Toward Interoperable and Globally Integrated
Open Science in Antarctic Research through Standards and Identifiers

1. Introduction

Antarctic research relies fundamentally on the continuous accumulation, preservation, and interpretation of diverse scientific data. These datasets ranging from long-term meteorological observations and cryospheric measurements to biological monitoring, geophysical surveys, and environmental assessments form the empirical foundation upon which present understanding and future projections of Antarctic systems depend. In Ukraine, the state institution National Antarctic Scientific Center (NASC) plays a central role in ensuring that such information is systematically collected, curated, and made accessible to the research community. As the operator of Ukraine's long-standing Antarctic programme and station, NASC is responsible not only for generating new data but also for maintaining the scientific integrity of its program over decades.

The distinctive nature of Antarctic science places exceptional demands on how data are managed. Many research questions in polar regions can be addressed only through continuous observational series spanning forty to fifty years or more. Climate dynamics, ocean ice interactions, ecological shifts, and atmospheric processes reveal meaningful patterns only when examined over multi-decadal timescales. The longevity and uniqueness of these datasets create a requirement for robust mechanisms that can safeguard them against technological obsolescence, data fragmentation, and loss of provenance. Moreover, the global relevance of Antarctic science its implications for climate models, biodiversity assessments, and international environmental governance necessitate data practices that facilitate transparency, reproducibility, and international comparability.

In this context, standards, persistent identifiers, and interoperable information infrastructures emerge as essential components rather than optional enhancements. Metadata standards ensure that datasets remain interpretable across generations of researchers and software systems. Globally recognised identifiers such as DOIs for datasets, ORCID identifiers for researchers, and ROR identifiers for institutions support persistent attribution, traceability, and accurate linkage between data, publications, people, and research facilities. Interoperable infrastructures, built on open protocols and harmonised schemas, enable Antarctic data produced by NASC to be efficiently integrated into regional and global repositories, incorporated into cross-disciplinary models, and reused in collaborative international research.

The aim of this paper is to articulate the conceptual principles and practical considerations that should guide NASC in adopting such standards, identifiers, and open-science infrastructures. By outlining a cohesive vision for data interoperability and long-term stewardship, the article seeks to contribute to establishing a sustainable, globally aligned framework that will enhance the resilience, accessibility, and scientific value of Ukraine's Antarctic research outputs.

2. Antarctic Research as a Long-Term Global Resource

Antarctic science is distinguished by its reliance on sustained observational programmes that span several decades. These records constitute one of the few continuous baselines available for understanding the Earth's climate system and its rapid transformations (Abram et al., 2013; Stauffer et al., 2000). Meteorological observations offer a prime example: stations such as Vernadsky, Amundsen–Scott, Halley, and Mawson maintain uninterrupted measurements of temperature, pressure, wind, precipitation, and radiation (Hughes et al., 2021). Together, these datasets form a continent-scale archive that allows researchers to examine variability across annual, decadal, and multi-decadal scales (Abram et al., 2013; Rogers et al., 2019).

Equally indispensable are ice-core records, which preserve atmospheric compositions reaching back hundreds of thousands of years (Lorius, 1992; Jong et al., 2022; Srivastava et al., 2023). By analysing trapped gases and isotopic signatures, scientists reconstruct past climates, identify natural cycles, and contextualise contemporary changes within a much longer climatic continuum (Lorius, 1992; Jong et al., 2022).

Long-term atmospheric chemistry monitoring, particularly of ozone, aerosols, reactive species, and greenhouse gases, provides direct evidence of anthropogenic influences on the atmosphere (Stauffer et al., 2000; Hughes et al., 2021). These records have been instrumental in tracking the progression and partial recovery of the Antarctic ozone hole as well as in refining global radiative forcing estimates (Abram et al., 2013; Stauffer et al., 2000).

In parallel, oceanographic and ecosystem observations, including those coordinated under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), document physical ocean properties, sea-ice dynamics, primary productivity, and the status of key marine species (Rogers et al., 2019; Gutt et al., 2022). These datasets underpin ecosystem-based management approaches, fisheries regulation, and biodiversity assessments across the Southern Ocean (Rogers et al., 2019; Gutt et al., 2022).

The exceptional value of Antarctic datasets stems from their temporal depth. Multi-decadal measurements are the only means to detect gradual or episodic shifts that would otherwise remain obscured by short-term fluctuations (Abram et al., 2013; Hughes et al., 2021). Climate signals such as stratospheric cooling, sea-ice reconfiguration, and changes in atmospheric circulation patterns emerge clearly only when analysed across extended time horizons (Srivastava et al., 2023; Rogers et al., 2019).

One of the most compelling historical illustrations is the discovery of the Antarctic ozone hole. The identification of this phenomenon was possible only through the integration of long-running and openly shared datasets collected by several national programmes (Stauffer et al., 2000; Hughes et al., 2021). The episode demonstrated not only the scientific power of sustained observations but also the importance of data interoperability and transparent exchange in enabling transformative scientific insights (Abram et al., 2013; Gutt et al., 2022).

Maintaining an uninterrupted observational series in Antarctica is inherently challenging. Personnel rotation, often occurring annually, introduces variability in methodological consistency and institutional memory (Hughes et al., 2021). Equipment replacement and calibration differences can create discontinuities in measurement series unless carefully documented and harmonised (Stauffer et al., 2000). Some stations are relocated or rebuilt due to changing environmental conditions, logistical constraints, or infrastructure ageing, which may alter the geographic context of observations (Gutt et al., 2022).

Additionally, broader political and administrative cycles influence funding stability and long-term planning. Shifts in national priorities may affect research institutions' ability to commit to multi-decadal data stewardship (Hughes et al., 2021; Rogers et al., 2019). These factors collectively highlight the need for robust standards, persistent identifiers, and interoperable data architectures that can preserve the coherence, traceability, and long-term scientific value of Antarctic datasets despite operational constraints (Abram et al., 2013; Gutt et al., 2022).

3. The Antarctic Treaty as the First International Model of Open Science

The intellectual and geopolitical landscape of the 1950s was marked by profound changes in how scientific knowledge was produced, shared, and governed. In the immediate aftermath of the Second World War, research became increasingly entangled with national security agendas, and secrecy, particularly in fields such as nuclear physics, geophysics, and atmospheric science, often prevailed over open exchange (Walton, 2011). At the same time, the rapid expansion of international scientific cooperation, symbolised by initiatives such as the International Geophysical Year (1957–1958), demonstrated a renewed interest in collaborative modes of inquiry that transcended political divisions (Walton, 2011; Berkman, 2025).

Against this backdrop, Antarctica emerged as a unique domain in which science could serve as a stabilising force. The remote and uninhabited continent offered a natural laboratory for studying global processes, and its scientific potential motivated states to negotiate unprecedented arrangements to ensure peaceful use and knowledge sharing. It is within this historical moment that the Antarctic Treaty (1959) introduced a radically new framework for scientific openness on a global scale (Secretariat of the Antarctic Treaty, n.d.-a).

Article III of the Antarctic Treaty is among the earliest formal international commitments to open scientific practice. It obliges Parties to exchange scientific observations, research findings, and results obtained in Antarctica “to the greatest extent feasible and practicable” (Secretariat of the Antarctic Treaty, n.d.-b). This obligation encompasses both raw observations and interpreted outputs, thereby establishing a norm of routine and systematic data sharing.

The Article also mandates the exchange of scientific personnel among national expeditions. This requirement not only fosters methodological alignment and mutual learning but also ensures transparency in research practices. Additionally, Parties must provide advance notice of their research plans, including field activities and the establishment of scientific stations. Such openness, embedded directly in a legally binding instrument, set a precedent for later frameworks governing research collaboration and data dissemination (ASOC, n.d.; Walton, 2011).

The implementation of Article III catalysed the creation of institutional structures that support large-scale scientific coordination. Organisations such as the Scientific Committee on Antarctic Research (SCAR) and its data management bodies, including the Standing Committee on Antarctic Data Management (SCADM), emerged to facilitate harmonisation of observational efforts, metadata standards, and data stewardship practices across national programmes (Walton, 2011).

Crucially, the Treaty also contributed to the depoliticisation of scientific information. At a time when Cold War tensions often constrained knowledge exchange, the Antarctic framework insulated data from geopolitical rivalries and established an expectation that scientific outputs remain accessible for the collective benefit of all Parties (Walton et al, 2018).

Moreover, the Treaty is widely recognised as a historical antecedent to contemporary open science policies, including the FAIR principles (Findable, Accessible, Interoperable, Reusable). Although formulated decades before these frameworks, the Treaty’s provisions anticipated many of their core tenets: transparency, reproducibility, interoperability, and the unrestricted circulation of scientific knowledge (Walton, 2011).

Antarctica has increasingly been conceptualised as an “open science commons”, a shared global resource in which data, observations, and research infrastructure are maintained cooperatively to advance knowledge. The continent’s environmental records, ecological datasets, and long-term monitoring series constitute a planetary public good, indispensable for understanding climate change, ocean circulation, biodiversity trends, and atmospheric processes (ASOC, n.d.; Secretariat of the Antarctic Treaty, n.d.-a).

By treating Antarctic data as a shared commons, the Treaty system underscores the idea that no single nation can claim exclusive ownership over knowledge generated on the continent. Instead, its scientific outputs contribute to a collective pool that supports global decision-making, environmental stewardship, and the long-term resilience of Earth's systems (Walton et al, 2018; Kennicutt et al., 2019).

4. Why Open Science is a Structural Necessity for Antarctic Research

Open science principles are not simply an aspirational framework for Antarctic research; they form the structural foundation that allows the scientific system on the continent to function across decades. The longevity of Antarctic monitoring programmes means that data are inherited by new generations of researchers who must be able to understand, validate, and reuse observations collected long before their involvement. This intergenerational continuity is possible only when documentation, workflows, and access pathways are transparent and maintained in ways that outlive individual careers or institutional cycles (Clarke, 1993).

In a region where field teams rotate frequently and research personnel seldom remain at the same station for extended periods, openness serves as the mechanism for preserving scientific memory. A further reason for the indispensability of open science is the need to ensure comparability between observations collected at different stations and across different national programmes. The continent hosts research infrastructures that vary widely in their equipment, capacity, calibration practices, and scientific traditions. Without a shared commitment to standardised metadata, interoperable formats, and harmonised terminologies, it would be nearly impossible to synthesise datasets across these diverse systems (Graiff et al., 2023; SOOS Data Management Sub-Committee [SOOS DMSC], 2022). Open science, therefore, acts as the methodological glue that binds disparate observational efforts into coherent scientific narratives, enabling cross-continental assessments and global modelling initiatives.

Antarctica's extreme environmental conditions add another layer of structural necessity. Data generated in such a fragile operational context is inherently vulnerable. Power outages, equipment failures, extreme weather, accidents, or station relocations may compromise local archives or result in abrupt interruptions to long-term observation series (Kennicutt et al., 2016). Storing data in distributed repositories and maintaining open online access operate as an insurance mechanism: even when local systems fail, redundant copies remain safe in trusted international infrastructures (NSF Office of Polar Programs, n.d.; Polar Data Catalogue, n.d.). Openness here is not a philosophical stance but a practical strategy for safeguarding irreplaceable scientific records.

The global relevance of Antarctic data further strengthens the argument for openness. Observations from the continent feed into international climate assessments, oceanic and atmospheric circulation models, biodiversity analyses and conservation planning under organisations such as CCAMLR, and even into studies of upper-atmosphere physics and space weather. These applications presuppose the availability of harmonised, high-quality data that can be ingested into models and decision-support systems without technical or legal restrictions. Closed data environments would fragment scientific knowledge and diminish the contribution of Antarctic research to global climate governance.

In this context, the FAIR data principles (Findability, Accessibility, Interoperability, Reusability) serve as a technological and conceptual framework that ensures datasets maintain their value across decades. Detailed metadata enable future researchers to interpret the methodological context of observations, while persistent identifiers guarantee stable referencing despite changes in institutional structures or digital platforms. Interoperable formats allow datasets to move seamlessly between tools, communities, and infrastructures (SCAR Standing Committee on Antarctic Data Management [SCADM] et al., 2025; SOOS DMSC, 2022). FAIR functions as an engine of long-term compatibility, ensuring that datasets produced today remain intelligible and reusable for the long term.

5. A Conceptual Model for Implementing Standards and Identifiers at the National Antarctic Scientific Center

For the National Antarctic Scientific Center, the creation of a coherent system of persistent identifiers represents the first necessary step towards a modern, interoperable information infrastructure. Assigning DOIs to datasets, observational series, expedition reports, and other research outputs stabilises their identity in the scientific ecosystem and allows them to be cited unambiguously in future work. Using ORCID to identify individual researchers, technicians, and expedition participants ensures that contributions are accurately recorded and linked to personal scholarly profiles. The adoption of ROR identifiers for institutional affiliations introduces consistency into the organisational metadata and facilitates automated linking across external systems. Together, these identifiers establish a structured network of relationships among people, institutions, datasets, and publications.

To achieve deeper semantic and structural coherence, this network must be embedded within a standardised metadata architecture. The CERIF (Common European Research Information Format) model, widely used in European research information systems (EuroCRIS, n.d.; European Commission, 2017), offers a flexible structure that can capture the full complexity of Antarctic research. Its entity–relationship framework enables the representation of not only datasets and publications but also instruments, research activities, field events, and logistical components. Through controlled vocabularies, geographic descriptors, and typological classifications, CERIF ensures that metadata remains consistent across the entire system. This approach makes it possible to trace the entire research sequence from a specific expedition using a particular piece of equipment, to the observations collected, the datasets curated, and eventually the publications derived from them.

Such a system gains its full potential when connected to the wider ecosystem of international open infrastructures. Integration with OpenAIRE enhances the visibility and discoverability of NANC's outputs at the European and global level. Collaboration with DataCite ensures high-quality DOI registration and facilitates metadata alignment. The use of ORCID and ROR provides authoritative identity and affiliation records that interoperate with platforms used by publishers, repositories, and funding agencies. Through engagement with SCAR and related disciplinary networks, NANC positions its data within domain-specific frameworks that consolidate Antarctic research internationally. Participation in international CRIS ecosystems further strengthens interoperability, enabling cross-institutional exchange of metadata and enhancing analytical capacities.

The convergence of these elements produces a range of benefits that extend far beyond administrative efficiency. Reducing manual work frees researchers from repetitive metadata entry and allows greater emphasis on scientific tasks. Full traceability of data provenance and relationships supports better reproducibility, quality assessment, and long-term stewardship. Enhanced metadata structures facilitate analytical functions such as expedition planning, instrument tracking, and programme evaluation. Ultimately, by adopting internationally recognised standards and identifiers, NANC enhances its scientific visibility and ensures that its research outputs fully participate in the global knowledge system.

6. International Models for Antarctic Data Governance: A Comparative Overview

International experience demonstrates that effective Antarctic data governance relies on coordinated national infrastructures, clearly articulated open data policies, and participation in global disciplinary networks (Clarke, 1993; Graiff et al., 2023; Southern Ocean Observing System Data Management Sub-Committee [SOOS DMSC], 2022). Several countries have established robust national data centres that function as the primary custodians and distributors of their Antarctic scientific outputs. The Australian Antarctic Data Centre (AADC), the US Antarctic Program Data Center (USAP-DC), and the UK Polar Data Centre (UK PDC) are among the most mature examples (United States National Science Foundation [NSF], n.d.; Polar Data Catalogue [PDC], n.d.). Each of these operates as an authoritative hub for aggregating, curating, and disseminating datasets generated by national programmes, providing stable long-term stewardship and ensuring that observational records remain accessible and interpretable over decades. Their mandates typically cover both digital data and documentation derived from expeditions, and in some cases extend to physical collections such as biological specimens, ice cores, rock samples, or instrument logs (SCAR Standing Committee on Antarctic Data Management [SCADM] & partners, 2025).

A defining feature of these data centres is the existence of formal Open Data policies that articulate the expectations placed on researchers concerning the handling, publication, and preservation of datasets. These policies are often linked to national research funders and require that each project submit a Data Management Plan (DMP) that outlines the lifecycle of data from collection to long-term archiving (SOOS DMSC, 2022). The DMP functions not as an administrative add-on but as an operational blueprint, guiding methodological decisions and ensuring alignment with national and international standards.

Data submission is typically governed by structured procedures that specify how researchers must prepare and deposit datasets. Many programmes rely on Data Transfer Agreements (DTAs) that clarify responsibilities for data quality, metadata completeness, intellectual property, and the timing of public release. These agreements formalise the flow of information from researchers to national repositories and ensure that deposited datasets meet minimum quality and documentation thresholds (NSF, n.d.; PDC, n.d.). The presence of such procedures has proven essential for reducing fragmentation and maintaining interoperability across research teams (Clarke, 1993; Graiff et al., 2023).

Persistent identifiers and standardised metadata frameworks are another cornerstone of international practice. DOI registration through DataCite is widely used to guarantee stable citation and long-term discoverability of datasets, while ORCID and ROR ensure that individuals and institutions are consistently identified. Metadata standards developed within SCAR, together with disciplinary vocabularies and ISO-based templates, provide semantic and structural consistency, enabling cross-institutional data integration (SCADM & partners, 2025). The application of these standards allows national data centres to contribute meaningfully to multinational synthesis efforts and enhances the utility of their holdings for global modelling initiatives (SOOS DMSC, 2022).

At the international level, coordination is facilitated by bodies such as the Scientific Committee on Antarctic Research (SCAR) and its the Standing Committee on Antarctic Data Management (SCADM). These organisations do not operate as data centres themselves but serve as governance and standard-setting platforms. They promote interoperability, harmonise metadata norms, and encourage the exchange of best practices among national programmes (SCADM & partners, 2025). SCADM in particular acts as a clearinghouse for policies and technical guidelines, helping ensure that national systems evolve in compatible ways.

An often-overlooked but vital component of Antarctic data governance is the stewardship of physical samples. Facilities such as the Polar Rock Repository in the United States, ice-core libraries in Australia and Europe, and biological collections maintained by various national programmes ensure that researchers have long-term access to irreplaceable material evidence. These repositories follow rigorous cataloguing and chain-of-custody practices, often integrated with digital PID systems, allowing physical objects to be linked directly to digital datasets and publications (NSF, n.d.; SCADM & partners, 2025).

Taken together, these international models illustrate the maturity of Antarctic data governance and underscore the need for national systems to operate within a coherent global framework. They also demonstrate that high-quality stewardship requires both organisational commitment and technical capacity, as well as formalised structures for documentation, preservation, and dissemination (Clarke, 1993; Graiff et al., 2023; SOOS DMSC, 2022).

7. Practical Recommendations for NANC Based on International Experience

Drawing on the practices observed in leading national Antarctic programmes, several strategic directions emerge for strengthening the National Antarctic Scientific Center's approach to data governance. The first and most foundational step is the adoption of an official Data Policy that defines principles, expectations, and obligations concerning the management and dissemination of research outputs. This policy should be complemented by a requirement that all funded or affiliated projects prepare a Data Management Plan at their outset. Such a requirement would embed good data stewardship into the research process and ensure that project teams consider preservation, documentation, and openness from the earliest stages of fieldwork or analysis.

Building on this policy foundation, NANC would benefit from the development or adoption of a dedicated subject-specific repository capable of providing long-term storage, metadata curation, and controlled access to Antarctic datasets. Whether implemented directly by NANC or through integration with an existing international repository, such a platform would centralise the agency's scientific outputs and facilitate compliance with global interoperability requirements. A formal deposition procedure should accompany this repository, specifying mandatory metadata fields, documentation standards, and submission milestones. Incorporating Data Transfer Agreements into this workflow would clarify responsibilities and ensure datasets are archived in a complete, reusable form.

The implementation of persistent identifiers represents another essential element of a modern data ecosystem. Assigning DOIs to datasets and expedition reports, maintaining ORCID records for all contributors, and adopting ROR for institutional affiliations would establish a coherent network of identifiers that makes NANC's research outputs discoverable and citable within global systems. Together, these identifiers enable richer metadata, reduce ambiguity, and support automated linking across platforms.

Equally important is the development of a clear access and embargo policy that defines when data becomes publicly available, under what conditions certain datasets may be restricted temporarily, and how researchers may request access to sensitive or time-limited materials. Transparent access rules not only facilitate reuse but also strengthen trust among international partners.

Finally, active participation in SCAR metadata initiatives would ensure that NANC's data infrastructure evolves in harmony with international standards. Engagement with these organisations would provide access to shared vocabularies, technical guidelines, and community-driven recommendations, all essential for maintaining interoperability. Alignment with these initiatives would also enhance NANC's visibility and integration within the global Antarctic research ecosystem.

The systematic adoption of open standards in the management of Antarctic data represents a critical strategic step for enhancing the National Antarctic Scientific Center's position within the global polar research ecosystem. In a landscape where research infrastructures are increasingly integrated through common metadata frameworks, controlled vocabularies, persistent identifiers, and interoperable formats, institutions that maintain high-quality, well-structured, and openly accessible datasets gain a significant competitive and collaborative advantage. For NANC, this translates into the ability to fully participate in international data-sharing programs, join multinational research initiatives, and engage in collaborative scientific projects that span multiple countries and research infrastructures.

Open and standardised data practices facilitate seamless integration of Ukrainian Antarctic datasets into global CRIS systems and broader European research infrastructures. Many of these systems operate exclusively with structured metadata, adhere to FAIR principles, and require formal Data Management Plans (DMPs), persistent identifiers such as DOIs and ORCIDs for researchers, and ROR for institutional affiliations. By aligning its infrastructure with these international norms, NANC establishes the foundational conditions for a coherent research ecosystem in which data, projects, individuals, and institutions are interconnected in a machine-readable, semantically consistent manner. This level of integration ensures that Ukrainian datasets can be discovered, cited, and reused effectively by the international scientific community.

A central benefit of adopting open standards lies in the long-term preservation of national Antarctic data. Observational records spanning decades cannot be effectively managed without robust governance systems, reliable repositories, rigorous documentation, and mechanisms that enable future researchers to reproduce the context in which the data were collected. Persistent identifiers, controlled vocabularies, and interoperable metadata formats guarantee that datasets remain interpretable and usable, even in the face of technological change, software updates, or generational turnover among research personnel.

Moreover, the adoption of standards catalyses broader international collaboration. When datasets are openly accessible, interoperable, and reliably linked to authors and institutions, they become instruments of collective research rather than isolated outputs. This openness fosters international partnerships, increases the visibility of Ukrainian scientists, and encourages joint publications. By aligning its data management practices with SCAR and other international initiatives, NANC ensures that Ukrainian Antarctic research is not only locally relevant but also fully integrated into global scientific efforts. The result is that NANC's outputs contribute to a shared, planetary-scale knowledge base, enhancing both the scientific and strategic value of Ukrainian Antarctic research.

8. Conclusions

Antarctic science is inseparable from principles of openness, interoperability, and long-term data preservation. The unique temporal and spatial scale of observations in the polar regions require a robust data management framework that ensures the continued utility of information collected over decades. These long-term datasets cannot retain their scientific value without structured documentation, persistent identifiers, and standardized metadata that make them accessible and intelligible to future generations of researchers. Consequently, the adoption of open standards and FAIR-aligned practices is not optional but a fundamental prerequisite for maintaining the integrity, continuity, and impact of Antarctic research.

Implementing an open science framework based on standardized data practices and persistent identifiers will significantly strengthen NANC's standing within the international research community. Standardized, interoperable datasets, transparent workflows, and integration into global research information systems will establish the Center as a modern, forward-looking research infrastructure that adheres to the highest international standards. Such an approach will expand opportunities for international collaboration, increase the visibility of Ukrainian Antarctic research, and enhance the Center's role as a reliable and strategically significant contributor to global polar science. Ultimately, by embedding open science principles into its operations, NANC ensures that its contributions remain discoverable, reusable, and impactful for decades, positioning Ukraine as a visible and influential actor in the global polar research domain.

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