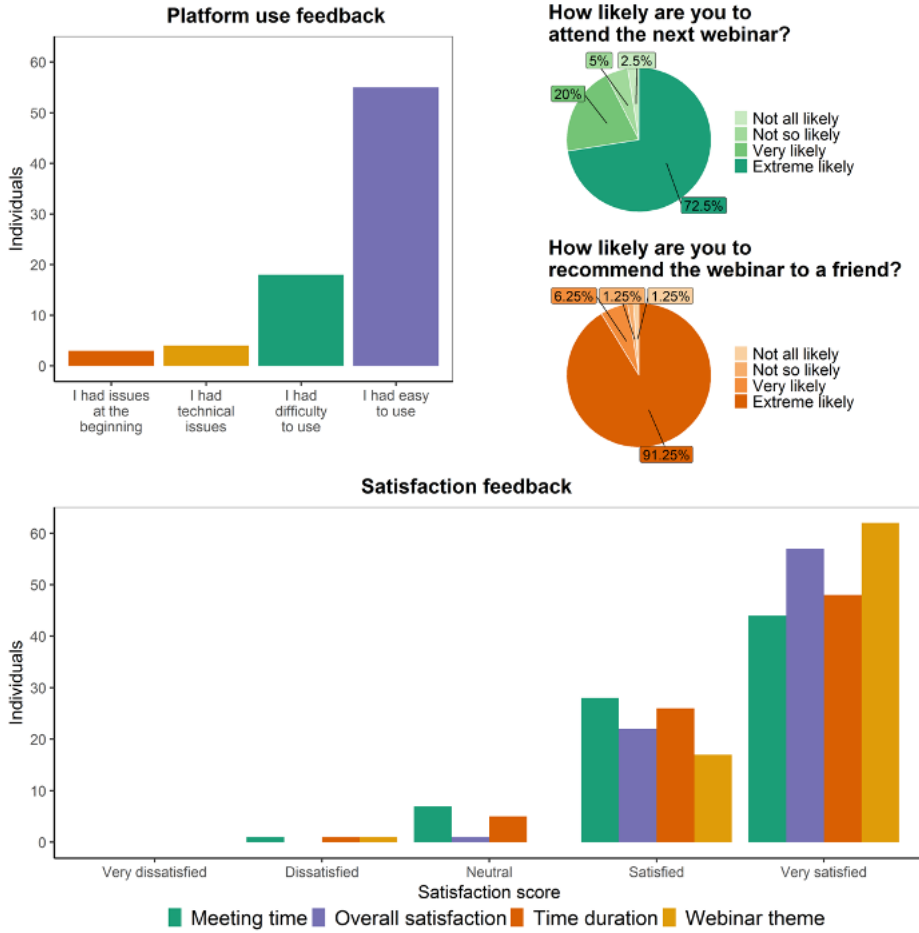
	1	2	3	4	5	
Very unlikely	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very likely

4 Would you recommend this event to your friends?
 Yes
 No Why not? Your answer _____

5 What is your opinion about the Go Brunch platform?
 Your answer _____

6 What improvements would you suggest for the next time?
 Your answer _____

7 Do you have any other feedback? If so, please let us know here:
 Your answer _____



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