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A call to strengthen international collaboration to assess climate change effects in polar regions

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Abstract

Climate change is exerting complex and transformative effects in the Arctic and Antarctic; regions that are essential to global climate, biodiversity, and sustainable futures. Given the polar regions' roles in Earth's system, a robust, coordinated, and innovative strategy to monitor and manage climate change effects is needed. Insufficient baseline data, inconsistent international collaboration, and short-term financing are obstacles to effectively monitor these changes. This hinders our understanding of biodiversity shifts, their implications for food security, and climate change mitigation. Confronting the impacts of climate change will require interdisciplinary collaboration and genuine participation of nations, including Indigenous communities. This sentiment includes facilitating international cooperation to address scientific objectives despite political tensions. Additional recommendations include establishing regular international requirements to track progress based on available science, optimizing the use of existing infrastructure and resources, enhancing data sharing practices, and securing long-term financing to sustain research. While the existing pan-Antarctic and pan-Arctic initiatives present useful strategies, these initiatives are not a silver bullet. They do, however, provide a starting point for further work. Ultimately, by building upon existing initiatives and harnessing their successful components, we can address limitations of short-term or fragmented studies. We outline tools and data resources for polar research, examples of existing collaborative efforts to build upon, and Indigenous knowledge systems that provide valuable resources for this undertaking.

Introduction

The Arctic and Antarctic regions are paramount to the balance of global climate systems and each harbors significant biodiversity [1], playing a critical role in both environmental health and sustainable futures [2]. As climate change increasingly transforms polar regions, the urgency to enhance monitoring and mitigation efforts intensifies [1, 3].

In just 25 years, a significant proportion of the Antarctic ice shelf mass has decreased, primarily due to ocean-driven basal melting and calving [4, 5]. The observed reduction of the cryosphere and the rapid warming in the Arctic and Antarctic are critical not only for their role in deregulating the climate system, global thermohaline circulation, and sea level [6], but also for their impacts on ecological and human systems. Reductions in polar sea ice and the depletion of the cryosphere in general have direct consequences on local populations in the Arctic, such as loss to resource access, reduced personal safety, and impaired physical health. Broader consequences include profound ecological and ecosystemic issues in both marine and terrestrial wildlife, such as trophodynamic alterations, physiological impairments, disruptions in food-web functioning, and the carbon cycle [7–10].

Addressing the complex, multifaceted challenges of polar regions require an approach that encompasses ecological, climatological, socio-economic, and cultural dimensions [2, 11, 12]. A critical aspect of this approach involves acknowledging and addressing the historical dominance of a ’western, privileged, white, male’ perspective [13], the domination by foreign powers over territories and people (colonialism), and more subtle control, often economic, over some countries after formal colonialism ends (neocolonialism) [14]. Such factors manifest in contemporary scientific practices through "parachute" and "helicopter" science, where researchers from dominant cultures or nations conduct studies in less privileged communities, including Indigenous territories, without genuine collaboration or benefit sharing, thus perpetuating historical patterns of exclusion and exploitation [15]. Indigenous communities are deeply connected to polar and subpolar ecosystems and therefore possess invaluable perspectives for developing effective adaptive strategies [16]. Such involvement also enriches the global dialogue on climate change, emphasizing the need for conflict resolution and culturally sensitive solutions for the sustainable use of resources for economic growth, improved livelihoods, and ecosystem health (e.g. the Blue Economy [17]).

The polar regions are spaces with diverse but often competing interests [16, 18]. The Antarctic Treaty System (ATS), centered on the 1959 Antarctic Treaty, which entered into force in 1961, prohibits any military activity, mineral mining, and nuclear testing, and is primarily recognized as a hub for scientific endeavors [19]. However, emerging influences such as geopolitical interests, national economic priorities, and drivers such as polar tourism and fisheries pose compounding challenges [19–22]. Unlike the Antarctic, the Arctic relies on the Arctic Council and the United Nations Convention on the Law of the Sea frameworks for governance and has witnessed escalating geopolitical attention due to its potential for resource extraction and the opening of new shipping routes. The recent geopolitical instabilities, particularly Russia’s invasion of Ukraine, have posed challenges to polar governance leading to the disruption of Arctic Council activities [20].

In an idealistic view, the primacy of scientific research is paramount; however, the current political landscape reveals science as a multi-purpose vehicle not only for the pursuit of knowledge but also significantly leveraged for military strategies, national security, and resource exploration [23–25]. If climate research were conducted without these competing interests, the priority would shift towards a concentrated effort on understanding and mitigating climate change, ensuring that global climate policies and strategies are directly informed by unbiased scientific findings. Scientific exploration is not only beneficial to those directly inhabiting these regions, such as Arctic Peoples, but for the broader global community. For example, understanding sea ice dynamics and water column temperatures is essential for accurate Arctic and Antarctic climate models to predict future global climate scenarios [21, 26]. Ultimately, science diplomacy defined by the strategic use of scientific collaborations among nations to address shared challenges, strengthen international partnerships, and inform foreign policy decisions, should be a key component of any effort to increase cooperation [27]. Despite their geographic differences, science diplomacy and scientific research serve as foundational elements for cooperation in both polar regions [20, 28, 29].

This paper outlines the necessity of a globally collaborative research strategy to better understand and respond to climate change at polar latitudes. A goal of this article is to build on global community responses to the task of climate and environmental monitoring through transparent data sharing mechanisms. We argue for increasing devoted resources to polar research to expand current efforts and the adoption of longer-term funding cycles that promote sustained monitoring programs capable of maintaining critical time series datasets as well as employment continuity for a specialized workforce. We advocate for the inclusion of a wide range of stakeholders within this workforce, including historically and currently marginalized groups (e.g. Indigenous knowledge holders) in order to address the complex challenges of polar research and ensure continued vitality and innovation. We highlight several international networks that currently serve as conduits for science diplomacy to extend beyond territorial rights and countries' self-interest and define specific measures to build on national scientific infrastructure. International networks, which include early career researchers, and the integration of social and human sciences with environmental and ecological sciences offer links between critical components of the science–policy interface [20, 30, 31].

Challenges and opportunities in monitoring climate change in polar regions

This section highlights existing internationally collaborative groups, logistic and data structures, and financial limitations of polar research. Current networks serve as stepping stones towards sustained collaborations to promote synergistic data collections to strengthen the precision of climate models, and secure research partnerships that enhance global unity. These collaborations can further bridge the gap between public education and the implementation of climate mitigation strategies, ensuring that scientific findings have a direct impact on public perspective, policy, and action.

Data

Polar regions are logistically challenging to study, and this has historically limited the amount of data available and the locations where data is accessible for continuous monitoring. This often translates into limited and patchy baseline datasets, if available at all. Due to issues related to coordination and the deployment of infrastructure and technology, the high latitudes remain some of the most poorly observed regions on the planet [32]. Without national infrastructure to support exploration in many locations, limited sampling capacity hinders our understanding of the current state of these ecosystems and the rate at which they are changing. This, in turn, can impair our grasp of biodiversity shifts, implications for food security, and climate change mitigation strategies.

The emergence of satellite remote sensing in the late 20th century has alleviated several observation gaps for sea surface, atmospheric, cryospheric, and terrestrial monitoring. Open access data records from the initial campaigns have been perpetuated through continued public support for scientific satellite missions such as the U.S. National Aeronautics and Space Administration ICESat-2 launched in 2018, and the upcoming European Space Agency Arctic Weather Satellite mission to provide frequent coverage for improved nowcasting and numerical weather predictions. Still, continued support is needed to build and maintain satellite infrastructure to fill critical observation gaps, such as multi-angular polarimetric sensors designed for ocean color applications [33]. To this end, the European Commission established the Copernicus Polar Task Force in 2022 to determine the future direction of the Earth observation component of the European Union's Space Programme [34]. However, even in the context of the European Union, the Copernicus Polar Task Force recommended greater political collaboration across borders for alleviating restricted data access and sharing in polar regions [35].

Numerous national research programs have enabled continued oceanographic expeditions, often even on an annual basis. These expeditions involve a range of scientific disciplines, leading to comprehensive studies that cover various aspects of polar environments. However, these efforts are conducted mainly by individual national projects and often confined to specific regions or species of interest, which results in significant data gaps in less prioritized or less accessible areas. A prominent gap stems from the summer-time restriction of traditional shipboard observations, limiting the understanding of seasonal progression and year-round variability. Advances and increased usage of autonomous platforms have led to significant improvements [36], though existing gaps still prevent a clear understanding of climate change effects in polar regions. New monitoring technologies such as aerial unmanned systems have also gained traction in polar research in recent years [37, 38]. Still, baseline data required from beneath the sea surface are lacking for many areas. For some coastal ecosystems, dive programs since the 1980s have provided insight into remote locations such as the East Antarctic fjords [39], and increasingly the use of both manned and unmanned submersibles are used to document marine biodiversity [40]. Additionally, the non-conventional usage of Argo floats in grounded mode can be effective for oceanographic observations in polar seas. Equipped with an ice-avoidance function and programmed to ground (or park) on the seabed between profiles, these platforms can obtain measurements under sea ice [41–43] and ice shelves [44]. An increase of such winter-time observations and especially the ones sampled close to or in ice-shelf cavities is necessary to gain insight into crucial ice-ocean interactions like heat transport and basal melting [45]. Systematic deployment of sustained moorings and other long-term platforms, autonomous instruments and dedicated deep-sea, under-ice and year-round observational programs are needed to address this critical data gap.

Another opportunity lies in the deployment of Deep Argo floats improving deep-ocean sampling coverage [46]. These profiling platforms have the potential to close the data gap for depths over 2000 m, giving unprecedented insight into the production and export of bottom waters [47] which are the driving force of the global overturning circulation, regulating climate through ventilation of the abyssal ocean and sequestration of anthropogenic heat and carbon from the atmosphere. For the program to be sustainable however, the implementation of the Deep Argo array must rely on the long-term commitments of international Argo partners and the production capacity of float and sensor manufacturers [46].

Specific initiatives such as the Synoptic Arctic Survey [48] are attempting to fill regional baseline data deficiency gaps. The Synoptic Arctic Survey is an international collaboration with the specific goal of providing unique baseline data to define the present state of the Arctic Ocean with the intention to repeat oceanographic surveys in coming decades. The program acknowledges, however, that this survey will not address all ongoing transformations but must be combined with additional field campaign efforts [48].

In the Southern hemisphere, Antarctic biodiversity provides several ecosystem services including carbon sequestration [49]. Interests in understanding species distribution, mechanisms driving spatial patterns of Antarctic species, as well as significance of underexplored taxons is rapidly growing. Efforts have been made to provide a baseline inventory by the Register of Antarctic Species (RAS) which provides a comprehensive list of Latin and common names of more than 12,600 marine and terrestrial species in Antarctica and the Southern Ocean [50]. In the north, the Arctic Register of Marine Species (ARMS) includes all multicellular animals and is currently being updated with the addition of marine plants and information on the habitat and habitat preferences of marine species [51]. Both taxonomic experts and database managers contribute to the development and maintenance of such databases in international collaborative efforts [52, 53]. Genetic data, when combined with specimens in RAS and ARMS, has been shown to significantly improve accuracy in biodiversity research. This is particularly important given the high number of misidentified species in databases, the abundance of cryptic and unidentified species in scientific institutions and natural history museums, and the global decline in taxonomic expertise [54]. Advances in genome sequencing and biogeochemistry have led to new applications that enhance our understanding of biological patterns and environmental records of species. These developments significantly increase the usability of global genetics databases such as GenBank for polar research [55].

Common data repositories and cloud-based tools

There are several data depositories designed for polar specific datasets (Table 1). Data sources, types, and formats distributed among depositories depend on several factors, including established data sharing policies outlined by funding agencies and governments. The Arctic Data Committee established by the Sustaining Arctic Observing Networks (SAON), has attempted a draft map to organize data repositories for polar ecosystem data (https://arcticdc.org/products/data-ecosystem-map). Still, there is a need for a centralized way to access datasets across the data repositories (such as STAC API) and utilize these in cloud-based workflows. Further, access to cloud-based workflows should be a public service so as to provide access to all researchers, not just ones that have expendable funds available. This is essential for an equity as well as educational approach because it is extremely likely that students and early career researchers will lack access to cloud-based technologies if fees are required for entry. Becoming comfortable with this new technology will take users time to learn and make mistakes in an iterative process. If cloud-based tools and access to cloud-based datasets, or hosting personal datasets online is costly, this will disincentivize upcoming researchers in utilizing such resources and acquiring skills and workflows to effectively scale their research. In fact, it is the ability to scale research that will alleviate disparities in trying to connect disjointed, unstandardized, small-scale studies towards a holistic perspective on environmental conditions through the connection of diverse studies.

The databases in Table 1 are operated by various public and private institutions. An initial proposal is to ensure that data collection is standardized so that data from various sources can be easily compared. Following open-access policies for datasets as well as collection protocols can facilitate standardization and increase the impact of research. Understandably, data sharing sparks concerns on copyright infringement and stolen intellectual property, which need to be resolved through framework and consortium agreements between partners, as sometimes already exists between certain players (for example, data pooled between European Union countries). To strengthen our capacity to conduct meta-analyses and big data-type analyses of polar environments, it is advisable to generalize data exchanges and establish IT gateways between the different data repository systems already in place. Ideally, we should end up with a centralized, global database used by all those involved in polar research, and across disciplines. Such initiatives have already been successful in other areas of research, such as biodiversity (GBIF-the Global Biodiversity Information Facility or the World Bank's Global Species Database) or genetics (Barcode of Life Data System-BOLD). This could be best achieved through an international agreement overseen by an internationally recognized institution. Scientific collaborations that already exist in the Arctic and Antarctic could be well-suited to initiate the construction of future joint data sets with appropriate support.

Table 1. Major polar repositories for public data and metadata.

Database	URL	Applications	Host Country	Region
Australian Antarctic Data Centre	https://data.aad.gov.au	T, M, A, C, G	Australia	Antarctic
SOOS map	https://www.soosmap.aq	T, M, A, C, G	Australia	Antarctic
Polar Data Catalogue	https://www.polardata.ca	T, M, A, C, G	Canada	Arctic, Antarctic
Copernicus Arctic Hub	https://www.arctic.hub.copernicus.eu/	T, M, A, C, G	European Union	Arctic, Antarctic
European Polar Infrastructure Database	https://www.europeanpolarboard.org/infrastructure	I	European Union	Arctic, Antarctic
Geoportal	https://www.geoportal.org	T, M, A, C, G	European Union	Arctic, Antarctic
INTERACT Data Portal	https://dataportal.eu-interact.org	T, M, A, C, G	European Union	Arctic
Database of the International Bathymetric Chart of the Southern Ocean	https://ibcso.org	G	Germany	Antarctic
Global Terrestrial Network for Permafrost	https://gtnp.arcticportal.org	T	Iceland and Germany	Arctic, Antarctic
Antarctic Seismic Data Library System for Cooperative Research	https://sdls.ogs.trieste.it/cache/index.jsp	G, M	Italy	Antarctic
Italian Antarctic Data Center	https://iandc.pnra.aq/srv/eng/catalog.search#/home	T, M, A, G	Italy	Antarctic
DueSouth	https://polardex.org/due-south	I	Netherlands	Antarctic
Polardex	https://polardex.org	I	Netherlands	Arctic, Antarctic
Norwegian Polar Data Centre	https://data.npolar.no/dataset	T, M, A, C, G	Norway	Arctic, Antarctic
Open Polar	https://openpolar.no	*	Norway	Arctic, Antarctic
Svalbard Integrated Arctic Earth Observing System	https://sios-svalbard.org/metsis/search	T, M, A, C	Norway	Arctic
SCAR Antarctic Biodiversity Database	https://www.biodiversity.aq/	T, M	United Kingdom	Antarctic
SCAR Antarctic Digital Database	https://www.bas.ac.uk/project/add	G, M, T, I	United Kingdom	Antarctic
SCAR ICE-READER	https://www.icereader.org	C	United Kingdom	Antarctic
Southern Ocean Diet and Energetics Database	https://diet.apps.aq	M	United Kingdom	Antarctic
UK Polar Data Centre	https://www.bas.ac.uk/data/uk-pdc	T, M, A, C, G	United Kingdom	Arctic, Antarctic
Alaska Ocean Observing System	https://portal.aoos.org/#	T, M, A, C, G	United States of America	Arctic
Antarctic Meteorological Research and Data Center	https://amrdcdata.ssec.wisc.edu	A	United States of America	Antarctic
Antarctic & Southern Ocean collection of the Marine Geoscience Data System	https://www.marine-geo.org/collections/#!/collection/UnitedStatesofAmericaP#dataSets	M	United States of America	Antarctic
Circumpolar Active Layer Monitoring	https://www2.gwu.edu/~calm/data/data-links.htm	T	United States of America	Arctic, Antarctic
GHub	https://theghub.org	C	United States of America	Arctic
International Arctic Buoy Programme	https://iabp.apl.uw.edu/data.html	M, A	United States of America	Arctic, Antarctic
National Oceanic and Atmospheric Administration	https://psl.noaa.gov/arctic/data	T, M, A, C	United States of America	Arctic
National Science Foundation Arctic Data Center	https://arcticdata.io	T, M, A, C, G	United States of America	Arctic

(*Continued*)

Table 1. (Continued)

Database	URL	Applications	Host Country	Region
National Snow and Ice Data Center	https://nsidc.org/home	T, M, A, C, G	United States of America	Arctic, Antarctic
Next Generation Ecosystem Experiments	https://ngee-arctic.ornl.gov	T, A, C, G	United States of America	Arctic
Polar Rock Repository Database	https://prr.osu.edu	G	United States of America	Antarctic
Polenet	https://polenet.org/g-net	C, G	United States of America	Arctic, Antarctic
QGreenland	https://qgreenland.org	C	United States of America	Arctic

This table lists data repositories hosted by different countries and/or programs, but it should not be considered a comprehensive inventory of datasets for polar regions. Application types include T = terrestrial, M = marine, A = atmosphere, C = cryosphere, G = geology, and I = infrastructure. *Indicates this site was under construction at the time of writing. The host country column identifies the host of the main organization's website while support from additional organizations and countries may be unlisted.

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Expanding geographic scope of field observations

Oceanographic data collection is concentrated in near-coast North American and European sectors of the Arctic Ocean. There is a deficit of observations in the Central Arctic as well as in the East Siberian, Laptev, Kara Seas, and Eastern Chukchi Sea [56–58]. Ongoing transformations of the Arctic Ocean involving Atlantification of seawater [59], shifts in primary production in the Eurasian Basin [60] and phytoplankton phenology in response to sea ice changes [61] influence ecosystem structure throughout the Arctic. While it is essential to maintain continuous measurements in current locations, there are many areas that still lack baseline observations as previously described.

The dearth of observations is true for the Arctic marine environment as well as terrestrial environments which has led to biased and incomplete understanding in Arctic climate change [62, 63]. For example, several studies corroborate the tundra region of Alaska to be a consistent net carbon source while the boreal region was either net carbon neutral or a sink depending on the year. However, similar detailed evidence does not exist for Siberia which contains the largest reservoir of permafrost [64]. This insight is incredibly important, especially in the context of tall shrub and tree expansion into tundra ecotones in Siberia [65]. Current knowledge on Arctic change on variables such as annual mean air temperature, permafrost temperature, total precipitation, snow depth, vegetation biomass, soil carbon, net primary productivity, and heterotrophic respiration is already biased due to dependence on relatively few research stations scattered across the Arctic without an optimal statistically determined sampling design [62, 66]. Consistent monitoring of these variables and others across the pan-Arctic region is needed for a more comprehensive and less biased understanding of Arctic change.

Russia's invasion of Ukraine in 2022 has prompted ongoing international withdrawal from cooperative polar research [67]. The current conflict marks the first time since the Falklands War that two Antarctic Treaty parties are engaged in active conflict. During the 44th Antarctic Treaty Consultative Meeting (ATCM) in Berlin in 2022, the ongoing war led to heightened diplomatic tensions, with strong condemnation of Russia. This unprecedented situation highlighted the challenge of addressing external conflicts within the ATS and associated bodies and institutions such as the ATCM, the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), the Committee for Environmental Protection (CEP), and the Standing Committee on Antarctic Logistics and Operations (SCALOP). The conflict raises critical questions about the mechanisms available for managing such issues in future meetings, ensuring the Treaty's commitment to peaceful diplomacy, and maintaining the spirit of international scientific collaboration in the Antarctic region [19].

Since the invasion of Ukraine, Russia has been excluded from the Arctic Council, a high-level intergovernmental forum that promotes cooperation and coordination of Arctic monitoring and development [67]. The Arctic Council was founded in a post-Cold War vision of Arctic and sub-Arctic peace. Among foreign ministries, the Arctic Council is unique in that it is the only international group that includes Indigenous leaders as equal stakeholders [67]. Based on its founding values and progressive structure, it is critical for the organization to prioritize scientific progress over current geopolitical tensions. Further, Russia's Arctic Ambassador, Nikolay Korchnov, has hinted at the option of Russia withdrawing from the Arctic Council completely. Without Russia's involvement, the effectiveness of the Arctic Council could be severely hindered [68]. While climate change continues to shape the Russian Arctic in ways unknown to the global community but entirely relevant to it, hard-earned partnerships that enabled environmental monitoring and response will be difficult to reestablish.

Addressing this conflict is vital for preserving the unique cooperative environment that the ATS and Arctic Council has fostered for decades. There have also been significant effects on funding decisions, exchange programs, international research expeditions and other fieldwork and travel including for scientific conference participation [69]. Russia contains over half of the Arctic Ocean coastline. Without cooperation with Russian scientists and safe access to Russian territories, including their exclusive economic zone stretching 200 nautical miles from the coast, we cannot hope to have a clear understanding of Arctic changes as a system. The pressure to resolve the constraints on data and resource sharing for scientific objectives is intensified by the fact that a lack of data from Russia may render Arctic climate forecasting "meaningless" [70]. Additionally, the conflict has disrupted Ukraine's Antarctic research program, threatening the continuity of a long-term temperature dataset [71] which should be supported by cooperative international programs in the near term.

Arctic scientific collaborations

Another significant challenge is international collaboration at the scale needed. A number of international bodies have formed in support of this research effort. For example, the European Union Arctic PASSION program [72], a consortium including partners from 17 countries, was formed to address fragmented components of current Arctic observation systems and expand and improve capacity. Successful components of Arctic PASSION include their work to increase interoperability and accessibility of application-ready Arctic environmental data for science, policy, and business and their efforts to increase retroactive observations of local conditions through Indigenous and local knowledge. However, funding for Arctic PASSION will conclude in 2025 [72]. While Arctic PASSION was funded by the European Union, many Arctic observation programs source their resources from various regional, national, and international funding agencies as well as private donors [73]. The absence of consistent, sustained international collaboration and dedicated funds can lead to gaps in monitoring efforts, making it difficult to get a comprehensive picture of the changes occurring in these regions over time.

Still, there are several examples of international feats in polar science. The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) was the largest Arctic science expedition in history, and an example of a successful international research initiative. In September 2019-October 2020, the German research icebreaker *Polarstern* spent a year drifting trapped in Central Arctic Sea ice to collect datasets related to the ice, ocean, atmosphere, biogeochemistry, and ecosystems. Experts from more than 80 institutions spanning 20 countries participated in or contributed to the $150 million expedition. A notable design in the MOSAiC program was its initiative to make all data collected freely available to the public beginning January 2023, less than three years following the end of the field collections. The data are hosted on various data repositories dependent on funding agency requirements, including those listed within Table 1.

An example of a more enduring Arctic monitoring program is the Distributed Biological Observatory (DBO; https://dbo.cbl.umces.edu). Beginning as a pilot program by the Pacific Arctic Group in 2010, the DBO has developed into an internationally coordinated network of defined observation sites where researchers conduct long-term monitoring of key environmental and biological parameters [74]. The DBO's design facilitates the integration and comparison of data across different sites and over time, offering an invaluable framework for detecting and understanding regional changes in ecosystem health and biodiversity. This collaborative model not only enhances the efficiency of data collection in challenging environments but also fosters international partnerships and data sharing among the scientific community. Owing to the DBO's adaptable framework and responsiveness to emerging scientific questions that can only be addressed through annual monitoring into a built time series, there are current efforts to develop DBO stations in Baffin Bay, North Atlantic, and the East Siberian Sea.

Consensus collaboration in the Southern Ocean

The establishment of the Antarctic Treaty and later, the ATS define Antarctica's history of collaborative efforts. However, collaborative efforts in Antarctica preceded the formation of the ATS span back to earlier International Polar Years (IPYs), including the 1957/58 International Geophysical Year (IGY) [75]. To ensure that Antarctica remains a place for peace and science, 56 states ratified the 1959 Antarctic Treaty. Over time, the rights and responsibilities of the ATS and signatory nations have expanded to include environmental protection and conservation measures, and there are calls to expand the focus further in light of climate change, especially in relation to the Southern Ocean Marine Protected Areas (MPAs), and climate-smart marine spatial planning [76, 77].

The CCAMLR convention was formed in response to rising economic interest in Antarctica in 1982 and while CCAMLR takes an ecosystem-based management approach and is precautionary, its focus is sustainable fishing. It is also important to note that CCAMLR has different spatially explicit conservation measures within the ATS that allow for targeted management and protection of specific habitats and ecosystems [78]. A notable success is the Ross Sea MPA, established in 2016, which at the time was the largest MPA in the world, covering 1.55 million km2 [79]. However, given CCAMLR's role in MPA implementation, they have faced some criticism for developing fisheries rather than implementing biodiversity or climate-change related conservation measures [80]. The main limitation to new MPAs is a lack of consensus decision making, even when MPA proposals are based on multi-year data and scientific advice [81]. For example, Russia and China have consistently obstructed the approval of an East Antarctic MPA in CCAMLR meetings through "decision-making by non-decision-making," thereby impeding consensus rule for over a decade [80].

Given that Antarctica is a shared heritage, it must be managed in a globally fair and inclusive manner. Within the ATS, cooperative mechanisms, equity considerations, global frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) [49], and the high seas biodiversity treaty have all been suggested to link global participation with the ATS and better address the shared consequences of climate change [76]. Given Antarctica's unique governance and legal structure, and decades of scientific research on biophysical processes and climate change impacts, the ATS and its treaty nations are well-positioned to develop unique, climate-smart [76], marine protections that benefit many.

Effective outreach and synthesis programs. There are currently several notable organizations that serve as networks to promote scientific collaboration, too many to describe each in detail. Prominent examples include the International Arctic Science Committee (IASC; https://iasc.info) that focuses on high northern latitudes and the Scientific Committee on Antarctic Research (SCAR; https://scar.org) in the south. SCAR presented the Antarctic Climate Change and Environment report to the ATCM in 2022, including an ambitious decadal plan [82, 83], and in response to the urgent need for coordinated international research in both Polar Regions, IASC and SCAR are currently collaborating to design the 5th IPY [68]. An IPY marks an international coordinated effort to share research expedition plans, observations, and analyses. Additional organizations including the Association of Polar Early Career Scientists and the World Meteorological Organization among others have also supported IPY initial planning efforts. In the annals of polar research, the IPY represents a significant milestone, exemplifying an extensive community-driven initiative encompassing both polar regions since the first IPY in 1880. This persistence underscores the robustness and adaptability of the IPY organizational structure, providing a compelling example of enduring scientific collaboration.

Synthesis and outreach are crucial stages in bringing scientific findings into coherent narratives accessible across a broad range of stakeholders. Synthesis activities amalgamize results from various studies and can lead to more effective research planning. For example, the Synoptic Arctic Survey coordinates international efforts to conduct synchronous, pan-Arctic observations to achieve a more holistic view of Arctic marine ecosystems. Additionally, publications such as IASC's State of Arctic Science Report and International Conference on Arctic Research Planning (ICARP) provide cohesive synthesis of international Arctic priorities as a roadmap for future research activities. Consistent assessments of observations such as the National Oceanic and Atmospheric Administration Arctic Report Card provides comprehensive updates on the state of the Arctic system within easy-to-digest chapters suitable for a non-scientific audience. Every few years, the Arctic Monitoring and Assessment Programme (AMAP; https://www.amap.no/), a working group of the Arctic Council, also publishes a report regarding the state of knowledge on snow, water, ice, and permafrost aimed for policymakers including careful transparency on their assessment of action-orientated recommendations [84].

Beyond data sharing and outreach, international collaborations have been formed to promote sharing of physical assets needed for polar research (Table 2). For example, the Forum of Arctic Operators (FARO; https://faro-arctic.org) is a country membership organization that facilitates dialogue on logistics and operational support for scientific research in the Arctic. Currently, 21 member countries meet annually coinciding with the Arctic Science Summit Week to exchange ideas and updates on operations and infrastructure necessary for Arctic research, including icebreakers and research stations. Successful facility sharing amongst various countries has been achieved through participation in programs such as the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT; https://eu-interact.org) and Svalbard Integrated Arctic Earth Observing System (SIOS; https://sios-svalbard.org). INTERACT and SIOS support transnational access to foreign research stations through centralized request systems. Continued commitment to these organizations by member states, including expanding inventory of participating shared resources, would promote access to research sites from Arctic and non-Arctic nations. Emphasis should be placed in developing research capacity in areas that are currently data poor to limit the impact of bias on our collective understanding of polar changes [62].

Table 2. Arctic and Antarctic research stations.

Country	Primary Antarctic Research Stations**	Primary Arctic Research Stations	Logistical Support	Operators
Argentina	Multiple stations including Esperanza, Almirante Brown		Icebreakers, aircraft	Argentine Antarctic Institute
Australia	Casey, Davis, Mawson		Icebreakers, aircraft	Australian Antarctic Program
Belgium	Princess Elisabeth		Shared logistics	Belgian Polar Secretariat
Brazil	Comandante Ferraz		Icebreakers, aircraft	Brazilian Antarctic Program
Bulgaria	St. Kliment Ohridski		Shared logistics	Bulgarian Antarctic Institute
Canada		Eureka, Alert, Resolute, Cambridge Bay, Western Arctic Research Center in Inuvik	Icebreakers, aircraft	Canadian Ice Service, Polar Knowledge Canada, Aurora Research Institute and Aurora College
Chile	Multiple stations including the Base Presidente Eduardo Frei		Icebreakers, aircraft	Chilean Antarctic Institute
China	Great Wall, Zhongshan, Taishan, Kunlun	Arctic Yellow River Station, China- Iceland Arctic Science Observatory	Icebreakers, aircraft	Polar Research Institute of China
Czech Republic	Johann Gregor Mendel	Czech Arctic Research Station at Longyearbyen	Ships	Czech Centre for Polar Ecology, University of South Bohemia in Ceske Budejovice
Denmark (Greenland)		Daneborg, Arctic Station at Disko Island, DMI Geophysical Observatory Qaanaaq, Summit, Villum, Zackenberg, Niaqornat, Nuuk	Ships, aircraft	Danish Meteorological Institute, Faculty of Science at the University of Copenhagen, Aarhus University, Greenland Institute of Natural Resources
Ecuador	Pedro Vicente Maldonado		Shared logistics	Ecuadorian Antarctic Program
Finland	Aboa	Kevo, Kilpisjärvi, Oulanka, Pallas- Sodankylä	Shared logistics	Finnish Antarctic Research Program, Finnish Meteorological Institute, University of Oulu
France	Dumont d'Urville, Concordia*, Robert Guillard-Cap Prud'homme Station*	Jean Corbel	Icebreakers, aircraft	French Polar Institute
Germany	Neumayer III, Kohnen	AWIPEV	Icebreakers, aircraft	Alfred Wegener Institute
Iceland		Mývatn, Rif	Ships	Icelandic Institute of Natural History, Northeast Iceland Nature Research Centre
India	Bharati, Maitri	Himadri	Icebreakers, aircraft	National Centre for Polar and Ocean Research
Italy	Mario Zucchelli, Concordia*, Robert Guillard-Cap Prud'homme Station*	Dirigibile Italia	Icebreakers, aircraft	National Antarctic Research Program
Japan	Showa (Syowa) Station	Ny-Ålesund, Longyearbyen	Icebreakers, aircraft	National Institute of Polar Research, Japan Agency for Marine-Earth Science and Technology
Netherlands	Dirck Gerritsz Laboratory	The Netherlands Arctic Station at Ny-Ålesund	Shared logistics	Netherlands Polar Programme, Arctic Centre of the University of Groningen
New Zealand	Scott Base		Icebreakers, aircraft	Antarctica New Zealand
Norway	Troll	NIBIO Svanhovd, NPI Sverdrup, Ny-Ålesund	Icebreakers, aircraft	Norwegian Polar Institute, Norwegian Institute of Bioeconomy Research
Peru	Machu Picchu		Shared logistics	Peruvian Antarctic Program
Poland	Henryk Arctowski	Polish Polar Station Hornsund	Shared logistics	Polish Academy of Sciences
Romania	Law-Racoviță		Shared logistics	Romanian Antarctic Foundation

(*Continued*)

Table 2. (Continued)

Country	Primary Antarctic Research Stations**	Primary Arctic Research Stations	Logistical Support	Operators
Russia	Multiple stations including Bellingshausen Station, Mirny, Progress, Vostok	Multiple stations in Siberia and Russian Arctic	Icebreakers, aircraft	Russian Arctic and Antarctic Research Institute
South Africa	SANAE IV		Icebreakers, aircraft	South African National Antarctic Programme
South Korea	King Sejong, Jang Bogo	Dasan	Icebreakers, aircraft	Korea Polar Research Institute
Spain	Juan Carlos I, Gabriel de Castilla		Icebreakers, aircraft	Spanish Antarctic Program
Sweden	Wasa	Abisko, Tarfala	Trains, aircraft	Swedish Polar Research Secretariat
Ukraine	Vernadsky		Shared logistics	Ukrainian Antarctic Center
United Kingdom	Rothera, Halley VI, Signy	NERC Arctic Research Station	Icebreakers, aircraft	British Antarctic Survey
Uruguay	Artigas, Ruperto Elichiribehety		Shared logistics	Uruguayan Antarctic Institute
United States of America	McMurdo, Amundsen-Scott, Palmer	Utqiaġvik Arctic Research Facility, US High Arctic Research Center, Toolik Field Station	Icebreakers, aircraft	U.S. Antarctic Program, U.S. Arctic Research Commission, Institute of Arctic Biology of the University of Alaska Fairbank, Sandia National Laboratory

Polar research stations and major assets for logistical support that are dedicated to scientific objectives. The operator indicates organizations that maintain activities at the research stations and may differ from the organization that owns the research stations. This table lists currently operating research stations as of November 2023 and should not be considered a comprehensive inventory of all polar research stations. *Concordia and the Robert Guillard-Cap Prud'homme Station are jointly operated by France and Italy. **Refer to the Antarctic station catalog for more details [85].

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Financing

Research projects and monitoring initiatives in the Arctic and Antarctic regions are typically funded for varying durations, depending on the specific objectives and priorities. For instance, AMAP has been conducting human health research for over two decades [84]. However, the issue of short-term financing in many programs poses a substantial challenge. As with most scientific projects, many research projects and monitoring initiatives in the Arctic and Antarctic regions are funded on a short-term basis, which can hinder the sustainability and continuity of research efforts [86]. Without long-term financing, it is challenging to maintain consistent monitoring efforts, leading to gaps in data and potentially missing critical changes in ecosystems. Given these challenges, there is a pressing need for a comprehensive strategy that emphasizes coordinated synergies fostering collaboration among nations and research projects. Regular international meetings can help track and adjust progress, while optimizing the use of existing infrastructure and resources. Moreover, securing long-term financing is essential to accelerate research, maximize resources, and improve data sharing. Existing international monitoring initiatives, like the IPY 2007–2008 initiative, with the upcoming 5th IPY in 2032–2033, serve as foundational steps towards achieving these goals.

Polar fieldwork is associated with foreseeable and unforeseeable costs and challenges compared to other types of fieldwork [87]. Scientists working in polar and marine environments often face unique risks and uncertainties, ranging from extreme weather conditions to logistical complexities in accessing study sites [31, 88]. Insurance coverage has become an essential component of research planning to mitigate potential financial losses and liabilities. However, obtaining insurance for scientific expeditions for personnel and property contributes to the extreme expense of conducting science in polar regions [89]. Despite challenges, it is important for stakeholders including funding agencies and policymakers to address these challenges collaboratively. A significant challenge in monitoring programs is securing long-term financing to fulfill associated costs in sustained data collection, processing, and analyses. Innovative financing mechanisms, such as public-private partnerships with international research grants, are essential to maintaining collaborative efforts. However, a necessary consideration is the implicit or explicit goals of funding agencies, particularly private funders, which cannot interfere with the scientific process to sway research designs or the interpretation of data. Otherwise, research programs dependent on biased sources for funding are at risk of becoming beholden to corporate interest. Funding structures that can separate research designs from funding agency input could be an option, but addressing this ethical consideration remains a challenge.

Solutions towards a comprehensive strategy for monitoring and mitigating climate change effects

The atmosphere and the high seas, including the Arctic Ocean, are regarded as global commons by international law. However, the Antarctic, governed by the ATS, holds territorial claims in abeyance (suspension), and no new claims can be made while the treaty is in force. An important factor to consider in this context is deep-sea mining. The ATS 1991 Protocol on Environmental Protection reference to the Antarctic Treaty, more commonly known as the Madrid Protocol, bans mining in Antarctica [90]. The protocol is scheduled for review in 2048. Using seabed mining as an example, it is crucial to recognize that the ecosystems on the seafloor that are currently protected from extractive industries are shared responsibilities for protection rather than common-pooled resources. This perspective urges nations to fund scientific monitoring in remote areas like the deep sea, which are crucial for carbon cycling and biodiversity protection.

Coordinated synergies among nations and research projects

While challenges in monitoring climate change in polar regions are significant, they are not insurmountable. The key to effective monitoring and mitigation in these sensitive regions lies in coordinated funding streams and synergies among nations and research projects in order to maximize the use of resources in challenging environmental settings [91]. By building on existing initiatives, fostering international collaboration, and ensuring long-term financing, we can bridge the gaps between scientific monitoring and the implementation of effective climate informed strategies.

Sustained commitment to existing international monitoring networks leverages successful frameworks to increase international partnerships, facilitate longer-term monitoring, and foster enduring research relationships [92–95]. This approach is true for high-level organizations such as the Arctic Council's working groups and the ATS, which have laid the groundwork for international collaboration, as well as specific international, multidisciplinary research programs such as the DBO and the Marine Ecosystem Assessment for the Southern Ocean (MEASO) [96]. Another example is the Southern Ocean Observing System (SOOS; https://www.soos.aq) which was established by SCAR and the Scientific Committee on Oceanic Research (SCOR; https://scor-int.org) to improve data management and sharing systems to reduce uncertainties in estimates of the future state of the Southern Ocean [36]. SOOS has made considerable progress toward designing a comprehensive observing system though there is room for improvement regarding the accessibility and integration of data from various sources.

Regarding coordinated science efforts in Antarctica, SCAR focuses on high priority topical areas through its scientific research programs. Among the three ongoing flagship programs, AntClimNow and INSTANT address climate change in the Antarctic region, while Ant-ICON guides international conservation and management policies for Antarctica and the Southern Ocean.

Another notable initiative stemming from SCAR is the Antarctic RINGS Action Group (https://scar.org/science/rings), an internationally coordinated Pan-Antarctic aero-geophysical exploration along the entire Antarctic coastal zone. The goal of RINGS is to assess the influence of bed properties on ice sheet coastal processes to quantify regional Antarctic ice sheet responses to future ocean and climate warming.

Effective data sharing forms the cornerstone of these synergies, ensuring that monitoring efforts are both comprehensive and actionable. Employing international standards for data formatting and metadata could improve interoperability of current databases including those listed in Table 1. Data sharing mechanisms should be leveraged to expand the versatility of existing data for integration within a centralized form. This includes ensuring data can be easily accessed and offered alongside associated products in accordance with the FAIR (Findable, Accessible, Interoperable and Reusable) principles that are tailored to the needs of stakeholders [97].

Adopting international standards for data management and exchange will be key in this process, which would require optimizing existing infrastructure and resources including data access tools and tutorials. Costs of data access, especially to publicly funded data, should be free to users always. These steps would maximize the utility of satellites, research stations, and digital platforms for near or real-time data analysis and effective, responsive decision-making.

Involvement of Indigenous communities in polar research

Through proper engagement with and recognition of Indigenous knowledge and academic science as equal but distinct systems, we can address several limitations of western science, including the lack of baseline data and long-term observations [98], and access to knowledge holders via protocols that assign credit and benefits to Indigenous participants [18]. However, facilitation is needed for respectful, ethical, and productive interactions between non-local scientists and local knowledge holders. Expanding access for diverse scientists and Indigenous knowledge holders requires formal and open collaborative networks. Data collection, administration, and sharing methods are also needed for community monitoring [99]. This integrated approach significantly enhances our ability to understand and manage local environmental phenomena, such as the development of protected areas [100], contributing to conservation and sustainability efforts. Additionally, it fosters a more comprehensive and contextual social understanding. An understanding that actively confronts the ongoing challenges of colonialism and neocolonialism in polar scientific research [14] and practices that break trust in local communities such as helicopter science [15]. Adaptation of more conscientious scientific practices sets the groundwork for a more equitable and inclusive scientific community [101].

The inclusion of Indigenous communities' knowledge in polar research provides significant benefits on a variety of scales, ranging from local community-driven priorities like human and ecosystem health and sustainable development to global concerns such as climate change, and wildlife populations. Indigenous and local knowledge serves as an important link enhancing scientific understanding with life experience and adaptations to changing environments [102, 103]. However, successfully integrating this knowledge into polar research presents several challenges, including reconciling methodological differences, ensuring cultural sensitivity and informed consent, and maintaining long-term and mutually beneficial partnerships. A respectful and ethical approach, including explicit agreements and suitable incentives for long-term collaboration, especially given the intergenerational nature of Indigenous knowledge is imperative in this context. Furthermore, successful incorporation of Indigenous viewpoints requires adherence to knowledge co-production norms. This includes aligning scientific goals with the capacities of Indigenous knowledge systems, guaranteeing compatibility in observation methodology and data management, and cultivating a respectful relationship that recognizes and honors Indigenous populations' contributions [18]. Addressing these challenges not only increases the impact of local observations on broader scientific priorities, but also paves the way for more comprehensive scientific practices that are gaining momentum within broader society [101].

There have been increasing attempts in polar regions to combine scientific inquiry with traditional wisdom. For example, First Nations populations in Canada [104] have long emphasized the need for climate change adaptation strategies that are sensitive to their unique circumstances, drawing from their extensive experience living in the Arctic for thousands of years and their deep understanding of sea ice practices and wildlife patterns [105]. The substantial inclusion of knowledge holders across the Arctic necessitates significant coordination and effort but is crucial for continuous, comprehensive monitoring across seasons. In particular, the Inuit (distributed throughout Alaska, Canada, and Greenland), the Sámi (in northern Norway, Sweden, Finland, and Russia), the Athabaskans (in Alaska and Canada), the Aleut (in Alaska and Russia), and the Yupiit (in Alaska and Russia) are the historical occupants in many Arctic locations [106]. A collaborative approach is vital to anticipate human and ecosystem responses to emerging challenges, like increased ship traffic and the northward movement of subarctic species [107]. Organizations like the Arctic Council, which includes Indigenous permanent participants, have played a role in such collaborations. Although the extent and effectiveness of these collaborations can vary, several Arctic nations have implemented community-based monitoring programs involving Indigenous knowledge holders, especially in areas like wildlife tracking and climate change observations. For example, the Alaska Arctic Observatory and Knowledge Hub (AAOKH; https://arctic-aok.org) is a network of Iñupiaq observers from northern Alaska coastal communities that work with researchers at the University of Alaska, Fairbanks. The AAOKH is an integrated observatory with goals to monitor environmental change, highlight Indigenous-led observations of the environment and their meaning, promote scientific and Indigenous knowledge exchange, and support community-led initiatives addressing changes in the cryosphere, wildlife, and other environmental aspects along the northern coast of Alaska [108]. Observations on local sea ice conditions are accessible to the greater scientific community through a database. Further, the data policy requires citation of individual observers of the data used in knowledge production. This arrangement provides local observations available to scientists indirectly, limiting the need for individual scientists to attempt relationship building with local knowledge holders who may be constrained in terms of time and interest.

In the Antarctic, the ATS encourages scientific collaboration among nations. While there are no Indigenous populations in Antarctica, there is a growing recognition of the value of diverse perspectives, including those of Indigenous researchers from countries involved in Antarctic research. SCAR and other organizations work towards effective data management and sharing, although these efforts are currently more focused on international scientific collaboration rather than integrating local or Indigenous knowledge. The relevance of Indigenous knowledge in shaping an inclusive polar future and understanding the past remains significant. Notably, the Māori people of New Zealand/Aotearoa, who are likely the first humans to have encountered Antarctic waters and possibly the continent [109], may provide perspectives on local environmental changes and adaptation techniques. This is especially pertinent in the context of the New Zealand Antarctic Programme [110, 111], which could incorporate Māori perspectives more fully and set a standard for cultural inclusion among the 56 treaty party nations under the ATS [112].

Steps towards bridging science to action

To address the complex challenges of polar research on a broader scale and achieve a more comprehensive understanding of polar systems, a strategic and collaborative approach is essential. To this end, we propose six actions that can be conducted in parallel and have deliberate overlaps to emphasize their connectivity.

1. The initial step in advancing polar research is to identify and use global forums to enhance monitoring efforts and establish clear goals. This approach, vital for overcoming the limitations of separate national programs, aims for a comprehensive understanding of polar dynamics. Coordinated collaboration among nations and research initiatives is crucial for efficiently using resources like polar stations and logistics personnel (Table 2). This strategy is key for gathering important polar observations and surpassing the constraints of small-scale national studies, while also ensuring effective information sharing among scientists, policymakers, and local populations, including Indigenous communities.

2. The second step involves advancements that can make data more accessible and actionable for the public, and improve the sense of involvement in polar science, thereby increasing awareness and support for climate change mitigation in polar regions. It implies more than just token inclusion of Indigenous communities; it requires their active participation in scientific research and policymaking. Integrating their ecological knowledge enhances our understanding of polar ecosystems. Additionally, engaging the broader public and involving diverse skill sets could further assist in ecosystem management and protection through the adaptation of technologies like unmanned aerial vehicles, artificial intelligence, and citizen science platforms.

3. The third step is to secure long-term funding and establish sustained monitoring cycles, which are essential for effective scientific action and developing solutions for studying and protecting the polar regions. Analyzing both successful and less successful international initiatives can guide the creation of general guidelines. Crucially, there is a need for ongoing, long-term financial support from various countries to build a foundation for tackling the complex challenges of climate change in polar regions. Potential funding sources could include governmental funds, business sector partnerships, and international collaborations. Addressing the multifaceted impacts of climate change requires trans-disciplinary funding across areas like climatology, ecology, and social sciences. Funding proposals should also consider the logistical and mental health needs of scientists, particularly early career researchers [113]. We need to build bridges between the disciplines that study climate, the cryosphere, oceanography, ecology, economics, social, and political sciences. Although agendas of potential funders, like resource prospecting, can hinder scientific cooperation, it is essential that we leverage these challenges to foster collaboration across as many areas as possible.

4. The fourth stage is developing existing technologies or testing new ones that will enable us to explore polar environments in depth, comprehensively and securely. These technologies include remote sensing and modern survey tools (satellites, unmanned aerial vehicles, sonars, radars, autonomous submersible vehicles, miniaturized sensors), molecular tools (environmental DNA (eDNA), multi-omics, bioinformatics, molecular barcoding), and IT

tools (large databases, participatory science, coupled models, artificial intelligence) that can be applied to a range of applications. For example, questions on how life evolved and adapted to cold environments with extreme seasonality can be better achieved using multi-omics and eDNA analyses [114]. Additionally, new methods based on satellite tracking and monitoring of disturbances such as from pollutants [115] can provide clearer links between human actions and the marine environment [116].

5. Decision making structures need to remain flexible to swiftly adjust responses to the various consequences of climate change in polar regions. There is a current initiative to develop a pan-arctic ocean observing alliance that would be recognized as a formal part of the Global Ocean Observing System (https://goosocean.org). The objective is to develop formal coordination mechanisms that will improve data-gathering and observational infrastructure [117]. The proposed framework differs from individual researcher-led programs previously mentioned in seeking to establish an internationally accepted governance structure with recognized authority centered on high-level policy objectives [117]. Planning coordinated research efforts that maximize societal benefit is desirable but alternate paths that result from independent, entrepreneurial effort should also be encouraged. For example, implementing novel technology or responding to natural events or new discoveries may lag if hierarchical structures are too rigid.
   Similarly, Antarctic programs such as SCAR's scientific research and the ATS' environmental protections demonstrate concentrated efforts to assess and anticipate climate ramifications. Regularly developing and publishing research priorities, building effective communication to better align research efforts, and securing sustained funding for collaborative initiatives will continue to be essential activities. The expected symmetry of the polar regions is limited by highly contrasting geographical components as the Arctic is a sea surrounded by land while the Antarctic is a continent surrounded by sea, with different climatic, ecological, and geopolitical constraints. Each region faces distinct risks though issues common among the polar regions are evident. Adopting effective frameworks (such as IPY and "Hope Spots") and aligning tactics with the Ocean Decade's vision serve as guiding principles for future research endeavors.

6. Greater efforts in science communication are needed to bridge the interests of polar regions with the greater public. Dissemination on the importance of polar and subpolar ecosystems is essential, as well as the ongoing threats they face such as increased ship traffic and environmental changes. Polar tourism, for example, is both an opportunity and a threat for scientific research and environmental preservation [26, 118, 119]. Lamers et al. [120] recently concluded that linking science and tourism generally had positive effects on visitor experience and the conduct of polar science projects, but also presented complex challenges, including a risk of greenwashing if the combination of science and tourism was not done with care. The development of citizen science in the polar regions (e.g., during touristic cruises) may enable broadened data collection but the risks associated with increased pressure on ecosystems need to be considered [121]. Therefore, ongoing discussion of human impact on the environment in terms of tourism, fisheries, and global shipping is needed to promote behavioral changes of consumers as well as apply pressure to governments and businesses to refine policies and practices.

Perspectives on Arctic and Antarctic “exceptionalism" are changing because of Russia's offense on Ukraine as well as warming temperatures increasing access to these regions [122, 123]. These events may cast doubt on the Antarctic and Southern Ocean's exclusivity and raise questions about the ATS's capacity for adaptation. In contrast, ’Arctic exceptionalism’ is characterized by the region's long-term habitation by Indigenous peoples and sovereignty claims by Arctic states. Governance is managed through national laws and the cooperative framework of the Arctic Council. Increasingly, there is pressure on the Arctic Council to collaborate with relevant partners to effectively address climate change. Both regions face similar human challenges such as disagreements over resource extraction, environmental preservation, and territorial claims [124]. Examples include Russia's territorial claims in East Antarctica and China's interest in Antarctic krill fisheries [125], as well as disputes over oil and gas exploration rights in the Arctic exemplified by tensions between Russia and Norway in the Barents Sea [126]. International science collaboration has become more complex given these geopolitical contexts, yet cooperation is increasingly essential in light of ongoing climate change. Multilateral efforts will therefore be required to close the gap between the needs of relevant scientific understanding and policy action for the polar regions. Necessary steps include funding polar research, incorporating scientific findings into decision-making at all levels, and encouraging diverse stakeholders to work together to solve complex problems and ensure good governance, environmental protection, and sustainability.

Summary and conclusions

Impacts of climate change in the polar regions are complex and require a globally coordinated response. Data and knowledge gaps, particularly due to the logistical challenges and seasonal limitations of conducting research, hinder a comprehensive understanding of these impacts. To overcome the limitations of small-scale and short-term studies conducted by individual national projects, sustained circumpolar exploration efforts are needed on an international level. However, different national agendas add complexity, as varying priorities and objectives can lead to fragmented efforts and policies.

Moreover, the urgency of environmental changes conflicts with the limited time available to properly evaluate and address their impacts. The 2023 Global Tipping Points Report (https://global-tipping-points.org/), which was recently presented at the 28th United Nations Climate Change conference (COP28; https://unfccc.int/cop28), highlights the urgency of these issues. The continuation of 'business as usual' approaches in policy and economic activities further aggravates the situation, underscoring the need to address the unique challenges of climate change in the polar regions.

With this paper, we argue that addressing these challenges demand a shift from short-term, fragmented approaches to long-term, integrated strategies. This shift necessitates improved international collaboration, inclusive of diverse stakeholders including Indigenous communities. Coordinated synergies fostering collaboration among nations and research projects will enable optimized usage of existing infrastructure as well as develop monitoring infrastructure in data poor regions in order to obtain unbiased observations in polar regions. Altogether, this will require increased resources dedicated to polar research.

Overall, access to data and infrastructure is essential to successfully assess the current and future states of polar regions. We, therefore, suggest that observations, methodologies, and data management practices should be harmonized and standardized across the different regions and research programs so that data can be made available based on the FAIR data principles. Improving the potential of desk-based work and data sharing arrangements could enable comprehensive research and would minimize the need of developing redundant physical infrastructure. This includes analyzing remote sensing and satellite data to monitor environmental changes, developing climate and environmental models, conducting meta-analyses of existing studies, and investigating historical data. Policy and governance research, citizen science projects, and the application of artificial intelligence to complex datasets will play crucial roles in this process. Open access to data as well as cloud-based technologies will facilitate these efforts.

Observations are needed at appropriate spatial scales to support modeling efforts, which requires substantial international pooling of logistic and scientific resources and capabilities. Synergies from existing initiatives like SOOS, IASC, UN Ocean Decade, the Southern Ocean Decade, COP29 and commitments such as Nationally Determined Contributions (NDCs) should be harnessed to ensure that individual activities align and contribute toward common goals. Further, it is essential that commitments such as NDCs are not merely symbolic, but rather substantiated by concrete, measurable actions and accountability mechanisms. Finally, we call for further involvement of early career researchers to strengthen future commitment to these collaborative international, interdisciplinary efforts.

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