



Improving Access and Interoperability of Cryospheric Data Across Research and Operations

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Abstract. Changes in the cryosphere have far-reaching physical and socio-economic impacts, regionally and globally. Observational data on sea ice, snow, glaciers, ice sheets, and permafrost are therefore critical. However, observations from polar and high-mountain regions are often fragmented, heterogeneous, and underutilised due to limited coordination, resulting in high consumer costs, caused by inconsistent data management practices. This paper addresses how access to cryospheric observational data can be improved by bridging the gap between research communities and operational agencies. It advocates for fully implementing FAIR (Findable, Accessible, Interoperable, Reusable) principles, emphasising interoperability and reuse. The World Meteorological Organization (WMO) is well-positioned to act as a convenor by co-developing data standards, aligning observation protocols, and leveraging global frameworks such as WIS 2.0 and the 5th International Polar Year, working with stakeholders to ensure the long-term preservation and broader reuse of essential cryosphere data. The paper concludes with recommendations focusing on standardisation, data governance, interoperability, and cross-community collaboration.

1 Introduction

The Earth's climate is changing rapidly, and with it, the cryosphere. In response to rising temperatures, sea ice cover, snow, glaciers, ice sheets, and permafrost are declining across much of the world (IPCC, 2019). These changes have far-reaching



impacts on communities and economies in cryosphere regions and beyond. Changes in snow cover, freshwater, sea ice,
35 glaciers, ice sheets, and permafrost impact water resources and ecosystems, including near-coastal and marine ecosystems. First-year sea ice is becoming prevalent in areas of the Arctic previously known for second or multi-year ice. Rising temperatures are melting the ice sheets of Antarctica and Greenland, driving sea-level rise and affecting ocean circulation and fisheries. Permafrost soils are vulnerable to the re-mobilisation of large greenhouse gas stocks (Hugelius et al., 2024). Permafrost degradation also threatens infrastructure (Hjort et al., 2022) and affects the livelihoods, cultural practices, food and
40 water security, and health of Arctic communities (Gartler et al., 2025). Mountain environments are warming faster than nearby lowlands (Pepin et al., 2025), with glaciers, snow cover, and water resources becoming particularly vulnerable (Adler et al., 2022). These changes potentially threaten the achievement of several of the UN's Sustainable Development Goals (Li et al., 2025; Wang, 2024; Wang et al., 2019; Anderson et al., 2017).

Understanding and addressing the impacts of these changes require access to observations from across the cryosphere,
45 including data collected by the full range of institutions and projects that monitor these regions. Snow cover occurs well into the mid-latitudes, while sea ice, land ice, and permafrost are found in remote areas of the polar regions and high mountains, including those in tropical regions. These areas are sparsely populated, many are characterised by harsh environments, and observational efforts are expensive. Monitoring is typically carried out by research institutions and academic groups, often as part of internationally organised and funded research projects. However, these activities are frequently distributed across
50 multiple initiatives with limited coordination. Observations are collected by diverse research teams using heterogeneous approaches, which may result in variability in sampling and documentation. Consequently, data may remain underutilised beyond their original purpose.

The costs of documenting observations and converting raw data into useful datasets are high and require extensive human intervention and processing. Costs and limited coordination make the preservation and discoverability of these datasets
55 difficult. To address these challenges, a workflow for data collection and publication is shown in Fig. 1. It covers the path from data collection through documentation and curation to publication and preservation. These steps are necessary to enable broad access to and use of the data, and thereby to generate positive impact.

A focus on sustainable implementation of the FAIR guiding principles (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016), with an emphasis on interoperability ("I") and reuse ("R"), is needed to advance cryospheric research
60 and applications. The various levels of FAIR maturity for data are illustrated in Fig. 2. The FAIR data ambition is to achieve machine-readable data with minimal or no human interaction and to support its reuse. Much of the gap between machine-readability and true interoperability (e.g., Wilkinson et al., 2016; FORCE 11, 2026) lies in the use of semantic annotations and the application of agreed-upon, controlled terminologies when describing the data. It also covers legal requirements, such as what a potential data consumer is permitted or not permitted to do with a specific dataset. The European INSPIRE Directive
65 (European Parliament & Council, 2007) defines the term 'interoperability' as "the possibility for spatial data sets to be combined, and for services to interact, without repetitive manual intervention, in such a way that the result is coherent and the added value of the data sets and services is enhanced" (see also Tóth et al., 2012). A similar definition is provided in the Data

Space Design Principles (Peeters et al., 2024). Improving data interoperability and reuse requires infrastructure, availability and utilisation of standards, long-term commitments, capacity building, and a collaborative framework. In addition, an understanding of the use cases and needs of data consumers is required (Wu et al., 2026).

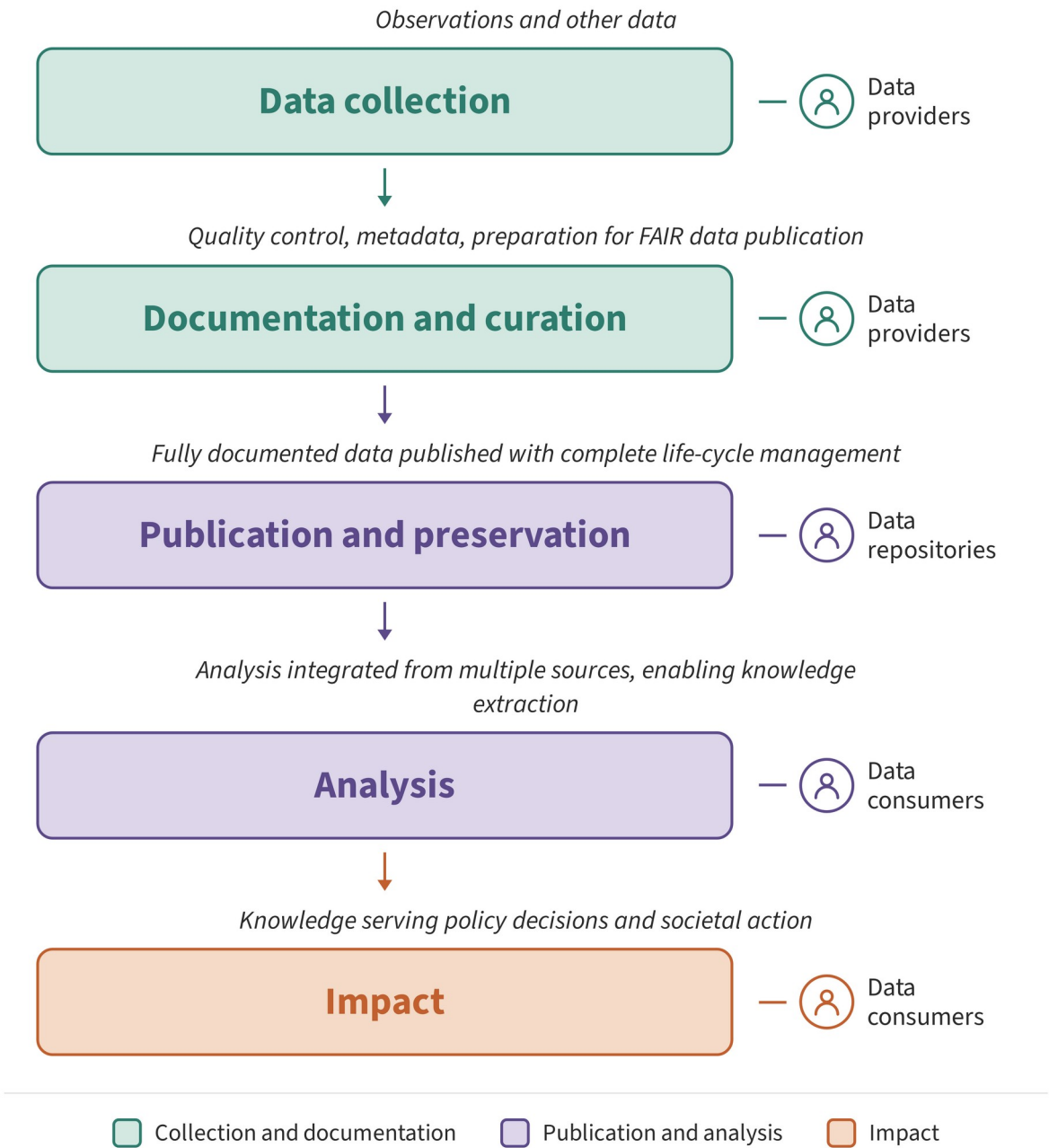


Figure 1: A generic workflow for the data discussed in this document.

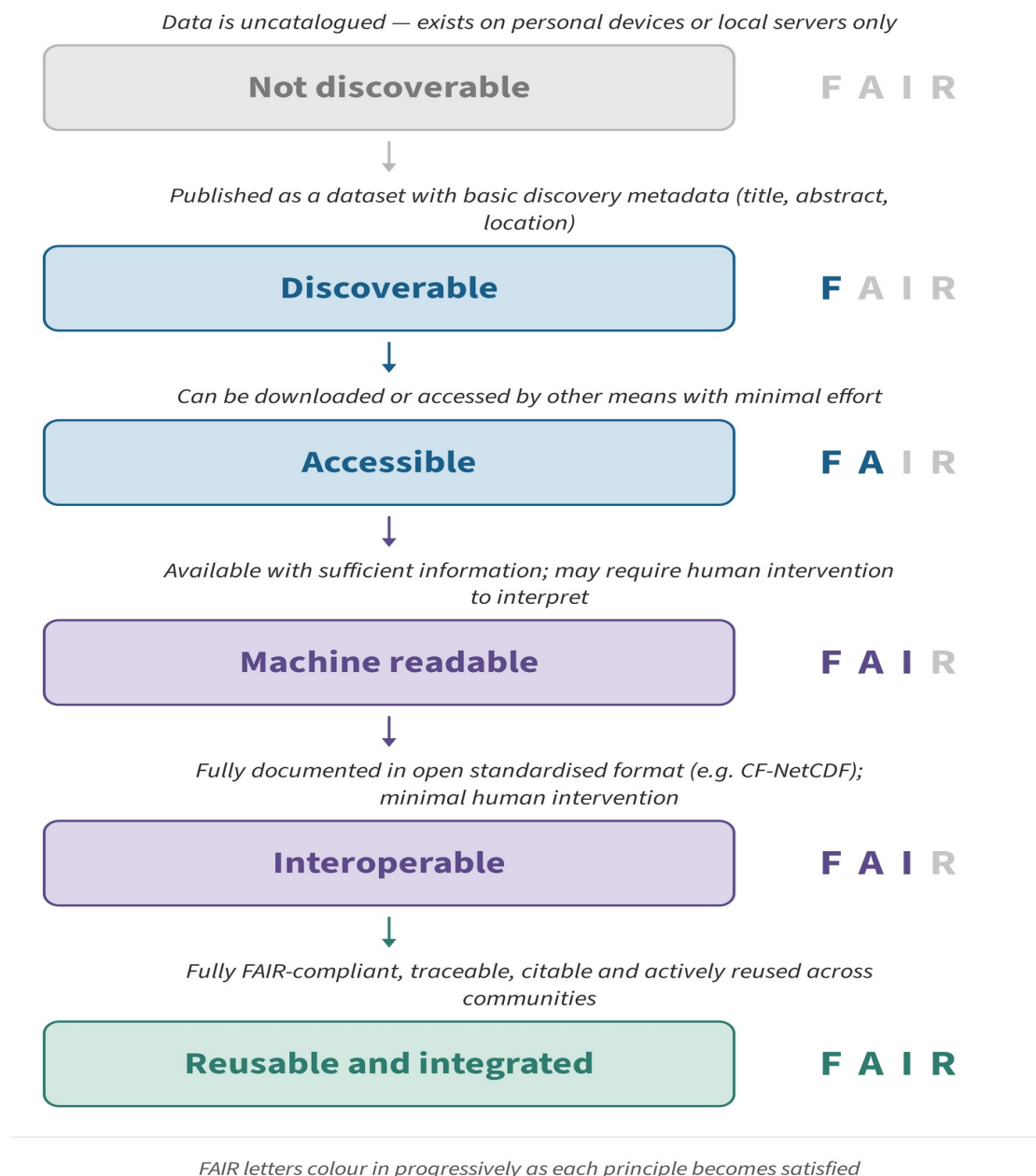


Figure 2: The various levels of FAIR maturity for datasets.

75 This paper examines how interactions between operational and research communities can be improved to increase access to, and use of, cryosphere observations from remote areas. It advocates for implementing the FAIR guiding principles with particular emphasis on interoperability and reuse, and considers the role the World Meteorological Organization (WMO) can play as a convener. Recommendations are aligned with the Global Climate Observing System (GCOS) Implementation Plan



2022–2027 (WMO, 2022a), which calls for the collection and unrestricted distribution of accurate, sustained cryospheric observations and advocates that "the longest possible time series need to be preserved in perpetuity."

80 At the national level, the National Meteorological and Hydrological Services (NMHSs) are the nationally mandated operational communities linked to WMO, which facilitates their international collaboration. This paper provides recommendations on how these institutions can more effectively engage with research communities, represented through universities, networks and independent research institutions, and which are the main operators of in-situ monitoring in polar and high-mountain environments. Bridging the data management functions of these two communities is essential for improved access to
85 harmonised observations, in support of research and operational applications. During the 4th International Polar Year (IPY) in 2007-2008, data management was a focal point; the 5th IPY (IPY5, 2032-2033) is similarly grounded in open science and data sharing "to produce actionable insights for mitigating and adapting to environmental changes" (<https://ipy5.info/>). IPY5 offers an opportunity to implement concrete actions, including on data management. Likewise, the UN resolution to declare 2025-2034 as the UN Decade of Action for Cryospheric Sciences, offers a similar opportunity for engagement.

90 The challenge of bridging research and operational data communities through FAIR implementation has been addressed in several other environmental domains. The ocean community has produced substantial work on this question through the Ocean FAIR Data Services framework (Tanhua et al., 2019) and the analysis of interoperability across the Global Ocean Observing System (GOOS, Smith et al., 2019), both anchored in Intergovernmental Oceanographic Commission (IOC)/The International Oceanographic Data and Information Exchange (IODE) and GOOS coordination. The broader environmental research
95 infrastructure community has explored similar questions through ENVRI-FAIR and related initiatives (Zhao & Hellström, 2020), and the biodiversity community has made significant progress through GBIF, Darwin Core, and the WorldFAIR programme. The IPCC's own implementation of the FAIR principles across the seventh assessment cycle (Lenhardt et al., 2024) represents a further parallel effort.

The cryosphere community faces several distinctive challenges that warrant domain-specific treatment: the geographical
100 remoteness and operational cost of observations, the fragmented state of mountain cryospheric monitoring, and others. The potential role of WMO as convenor through practical implementation of the WMO Unified Data Policy (WMO, 2021; WMO, 2022b), broadening the scope of WIS 2.0, and the bridging of communities through Global Cryosphere Watch (GCW) are opportunities to address these challenges. This paper builds on the lessons from those neighbouring domains while setting out a path specific to cryospheric data and the IPY5 implementation window. The ideas presented are the result of discussions that
105 emerged during and after a workshop convened by GCW in December 2024.

2 Data exchange and stakeholders

Throughout this paper, 'dataset' follows the definition in the EU INSPIRE Directive (European Parliament & Council, 2007): an identifiable collection of data with a spatial and temporal reference. A dataset may be based on direct observations or on derived quantities; the latter are often denoted as products. The focus here is on observational datasets (e.g., a time series of



110 snow depth) from research communities monitoring cryospheric environments. For a dataset to be accessible beyond its provider, it must meet requirements for granularity, structure, description, and repository functionality, as defined by widely accepted standards. Sharing these practices between the scientific and operational communities enables the effective use of limited resources through a coordinated effort among three stakeholder groups: data providers, data repositories, and data consumers (Callahan, 2020; Fig. 3).

115 Standardised documentation requires defining metadata at the discovery and use levels (Fig. 4), together with machine-readable data representations. Semantic resources — controlled vocabularies, thesauri, taxonomies, and ontologies — identify variables, units of measurement, missing-value encoding, and the who, what, where, and when of the published data, avoiding ambiguous free-text explanations.

Any institution or community can play one or more stakeholder roles, whether research or operational, and providers are often consumers as well. There could be significant mutual benefits if WMO plays a more active role in supporting access to data from research communities, particularly in data-sparse polar and high-mountain regions. The primary benefits of data sharing are increased visibility and recognition of datasets across communities, formal publication of data, robust services provided by data management systems, and the availability of data for applications and across applications, beyond their primary purpose – now or in the future. For research communities, contributing cryospheric data and observations as a global public good brings clear benefits. This would however require some form of formal recognition of data contributions supporting demonstrable operational impact. Potentially this could release sustained funding if recognised as an advantage by funding bodies. It could enable access to complementary operational datasets for validation and synthesis, and access to standardisation activities on data documentation and exchange and observation protocols organised by WMO. It would bridge across research and other communities that wouldn't otherwise engage or exchange those active in high mountains in different regions across continents. For WMO, it would be beneficial to collaborate with research communities, both to extend the observational foundation for WMO activities, but also to gain insight into observation protocols and approaches and practicalities under harsh and remote conditions as well as the active research on data management practises and related research oriented data interoperability frameworks. Long-term funding and commitments are critical to preserve climate datasets with records spanning decades.

135 **Data providers** collect or produce data and document them for publication, capturing instrument characteristics, observation methods, calibration, processing, and software. They include research and academic communities deploying in-situ instruments, researchers producing high-level satellite products, satellite agencies producing operational products, NMHSs, and industry (e.g., wind farms, offshore platforms, fisheries).

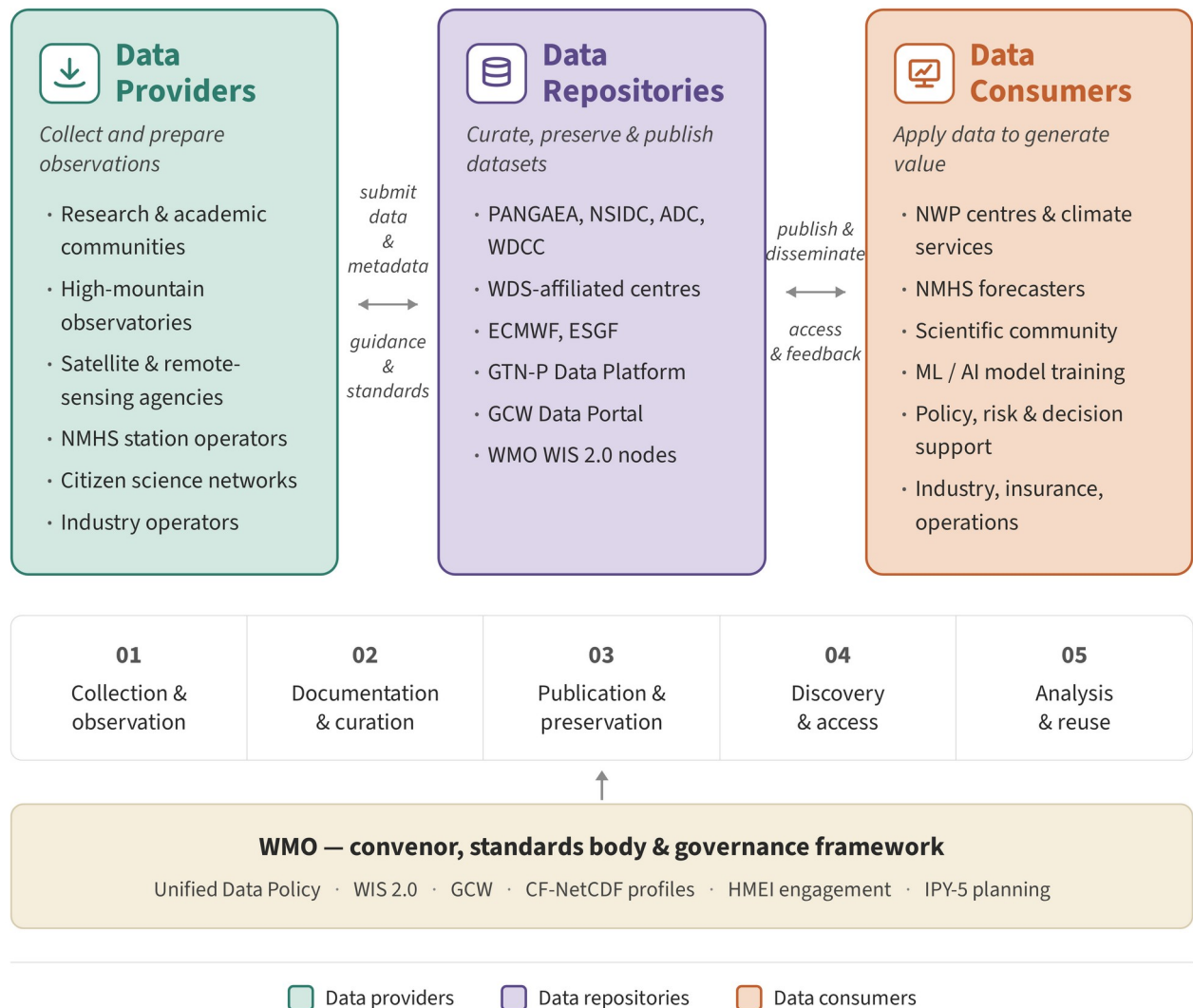


Figure 3: The three stakeholder communities in the cryosphere data ecosystem — data providers, data repositories, and data consumers — exchange data, metadata, and guidance across the dataset lifecycle. WMO plays a convening and standards-setting role that operates across all stakeholder groups.

140 **Data repositories** house and manage the life cycles of datasets from one or more providers, guarantee long-term preservation, and handle their publication — the process of announcing a dataset's existence and making it available to consumers. A data centre is a repository that typically offers a wider range of services and enforces standardised documentation at the use level. Repositories managing research data increasingly aim for adherence to FAIR (Wilkinson et al., 2016), CARE (Collective Benefit, Authority to Control, Responsibility, Ethics; Carroll et al., 2020), and TRUST (Transparency, Responsibility, User

145 focus, Sustainability, Technology; Lin et al., 2020) principles. FAIR addresses how to document and share data; CARE addresses ethical dimensions concerning indigenous communities and territories; TRUST addresses repository trustworthiness.



FAIR is widely recognised in research communities, though its implementation to date has focused on findability and accessibility. Interoperability is harder to achieve in practice but is essential for cross-stakeholder sharing and reuse.

Metadata type	What it does	Standards & conventions
Discovery <i>Finding data</i>	Makes datasets findable . The digital equivalent of a library index card: who did what, where and when, how to access the data, and any constraints. Links to further information, including site metadata.	ISO 19115, GCMD DIF, ACDD, MMD, EML
Use <i>Interpreting content</i>	Makes dataset content interpretable . Describes what is in the data and how it is encoded — variables, units, missing values, projections — so that users can work with the data without contacting the provider.	CF Conventions, BUFR, GRIB, DwCA
Site <i>Contextualising observations</i>	Makes observational context interpretable . Describes where and how observations were made — location, instrumentation, procedures. Overlaps with discovery metadata but extends it, and supports observation-network design.	WIGOS, OGC O&M

Acronyms. ISO 19115 — International Organization for Standardization geographic information standard; GCMD DIF — Global Change Master Directory, Directory Interchange Format; ACDD — Attribute Convention for Data Discovery; MMD — MET Metadata Model; EML — Ecological Metadata Language; CF — Climate and Forecast (Conventions); BUFR — Binary Universal Form for the Representation of meteorological data; GRIB — General Regularly-distributed Information in Binary form; DwCA — Darwin Core Archive; WIGOS — WMO Integrated Global Observing System; OGC O&M — Open Geospatial Consortium Observations and Measurements.

Figure 4: Types of metadata required to support findable and interpretable cryospheric datasets. Discovery metadata make datasets locatable; use metadata describe dataset content and encoding; site metadata describe observational context and support network design. Representative standards and conventions are shown for each type.

150 These concepts are less widely adopted in operational NMHS communities but are actively promoted by bodies affiliated with the International Science Council (ISC), including the World Data System (WDS), the Committee on Data (CODATA), and the Group on Earth Observations (GEO). FAIR and TRUST are also cited in the 2022 GCOS Implementation Plan (WMO, 2022a). Researchers typically publish through WDS- or CODATA-affiliated repositories, while NMHSs publish through WMO systems; their data are often stored in institutional repositories, at ECMWF, or, in some cases, not formally preserved.



155 **Data consumers** access and use data for operations, research (e.g., validation, synthesis), or decision support (e.g., risk management, policy). Consumer communities include NMHSs, public and private operational services such as the North American Ice Service (NAIS), industry and insurance sectors, and the scientific community. Data can be accessed in real or near-real time from providers and repositories, or in delayed mode from repositories — the latter common for climate datasets released only after quality control. Consumers must comply with access terms (licences, use agreements) that may include attribution requirements and usage restrictions reflecting the provider's and repository's business models. Since operating conditions vary widely, different challenges arise in complying with these terms.

2.1 WMO as a stakeholder

WMO was established by the World Meteorological Convention in 1947 to provide "the framework for international cooperation to advance meteorological, climatological, hydrological, and related environmental services, to improve the well-being of all" (WMO, 2023). Its work has long focused on the rapid exchange, standardisation, and uniform publication of meteorological observations.

In 2021, WMO approved a Unified Data Policy (WMO, 2021; WMO, 2022b) that broadens the scope of data exchange to cover meteorological, climatological, hydrological, cryospheric, and environmental data. The Policy includes clear provisions for delayed-mode climate data, partner-community data, and cryosphere data for hydrometeorological and climatological services. A dedicated cryosphere focus is provided through GCW, a legacy of IPY 2007–2008 that serves as a bridge between research and operational communities — supporting stations, data management, and knowledge transfer worldwide (WMO, 2024).

Historically, WMO has focused on real-time exchange of meteorological data for operational forecasting, including Numerical Weather Prediction (NWP), via the Global Telecommunication System (GTS). GTS is now being replaced by a publish/subscribe approach (MQTT) within the WMO Information System (WIS 2.0), which is web-based with a cloud-native architecture for discovering, accessing, and subscribing to global meteorological information. Data are published through WIS 2.0 nodes using open standards (GRIB, BUFR, NetCDF, JSON), with open-source tools available for downloading and processing streams.

2.2 High Mountain Research Community

180 The polar research communities have strengthened their collaboration in recent years, particularly through the International Polar Years. In contrast, the cryosphere communities active in high mountains tend to be more fragmented and regional, and so is their approach to data management. Formal, coordinated engagement between mountain research communities and NMHSs is limited, and focused research activities often have constraint support and visibility (Shahgedanova et al., 2021). Dedicated mountain data management is largely confined to specific institutions, such as the National Tibetan Plateau Data Center (Pan et al., 2021), which, while focused on the Tibetan Plateau, also supports wider Earth system science. At the



regional scale, initiatives such as the International Centre for Integrated Mountain Development (ICIMOD) demonstrate the potential for more coordinated approaches.

The Mountain Research Initiative (MRI), a long-standing global research coordination network supported by the Swiss Academy of Sciences, co-leads the Global Network on Observations and Information in Mountain Environments (GEO Mountains). Between 2020 and 2024, through contributions from the Swiss Agency for Development and Cooperation (SDC) and the MRI, GEO Mountains convened regional workshops across Central Asia, East Africa, the Andes, Hindu-Kush Himalaya, and the South Caucasus, bringing together academics, practitioners, and operational professionals from NMHSs. A recurring challenge identified was the limited duration of research projects: publication of research-derived data often marks the end of the project, with little follow-through into operational integration. Opportunities identified include capacity-building on mechanisms and methods for data interoperability, integration and governance conferring with the conclusions and outcomes of the WMO High Mountains Summit, held 29-31 October 2019. Additionally, the workshops themselves served as a forum and opportunity for these diverse communities to meet.

The MRI community has produced a substantial body of work on elevation-dependent warming and mountain climate change (e.g. Pepin et al., 2015, 2022, 2025; Napoli et al., 2023; Chimborazo et al., 2022), underpinning further contributions including analyses of in-situ observation coverage (Thornton et al., 2022), a metadata inventory (GEO Mountains, 2025), and proposals for Essential Mountain Climate Variables (Thornton et al., 2021). Despite these substantive contributions, further work is needed to integrate research-oriented with operationally derived data, and machine-to-machine interfaces remain limited.

3 Challenges in bridging communities

In the domain of cryosphere sciences and applications, different communities have developed their own data management practices. Sharing data between research and operational communities offers important benefits for both sides. However, because their business models and priorities differ, understanding and bridging these gaps is essential to ensure that each community has timely access to data. Achieving this requires mutually acceptable data management standards and practices.

3.1 Data collection

The completeness of documenting observation protocols plays a significant role in data collection. Within the WMO community, observation protocols are shared globally, and their governance structure is clearly defined and has proven sustainable over time. In contrast, research communities exhibit significant variability in their observing protocols and have limited governance. There is substantial regional and domain-specific variability, and in some cases, protocols have remained undocumented. In recent years, this situation has improved as research infrastructures align observation protocols at sites that contribute to specific research projects, primarily through internationally funded initiatives, such as Arctic PASSION, SIOS, ESFRI Infrastructures and the MRI's GEO Mountains.



Research projects often test new observation approaches, technologies, and configurations. The results of these may bring significant benefits by improving observing capabilities for all communities if they are published and disseminated. While this remains a challenge, it can be mitigated by regularly organising and publishing inter-comparison results from observations made by different communities. In fact, WMO has a mandate to organise inter-comparisons in collaboration with meteorological equipment manufacturers. It would be beneficial for WMO to expand this role by facilitating inter-comparisons that bridge research activities and operational applications, advancing observing capabilities for the cryosphere.

3.2 Data documentation and curation

The documentation of data by the data providers is critical to long-term preservation and effective use by data consumers. Often, data providers publish data primarily to meet funding agency requirements rather than to simplify and maximise data utilisation. This can limit the usefulness of the data as the data consumer's perspective may differ significantly from that of the data provider. For example, a numerical modeller has different expectations than an observational researcher.

Data providers need guidance on best practices for data publication from data repositories, particularly regarding granularity. However, guidance alone is likely insufficient to ensure optimal data usability. For such guidance to be effective, technological and skill gaps must be addressed through proper training, as well as the development and the sustainable maintenance of tools and services. Achieving this requires appropriate funding for data providers and data repositories, coupled with the development of mutually agreed guidance supported by the interested communities.

3.3 Data publication and preservation

An important component of implementing the FAIR guiding principles is the requirement to use data licences as legal documents accompanying datasets. Licenses matter to individual researchers and research groups acting as data providers: they formally recognise contributions and provide visibility that supports future funding. However, as the number of data providers increases, data consumers face challenges managing the varied conditions imposed by different licenses. A standardised approach to data licensing and attribution would ensure appropriate recognition, promote consistency, and provide a more manageable set of conditions for data access.

Under the WMO Unified Data Policy (WMO, 2022b), “Core” data is made available without charge or use conditions. For “Recommended” data, providers and publishers are free to set terms and conditions for its use. Within the WMO Core Metadata Profile version 2 (WCMP2) (WMO, 2025b), the licence is mandatory for “Recommended” data but optional for “Core” data. Licenses such as the Creative Commons CC-BY 4.0 meet this requirement, allowing for attribution as a condition of use.

WMO data management practices have focused on exchanging observational weather reports and NWP output in real-time or near-real-time to support weather forecasting and the provision of weather and early warning services. Weather reports were typically bundled into bulletins, each covering multiple stations at a given reporting time, and published on the GTS and WIS. Under WIS 2.0, there has been a shift to publishing individual reports in real time, avoiding delays in data publication caused by late reports from a station. For non-real-time data, data management responsibilities have remained with the provider, that



provides access via its own portal or API. Improved documentation and guidance on the handling of climate datasets through the WIS would benefit the climate research and services community.

250 For climate services and climate research, the focus is on long-term climate datasets spanning days, seasons, and decades. Climate data are published in delayed mode as datasets (quality-controlled collections of data points), while real-time exchange focuses on the fast transmission of individual data points (observations). Currently, climate datasets are mostly published through research-oriented data management systems, such as the Earth System Grid Federation (ESGF) and PANGAEA. These systems generally follow principles outlined by bodies affiliated with the International Science Council (ISC), such as
255 the World Data System (WDS, <https://worlddatasystem.org/>) and the ISC Committee on Data (CODATA, <https://codata.org/>). Such data repositories normally announce their data catalogues using standardised machine interfaces for exchange of discovery metadata and not the approach of WIS 2.0. Improving the ability of WIS 2.0 to interact with such repositories would be mutually beneficial.

Research stations may transmit their data in real time via WIS 2.0 if formally connected to a WIS 2.0 node and if following a
260 WMO established protocol. These nodes are operated, in most cases, by the NMHSs and apply WMO-specified data representation models, such as BUFR, or more recently, NetCDF. However, observing stations for most cryosphere research projects are in remote areas, where high communication costs and other technical limitations make real-time data transmission difficult. Consistent and easy-to-apply data representation, standardised technological solutions for real-time transmission, and clear protocols for transferring datasets in non-real time to selected repositories would enable data providers to publish their
265 data more cost-effectively.

Data management efforts are generally under-represented in funding proposals and often underfunded. Many funding agencies require that data collected through projects they support be made available and published in nationally mandated data repositories. However, many developing countries, particularly in high mountain regions, lack robust national data repositories, and data providers therefore transfer their data to repositories they are aware of on a best-effort basis, or retain them at local
270 level.

Currently, in the research domain, data providers use several data repositories, most of which are hosted by institutions in developed countries (e.g., NSIDC, PANGAEA, MET/ADC, ECMWF). Some have existed for decades, are affiliated with WDS, and adhere to FAIR and/or TRUST principles. However, many data providers rely on data repositories hosted by universities or institutions with limited technological capacity and uncertain long-term commitments. These pose significant
275 risks for both data providers and data consumers regarding the guaranteed functionality of data repositories and long-term sustainability. The risk is particularly high for long-term climate-quality datasets. This situation also hampers the implementation of new technologies and effective interaction within a network-oriented data management system, whether at the national or international level.

Because most research and operational organisations rely on public funding, two challenges must be addressed. The first is
280 ensuring long-term incentives and commitments for the transfer, documentation, curation, and preservation of datasets from data providers to data repositories. The second is establishing a framework for recognising trusted data repositories that apply



interoperable standards and best practices to ensure the content in these repositories is discoverable and reusable by both humans and machines (e.g., Tronstad et al., 2021). The GCOS 2022 Implementation Plan calls for the establishment of Climate Data Centres for in-situ Essential Climate Variables (ECVs), with improved discovery and access to both data and metadata.

285 While WMO has operated its network-oriented data exchange for decades, this approach is relatively new to most research-oriented data repositories. During the International Polar Year (IPY, 2007/2008), the IPY Data and Information Service (IPYDIS, Parsons et al., 2011) established networks among research-oriented data repositories operating in the polar regions. This approach has continued under the umbrellas of the joint Sustaining Arctic Observing Networks/International Arctic Science Committee (SAON/IASC) Arctic Data Committee (ADC) and the Scientific Committee on Antarctic Research's

290 (SCAR) Data Management Committee (SCADM). The joint work of these communities resulted in principles for aligning Polar Data Policies (Tronstad et al., 2021). To better understand how to navigate research-oriented data repositories, a mapping effort of the polar data ecosystem (Pulsifer et al., 2020) was undertaken, showing the complexity of these interactions. During IPY 2007-2008, many researchers were introduced to modern data management practices for the first time. The learning curve was steep for some, particularly for researchers encountering the concept of metadata for the first time, but

295 there were also many success stories in which data publication led to new research collaborations. Often, these successful examples were the result of dedicated efforts between data providers and data repositories. Data repositories provided training and developed tools and services that simplified data publication. In the process, valuable information was exchanged among the actors involved. These achievements were made possible by strong community commitment and by available funding for tool development.

300 WMO and research-oriented data management practices have developed along somewhat different lines. Under the GTS and WIS, discovery metadata could and did point to WDS- and CODATA-inspired repositories, providing a degree of cross-community linkage. A concrete example of this desired linkage is the ISO 19115 formatted WIS record for the GCOS Earth Heat Inventory (EHI) 1960 – 2020 Permafrost Heat Content dataset (Nitzbon et al., 2022), produced by the Alfred Wegener Institute and published through the DWD GISC portal and WIS catalogue¹. In this case, the metadata explicitly link to the

305 World Data Centre for Climate (WDCC), a WDS-affiliated repository, for data access, illustrating effective cross-repository connectivity.

At the broader system level, however, a divergence existed in the granularity of discovery metadata records under WIS, with many fine-grained records each covering only a handful of stations. This has been addressed in WIS 2.0 with the shift to single records covering a country's entire synoptic network. Depending on the use case of consumers, this could be counterproductive.

310 Wu et al. (2026) recommend describing data at different levels of granularity (e.g., collection, item, variable) to meet consumer requirements. Since data providers tend to publish through the repositories with which they are most familiar, a gap in practice remains between WDS- and CODATA-inspired repositories and WMO-inspired repositories.



4 Opportunities

The strength of the WMO community lies in real-time data exchange, standardisation for data documentation and observing protocols, and structured collaboration with the equipment industry. The strength of the research community lies in their focus on observational datasets and their preservation and traceability. There is a clear opportunity to bring these two perspectives and approaches together, emphasising equity and collaboration in the process of bridging them.

The theme on managing data in the 2022 GCOS Implementation Plan (WMO, 2022a) recommends that “Every ECV needs to have a recognised global data repository, and where there is one, it should be complete, adequately supported and funded”, with appropriate governance and requirements, including discovery and access to data and metadata. These recommendations provide an appropriate framework for accelerating the bridging of operational and research communities by building on current initiatives and practices, including those of the WMO Information System.

Implementing interoperability interfaces between existing repositories would enable the creation of virtual data repositories spanning institutions within the same country or across different countries. Such collaboration would address the challenge of “data at risk” through mutual backup procedures and provides access to data beyond that collected locally.

Data collection in remote regions rarely has a commercial aspect. Most of it is supported by public funds. Funding agencies often require that data generated be made as openly accessible as possible. Standardisation of measurements, observing protocols, and data documentation (metadata) is essential to fully realise the potential for reusing collected data. Increasing the visibility of data collection efforts and maximising the utilisation of these observations are thus key performance indicators (KPIs) for the activities that undertake these efforts.

The main purpose of observations is to be used for various applications. Examples include numerical simulations, statistical models or analyses, and, more recently, machine learning. For this to be a smooth process, data have to be harmonised across providers. Within WMO, such harmonisation exists, although it is not necessarily aligned with modern standards and needs. In the research community, such harmonisation is, with a few exceptions (e.g. ESGF and GBIF), non-existent. It would be beneficial to reduce the degrees of freedom across communities for as many observation types as possible and make the analysis smoother.

Bridging research and operational communities should include co-developing observation protocols, data standardisation, and best practices, to enhance the comparability of observations over time and across regions and to expand the available datasets. This is an effective way to exchange data management approaches and practices, building on each community’s strengths. WMO is well positioned to serve as a convenor and to take a balanced approach that draws on the research community’s experience. This aspect has been pursued in the implementation of the GCW Data Management, in particular through the GCW Data Portal and the GCW Data Publication Service (Bavay et al., 2020).

The 5th International Polar Year (IPY5), planned for 2032-2033, presents multiple opportunities to advance bridging between communities by building on the experience of the IPY 2007-2008. In the lead-up to IPY5, an integrative approach across research and operational communities should be pursued, which could also contribute to the GCOS call on data centres. These



efforts should also reflect and help address similar needs in high mountain research communities, even if they are not directly involved in IPY5. It was evident from the previous IPY that coordinated efforts and dedicated funding are required to maximise the reuse and thus the impact of its data. The FAIR guiding principles provide a strong foundation for such collaboration, though they are broad in scope. More concrete guidance on how to implement them in a common, standardised manner is required.

There are already good examples of such interactions that have improved and simplified access to research data for a wider community. Illustrative examples are PROMICE and GC-Net stations (operated by the Geological Survey of Denmark and Greenland, GEUS) and the Argo float programme that were initiated by the research community and are now widely used in operations. A further example is WMO's adoption of the NetCDF Climate and Forecast (CF) Metadata Conventions and the NetCDF data format (CF-NetCDF), long used in research as the backbone of ESGF via the Climate Model Output Rewriter (CMOR), which harmonises climate model output. The CF Conventions are flexible by design, however, with significant degrees of freedom for representing the same data differently. For operational use and improved interoperability, profiles are needed that constrain these choices to best practices. Within WMO, this is the task of the Expert Team on Data Standards, with profiles documented in the Manual on Codes (WMO, 2025a) — a strong example of WMO governance strengthening interoperability within and across communities. Bridging also flows in the other direction: the Year of Polar Prediction (YOPP) dataset, a deliverable of WMO's Polar Prediction Project, was hosted and made openly available by ECMWF with a CC-BY 4.0 licence (Bauer et al., 2020) — an example of an operational centre acting as a repository for research-phase data.

The co-development and publication of CF profiles for all cryosphere-related data by WMO would further support bridging the gap between operational and research cryosphere communities. A first step has already been taken, focusing on the data contributing to the permafrost Essential Climate Variable (ECV) as defined by GCOS. A dedicated subgroup under the WMO Expert Team on Data Standards, in collaboration with GCW, was established to enhance data interoperability and reusability by developing a permafrost-specific data profile based on the CF-NetCDF standard. Once defined, datasets conforming to this profile will be made available via the Global Terrestrial Network for Permafrost (GTN-P) Data Platform (<https://data.gtn-p.org/>). The platform serves as the central repository for permafrost ECV data and is recognised as a GCOS Affiliated Network. Data providers and the broader permafrost research community are engaged throughout to ensure the profile's practicality and relevance. The group's collaborative approach, bringing together diverse data stakeholders, exemplifies how data standardisation through WMO frameworks can effectively strengthen interoperability and long-term usability. Such community-driven initiatives play a key role in enabling true data interoperability and can provide a model for other Arctic science-driven data domains (Lübker et al., 2026).

In recent years, Artificial Intelligence (AI) and Machine Learning (ML) have been adopted in new areas, including weather forecasting and predictions. Their application presents opportunities to accelerate bridging between all communities regarding cryosphere data availability and use. AI technologies have been used in data management for years; ML, a subset of AI, is increasingly an important data consumer. A prerequisite for efficient ML is access to harmonised datasets for training, evaluation and testing. For the cryosphere, where data sources remain limited, ML needs access to all available data from both



380 research and operational communities, supported by an efficient data management system. Thus it present strong arguments for accelerating the bridging across these communities.

5 Recommendations

The critical societal consequences of cryospheric change heighten the need to bridge operational and research communities. Given its link to the operational NMHSs, WMO is well-placed to facilitate collaboration at multiple levels, focused on mutually
 385 acceptable data-documentation standards and observing protocols grounded in the specific business models of each community.

Fig. 5 maps the recommendations made and the challenge domains they address, distinguishing primary responses from supporting contributions. Several recommendations — particularly the IPY5 integration framework and the FAIR co-development agenda — cut across all four domains, reflecting their role as enabling actions rather than single-domain fixes.

390 Since several data management systems already exist (e.g. WDS/GEO and WMO), it is recommended that concrete steps are taken to increase their active engagement to maximise the utilisation of data generated through each system. This would require adapting practices across these communities through co-development of improved guidance, best practises and tooling that make data discoverable across both WDS/CODATA-affiliated and WMO-affiliated repositories. It would be mutually beneficial to focus on the practical implementation of the FAIR guiding principles, with an emphasis on interoperability and
 395 reusability, and to provide guidance on granularity that helps bridge the perspectives of data providers and data consumers. Central to bridging are mutually acceptable definitions, in particular of dataset and granularity, together with guidance on applying them and resources to implement. Concerted WMO advocacy within the cryosphere research community is needed, together with access to training, capacity-building and sharing opportunities that add value beyond meeting technical requirements, to clarify, in practical terms, what using WMO systems for real-time and delayed-mode data access requires.

400 The standardisation of observing protocols involves developing and implementing standards that meet data providers' needs. Their implementation rests, also, with the manufacturers of measuring instruments and of data loggers. WMO can facilitate coordinated engagement with industry through the HydroMeteorological Equipment Industry Association (HMEI, www.hmei.org). Manufacturer implementation of recommended standardised data-representation models at the instrument and the logger levels would improve the efficiency and cost-effectiveness of preparing data for publication.

405 Equally important is the need to fully understand and adhere to the business models of the communities involved. These business models vary globally and are addressed only implicitly in the FAIR guiding principles. Direct guidance on how to handle them in practice would benefit all stakeholders.

Given the importance of licensing for data providers' recognition and funding, there needs to be a standardised, practical, and widely recognised licensing approach. The broader use of DOIs with proper credit in a cascading form for data contributors is
 410 a practical approach if it is widely implemented by the research and operational communities.



Recommendation	Data collection	Documentation & curation	Publication & preservation	Opportunities
Harmonise observing protocols via WMO inter-comparisons				
Co-develop FAIR guidance with emphasis on interoperability and reuse				
Standardise data licensing; extend DOI credit cascading				
WMO to lead CF-NetCDF profile development for cryosphere ECVs				
Recognise trusted repositories; address long-term funding gaps				
Use IPY5 as integration framework; include mountain communities				
Engage HMEI for logger-level data standardisation				

Primary response to challenge domain Supporting contribution No direct link

Figure 5: Traceability matrix mapping recommendations to the challenge domains identified in the paper (data collection; documentation and curation; publication and preservation) and to the opportunities discussed. Filled markers denote primary response.

410 The adoption and development of data standards based on CF-NetCDF by WMO should continue, with a focus on cryosphere data, as a step towards enhancing data interoperability and usability. The collaborative approach to standardisation would benefit both operational and research communities.

IPY5's focus on climate change impacts in the Arctic and Antarctic offers a timely framework for engagement across research and operational communities (including WMO) and indigenous knowledge holders. Its planning should incorporate actions

415 addressing the challenges and opportunities outlined in this paper. The actions should aim to achieve the goals of Interoperability and Data Reuse, as defined by FAIR. IPY engagements should include mountain cryosphere communities as



stakeholders, so that their capabilities and knowledge can develop alongside those of the polar communities through synergistic partnerships.

420 The data-management theme of the 2022 GCOS Implementation Plan focuses on establishing recognised data repositories with appropriate governance and requirements, and on bringing in additional stakeholders, including those within the UN Framework Convention on Climate Change (UNFCCC). These specific actions provide a global framework for co-developing solutions focused on the opportunities identified in this paper, with WMO acting as a potential convenor.

Through the continued development and implementation of WIS 2.0, WMO can foster co-development of the technical standards and practices needed to achieve these goals.

425 The cryosphere research communities in high mountain regions would be a net beneficiary of sustained international engagements on data integration, governance, and increased visibility, to overcome challenges from jurisdictions, regional fragmentation, and funding mechanisms.

430 The success of improving cryosphere data exchange between research and operational communities is critically conditioned by the international collaboration and coordination among these communities and the individuals within them. It is a joint effort across disciplines, requiring dedicated efforts of data providers, data repositories (data managers), data consumers and funding sources. Coordination must address both technical interfaces — including data documentation and exchange — and governance, including the appointment and approval of data centres and sustained funding.

6 Author contributions

435 ØG, RN, and JK conceptualised the paper, visualisations were prepared by EP, writing (original draft preparation) was done by ØG, RN, JK, SM and EP and writing (review and editing) was done by CA, BD, JF, KA, MCL, MB, MS, DIB, EP, RYY, RZ, RM, TL, WM, and XZ. All authors contributed to the intellectual discussion and development of the manuscript and approved the final version.

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