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Scientific Cooperation: Supporting Circumpolar Permafrost Monitoring and Data Sharing *

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Abstract. Scientific cooperation is a well-supported narrative and theme, but in reality, presents many challenges and counter-productive difficulties. Moreover, data sharing specifically represents one of the more critical cooperation requirements, as part of the "scientific method [which] allows for verification of results and extending research from prior results." One of the important pieces of the climate change puzzle is permafrost. Currently, most permafrost data remain fragmented and restricted to national authorities, including scientific institutes. Important datasets reside in various government or university labs, where they remain largely unknown or where access restrictions prevent effective use. A lack of shared research—especially data—significantly reduces effectiveness of understanding permafrost overall. Whereas it is not possible for a nation to effectively conduct the variety of modeling and research needed to comprehensively understand impacts to permafrost, a global community can. However, decision and policy makers, especially on the international stage, struggle to understand how best to anticipate and prepare for changes, and thus support for scientific recommendations during policy development. This article explores the global data systems on permafrost, which remain sporadic, rarely updated, and with almost nothing about the subsea permafrost publicly available. The authors suggest that the global permafrost monitoring system should be real time (within technical and reasonable possibility), often updated and with open access to the data. Following a brief background, this article will offer three supporting themes, 1) the current state of permafrost data, 2) rationale and methods to share data, and 3) implications for global and national interests.

Keywords: *permafrost, permafrost monitoring, permafrost data, data sharing, national security.*

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Введение

While the world continues to work toward an understanding and projections of climate change impacts, the Arctic is widely recognized to be a critical component as a bellwether region [1]. Global scientific cooperation, including data sharing, is recognized to be an integral element, but in reality, it presents many challenges and counter-productive difficulties [1, Akiho S., Raita M., pp. 129–162]. As John Porter noted in his work on the Long-Term Ecological Research Network (established in 1980), "In the abstract, the advantages of sharing data are manifest. No individual scientist, or even a small group of scientists, can collect all the data that are needed to address today's major ecological research questions, especially those dealing with global, regional, or long-term phenomena [2, Porter J., p. 14]." As Porter acknowledged, despite all of this intuitive value in data sharing, the scientists concerned struggled to share with one another throughout the 1980s.

Porter's cautious study of ecological data sharing mirrors other studies by historians of science and technology, especially those focusing on the Cold War era [3, Aronova E., pp. 307–327]. Much of this scholarship has revealed a mélange of challenges, barriers, and opportunities for data sharing by posing three questions: First, what makes data sharing possible? Second, what is the perceived and actual value of data sharing to local, national, and international stakeholders, and how does protocols around data quality assurance and control influence sharing economies? Third, how does prevailing geopolitics and security dynamics complicate those data-sharing practices and experiences [4, Turchetti S., Roberts P.]? Depending on the discipline and geographical region, the histories and geographies of data sharing have been shown to depend on the intersection of epistemologies, ideologies, personalities, practices, and technologies. Additionally, while we might focus on data sharing as a mechanism for making data available to those who were not involved in the generation of that material, the role of data repositories (for example, World Data Centers during and after the IGY) has also been an area of scholarly interest, with implications for what has been termed 'data diplomacy' [5, Boyd A. et al.]. Moreover, data reuse specifically represents one of the more critical cooperation requirements, as part of the "scientific method [which] allows for verification of results and extending research from prior results [6, Tanopir C., et al. p. 6; 7, Michener W.K., pp. 33–44]." Reuse is integral to the scientific practice of reproducible research and thus considered to be highly desirable.

One of the important pieces of the climate change puzzle is permafrost, and the state of permafrost data sharing illustrates well that scientific practices such as reproducibility and verification have not been as straightforward as these norms might imply [8, Jasny B.R., pp. 1–15]. In general, observational data on permafrost characteristics are limited. As Boris Biskaborn and colleagues concede, "The current global coverage of permafrost temperature monitoring is not yet

[1] The Intergovernmental Panel on Climate Change (IPCC). United Nations Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere 2019. URL: https://www.ipcc.ch/srocc/ (accessed 17 December 2020).

ideal, due to the limited sampling and lack of collaborative network in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes mountains." To be sure, collaboration exists, but perhaps not to nominal or ideal standards for collective permafrost purposes. Currently, most permafrost data remain fragmented and restricted to national authorities, including scientific institutes. The preponderance of permafrost data is not available openly—important datasets reside in various government or university labs, where they remain largely unknown or where access restrictions prevent effective use [9, Bush E., p. 86; 10, Joseph M.P., pp. 24–28]. Although highly authoritative, separate data efforts involving creation and management result in a very incomplete picture of the state of permafrost as well as what to possibly anticipate. While nations maintain excellent individual permafrost research programs, a lack of shared research—especially data—significantly reduces effectiveness of understanding permafrost overall. Improvements can be pursued. For example, cost benefits would easily be captured by the lack of need to duplicate borehole efforts for proximal data, especially in remote locations. Nations with scientific comparative advantages could help provide information or services to others toward contributions in support of shared data. Current efforts by the World Meteorological Organization (WMO), Global Cryosphere Watch and the Global Terrestrial Network for Permafrost (GTN-P) are demonstrating the need to continue progress to implement permafrost temperature interoperability. Lastly, a single touch point of shared data will invariably be cheaper than the current multiple systems.

The importance of shared scientific data continues to be demonstrated by other global actors, like the WMO. The WMO Global Telecommunications System (GTS) was established in the 1970s to enable support of World Weather Watch (WWW). This worldwide coordinated telecommunication system allows members to share data and products with each other in support of operational weather forecasting. In November 2020, the WMO hosted a data conference to review the flow of data and updated protocols on data production, monitoring and sharing. In Africa, it was estimated that only 25 percent of weather monitoring stations met WHO reporting requirements recently which indicates a significant digital and equipment divide.

Different nations resource and employ various approaches to studying permafrost, including the growing complexity of scientific modeling [2]. Some are more effective than others and some achieve different purposes than others. Whereas it is not possible for a nation to effectively conduct the variety of modeling and research needed to comprehensively understand impacts on permafrost, a global community of permafrost researchers could in principle. What other studies in fields such as geonomics have demonstrated is that scientific communities are not necessarily invested in sharing data—for reasons that range from concerns about intellectual property rights, data policies and protocols, military-industrial-strategic sensitivities, funder restrictions and cross-national scientific rivalries. However, decision and policy makers, especially on the international

[2] Stanford Encyclopedia of Philosophy Stanford University. Models in Science. 2020. Available online: https://seop.illc.uva.nl/entries/models-science/ (accessed 5 August 2020).

stage, struggle to understand how best to anticipate and prepare for changes to permafrost, and thus connect scientific recommendations to robust policy development [11, Kowarsch M., et al.].

To date, there is a lack of research exploring the drivers that have shaped limited circumpolar permafrost data and what is required to cultivate a more generous data-sharing economy. This article will explore the global data systems on permafrost, which remain sporadic, rarely updated, and with almost nothing about the subsea permafrost publicly available. The authors suggest that there is scope and potential for the development of a global permafrost monitoring system which should aspire to be real time (where this is feasible), often updated and with open access to the data. Other subject areas such as oceanography have had the benefit of an Intergovernmental Oceanographic Commission (established in 1960), involving nearly 150 countries who commit themselves to sharing data on sea-based measurements. Permafrost research data, by way of contrast, has not had that high-level investment by a UN body for reasons that are closely tied to geographical specificity and national sensitivities about cold environment research [12, Herzberg J., et al.].

Following a brief scientific background to permafrost, this article will advance and interrogate three supporting themes, 1) the current state of permafrost data and their availability, 2) rationales and methods to share data, and 3) implications for global and national interests with a particular focus on the United States, Canada, Russia, and emerging permafrost scientific powers such as China, and 4) the state of play regarding permafrost data recognition. This interdisciplinary investigation contributes to studies on the historic data-sharing activities as well as responds to the challenge of thinking about how methods, resources and tools such as data-sharing systems mediate between global scientific co-operation and national security priorities.

Background

Permafrost

Permafrost is typically defined as a ground layer with a temperature remaining at or below 0 °C for at least two consecutive years. It refers to a physical state rather than material form. Every year, the surface layer of frozen ground that freezes in the winter but thaws in the summer is referred to as the active layer. The active layer will freeze again in the autumn. Changing climatic conditions affect the state of permafrost in direct and indirect ways: among the factors that influence a frozen ground are rising air temperatures, changing snow regimes, and condition of vegetation [13, Romanovsky V.E., et al., pp. 106–116; 14, Rasmussen L.H., et al., pp. 199–213]. A typical classification, first developed in 1927 [15, Sumgin M.I., p. 372], recognizes continuous permafrost (underlying 90–100% of the landscape), discontinuous permafrost (50–90%), and sporadic permafrost (0–50%). The permafrost region covers approximately 24% of the Earth's land surface in the Northern Hemisphere, including large areas of the Arctic. Permafrost (continuous, discontinuous, sporadic or isolated) covers some 22.8 million square kilometers: Canada and Russia contain the

most extensive areas of permafrost—approximately 50% and 65% of their territories, respectively [16, Streletskiy D., Shiklomanov N.I., pp. 201-220]; 22% of China; and 82% of Alaska (approximately 15% of total land mass in the continental United States) [3].

The area of near-surface permafrost in the Northern Hemisphere is projected to decline by 20% relative to today's area by 2040 and could be reduced by as much as two-thirds by 2080 under a scenario of high greenhouse gas emissions. Impacts will vary widely at regional and local scales, but local effects are difficult to project given the lack of fine-scale detail in models and will involve a range of other environmental risks such as mercury contamination [4].

Why is it important to monitor permafrost state? With thawing permafrost projected to release significant amounts of carbon and methane in response to climate change, as well as being a reason for ground subsidence [17, Hjort J., et al., p. 5147], it may even reawaken dormant diseases. Widespread permafrost degradation is permanently changing local hydrology, increasing the frequency of fire and erosion disturbances. Moreover, the environmental transformations caused by climate change affect indigenous peoples and their traditional way of life, for example, reindeer herders have to find new areas available for use of grazing land due to disruption to food availability and the establishment of campsites integral to reindeer management [18, Doloisio N., Vanderlinden J.P., p. 26]. In other parts of the Arctic, thawing permafrost can play havoc with traditional ice cellars. In northern Alaska, it is not uncommon for Inupiat to dig underground vaults where the frozen ground helps to preserve whale and seal meat. Thawing ground leads to traditional food supplies spoiling [5]. Urban landscapes have been dramatically changed by thawing permafrost. According to researchers, a significant (approximately 25%) decrease in the urban infrastructure stability throughout Russia (permafrost region) should be expected by the mid-21st century [19, Shiklomanov N.I., et al., pp. 125-142]. Additionally, thawing permafrost poses a challenge for the oil and gas industry, as soon as the degradation of frozen ground results in damaged industrial installations [6].

Current State of Permafrost Data Sharing

Global permafrost data collection and sharing are patchy. Efforts have been made by the World Meteorological Organization (WMO), Global Terrestrial Network for Permafrost (GTN-P),

[3] Canadian Geographic. Arctic Permafrost is Thawing: Here's What that Means for Canada's North and the World. URL: https://www.canadiangeographic.ca/article/arctic-permafrost-thawing-heres-what-means-canadas-north-and-world (accessed 12 April 2021).

[4] Strong W. Arctic Understanding Limited by Patchy Field Work, Scientist Say. CBC News. URL: https://www.cbc.ca/news/canada/north/arctic-study-understanding-limited-climate-change-1.4781405 (accessed 30 April 2021).; Schaefer K., Elshorbany Y., Jafarov E., Schuster P.F., Striegl R.G., Wickland K.P., Sunderland E.M. Potential impacts of mercury released from thawing permafrost. *Nat. Commun.* 2020. URL: https://www.nature.com/articles/s41467-020-18398-5 (accessed 2 June 2021).

[5] CBC News. Failing Ice Cellars Signal Changes in Alaska Whaling Towns. 2019. URL: https://www.cbc.ca/news/canada/north/alaska-ice-cellars-permafrost-whaling-1.5372449 (accessed 2 June 2021).

[6] Harball E. Oil Industry Copes with Climate Impacts as Permafrost Thaws. NPR, 2018. URL: https://www.npr.org/2018/06/11/617240387/oil-industry-copes-with-climate-impacts-as-permafrost-thaws (accessed 5 May 2021).

International Permafrost Association (IPA), Circumpolar Active Layer Monitoring (CALM), Arctic Coastal Dynamics (ACD), Thermal State of Permafrost (TSP), GlobPermafrost and others to improve data coordination and exchange. Two global networks cover most areas of permafrost in the Arctic region with the TSP network measuring permafrost temperature at various depths in 860 boreholes, and the CALM network addressing the thickness of the active layer at 260 sites.

The Global Terrestrial Network for Permafrost (GTN-P) was initiated by the International Permafrost Association (IPA) to organize and manage a global network of permafrost observatories for detecting and monitoring changes in permafrost system which is critical in climate change impact assessments (Fig. 1) [7]. As Figure 1 suggests, borehole stations are highly concentrated in select parts of Alaska, Russia, Northern Scandinavia, China, and northern Canada but vast areas of the Canadian, Greenlandic and Russian Arctic are without such coverage.

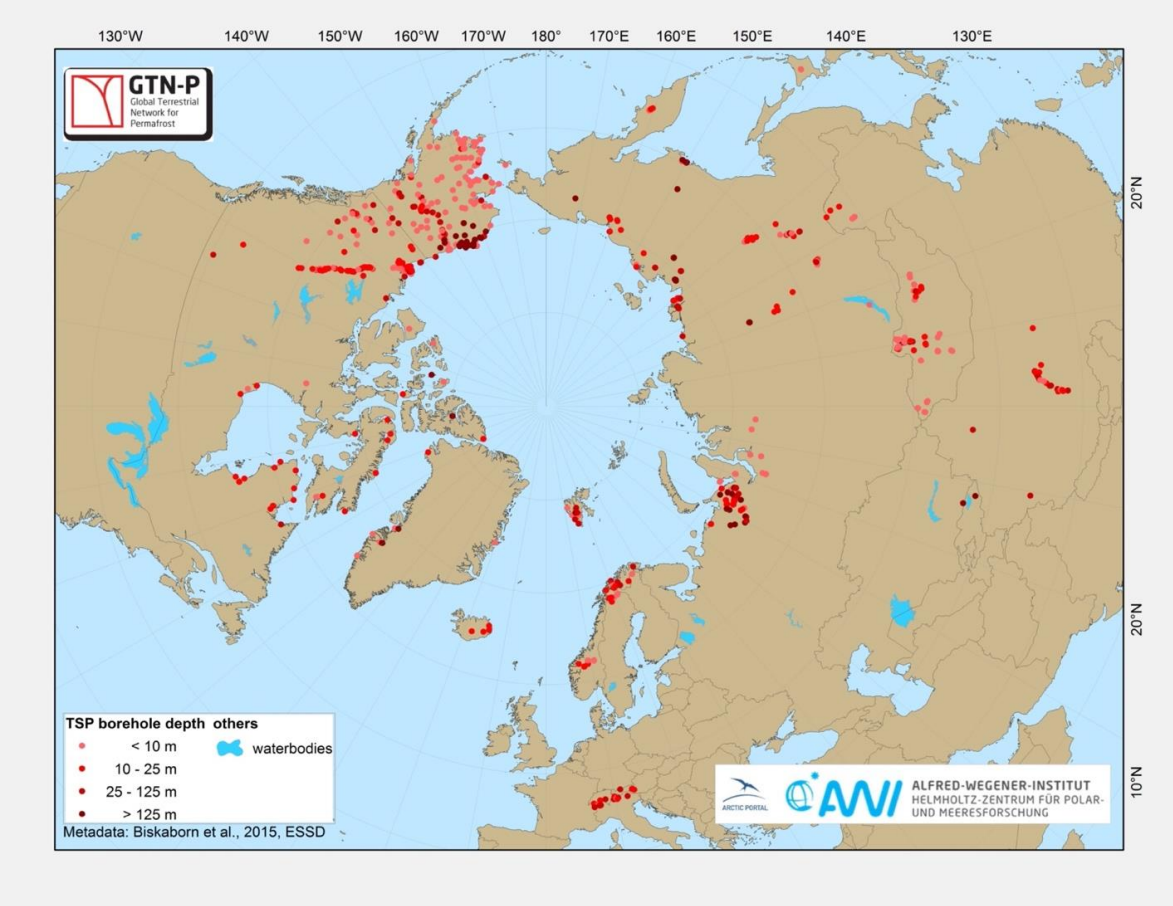

Fig. 1. Arctic Borehole Map. Accessed 02 June 2021 [8].

The network, authorized under the Global Climate Observing System (GCOS) and its associated organizations, consists of two observational components: the active layer (the surface

[7] IPA Artic Portal. The Global Terrestrial Network for Permafrost (GTN-P). URL: https://ipa.arcticportal.org/products/gtn-p (accessed 20 April 2021).

[8] Source: URL: https://gtnp.arcticportal.org/resources/maps/12-resources/37-maps-boreholes (accessed 20 April 2021).

layer that freezes and thaws annually) and the thermal state of the underlying permafrost [9]. The Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS) under the Terrestrial Observation Panel for Climate (TOPC) and the World Climate Research Program (WCRP) have identified permafrost thermal state and permafrost active layer as key variables for monitoring the cryosphere. Permafrost cannot be directly observed from space, but in order to understand the permafrost state scientists can use a combination of data obtained from in situ measurements and the satellites (monitor indicators and parameters used in models) to put together a picture of what is happening.

The development of a spatially distributed set of observations on past and present status of thermal characteristics of permafrost and thickness of active layer were a focus for the International Permafrost Association during the International Polar Year (2007–2008). While the importance and need of a shared permafrost monitoring system is considered overwhelming to many permafrost experts, it has proven challenging to implement [10]. Limited access to remote locations and a sparse system of sampling sites in Siberia, central Canada, Antarctica and Alpine regions (Andes, the Himalayas) result in substantive gaps in the time series of existing data [20, Biskaborn B.K., et al., p. 264].

In 2020, a non-profit center GRID-Arendal (Norway), as a part of Nunataryuk research project (an EU-funded Horizon 2020 project coordinated by the Alfred Wegener Institute in Germany), produced a new map (Fig. 2) that shows terrestrial and subsea permafrost in the Northern Hemisphere [11]. Some areas are observed better than others and this in turn reflects national funding priorities, shaped by infrastructural and military commitments in the Canadian North and Alaska, including the Alaska-Canada (ALCAN) Highway [21, Ferrians O.J., et al., pp. 1–37; 22, Lackenbauer P.W., Farish M., pp. 920–950].

With a more extensive borehole network, there would be opportunities to improve our understanding of terrestrial permafrost, while subsea permafrost remains understudied rather than simply subject to patchy data collection [12]. As a result of a significant lack of borehole data, the awareness of the state of the subsea permafrost is only recently known, and very little at that. Additionally, emerging subsea knowledge clearly indicates that such data development will be significantly more expensive and dependent on technological challenges still being explored.

[9] Streletskiy D., Biskaborn B., Smith S.L., Noetzli J., Viera G., Schoeneich P. GTN-P—Strategy and Implementation Plan 2016-Technical Report, Global Terrestrial Network for Permafrost. URL: http://library.arcticportal.org/1938/ (accessed 3 April 2021).

[10] Streletsky D. We Need a Permafrost Monitoring System. The Arctic. URL: https://arctic.ru/analitic/20200616/948752.html (accessed 12 December 2020).

[11] GRID-Arendal. Permafrost in the Northern Hemisphere. URL: https://www.grida.no/resources/13519 (accessed 15 March 2021).

[12] MacKenzie S. UN Environmental Assessment Shows a Need for More Offshore Permafrost Research. Eye on the Arctic. URL: https://www.rcinet.ca/eye-on-the-arctic/2020/12/24/un-environmental-assessment-shows-need-for-more-offshore-permafrost-research/ (accessed 2 April 2021).

Pressure (clathrates) also plays a critical role in the state of subsea permafrost unlike its terrestrial counterpart.

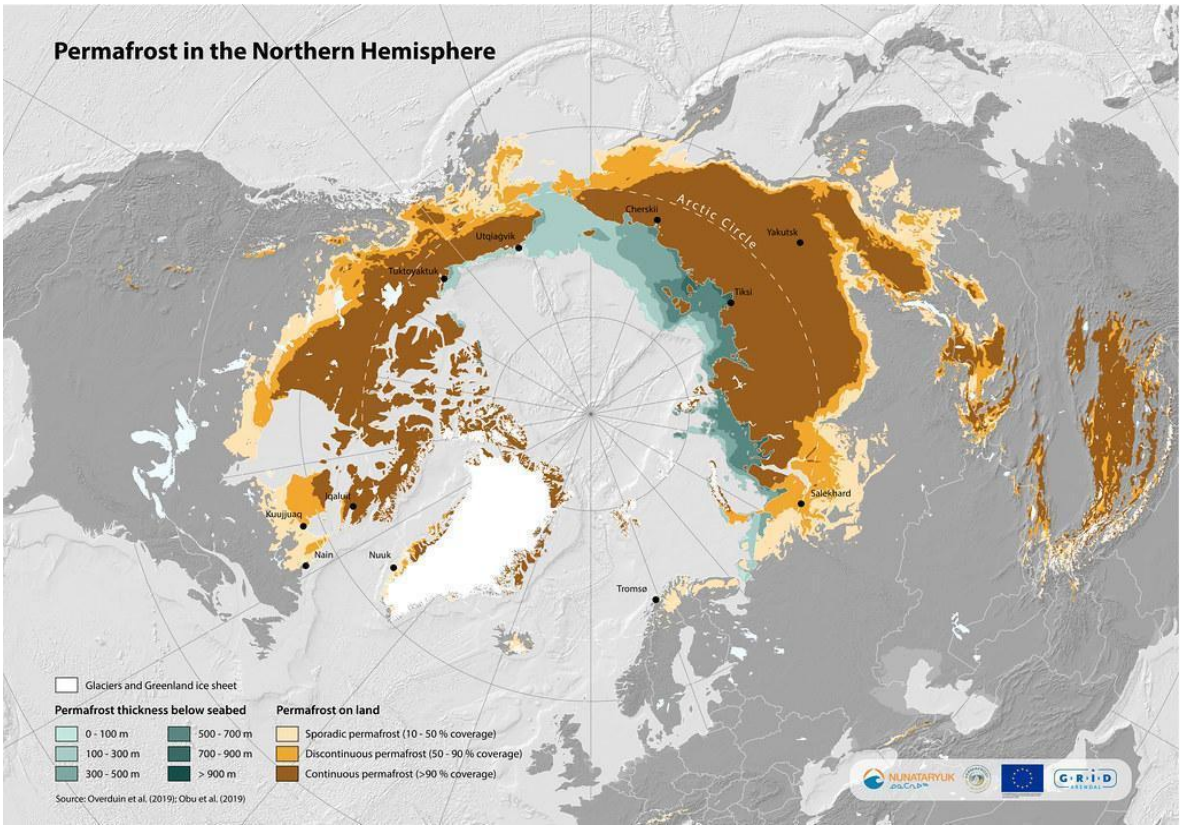

Fig. 2. Permafrost in the Northern Hemisphere [13].

Here, we aim at highlighting critical gaps that exist in a global permafrost monitoring. In the Arctic, the needs are acute for monitoring of terrestrial and subsea permafrost. Among numerous voids are the following:

- Existing permafrost temperature and active layer networks need to be expanded in order to get reliable control and to forecast situations in the permafrost areas.
- Satellite monitoring measures variables that can be used to derive permafrost temperature and extent, but has high uncertainty and does not provide information about deeper layers of frozen ground which require field-based investigation.
- Different types of permafrost require appropriate study techniques. Another challenge is to integrate data obtained from different sources (satellites and ground-based data).
- An irregular distributed system of sampling sites in the Arctic region, with 'gaps' in northern Canada and Russia, in particular—government support with collaborative networks, staff and facilities to aid research in specific areas of interest has helped to reduce spatial gaps.
- Past histories of restriction and access control, especially in Russia.

[13] Source: URL: https://www.grida.no/resources/13519 (accessed 13 January 2021).

Rationale and Methods to Share Permafrost Data

Challenges of Data Networks

Data hold significant importance in the domains of both scientific research and applied decision making. The process of gathering, curating, and making a dataset available often involves substantial time, funding, and resources on the part of research teams or collaborators, making that data an asset (which carries with it implications for data access and sharing). The level of quality of a dataset influences not only the ability to derive useful scientific knowledge, but also a level of trust and reliability in the underlying information that it contains, and therefore in the ability to develop plans or decisions based on that data [14]. However, the quality of a dataset alone is not sufficient for its use in large-scale decision making. For it to have broader utility to the research community, it is important that the data conform to field standards and that they are made available to interested groups—all of which remain a work in progress as Sjoberg et al. acknowledge:

Research in northern Europe, Russia and the USA is relatively well integrated, while Canadian research is more dispersed and either focused on the Eastern Arctic or Western Arctic, and similarly, China is relatively isolated but with some ties to US institution. Our survey respondents mentioned the importance of International Permafrost Association permafrost conference proceedings as sources of inspiration, especially the earlier ones (Supporting Information). More recent international collaboration efforts include developments of databases, such as the databases for permafrost region soil carbon, ponds and the thermal state of permafrost.

The standardization of data involves tasks like the conversion into commonly available formats for ease of use, conformity to units of measure, proper geospatial references for the region (where applicable), and additional information such as metadata that helps describe the dataset, its features, and additional information that may be relevant for its use and understanding. Common formats allow for greater use in industry or field standard analysis programs and toolsets, making the barrier to entry lower for working with that dataset, and this increases the likelihood that it may be explored by groups outside of the initial research team—a form of open science that has been described as an exemplar of the democratic school—open access to data and publications [23, Feche B., Friesike S., pp. 17–47]. Metadata also play a significant role in that wider adoption as well, as they convey vital information about the collection, utility, and even limits that can be applied to certain datasets. However, metadata are often limited in completeness, making it difficult for end users to understand the nuance required for performing subsequent research, or for searching and identifying relevant datasets [24,

[14] Elsevier Customer Insights. Trust in Research—Research Survey Results June 2019. URL: https://www.elsevier.com/__data/assets/pdf_file/0011/908435/Trust_evidence_report_summary_Final.pdf (accessed 2 June 2021).

Streletskiy D., et al. p. 42]. While standards for metadata exist in geospatial data, large portions of those fields remain optional and are subject to the time and resources of data producers [15]. Implications involving a shortage of permafrost data sharing indicate broader, holistic problems also, stated by O'Neill et al. (2019): "Northern communities and stakeholders require expert knowledge and predictive models to support adaptation strategies. Such predictions are useful only if the representation of landscape-scale processes is accurate. Invoking simplifying assumptions to operate global-scale simulations can generate predictions that may be misleading".

Another major hurdle to widespread adoption of scientific data is often less about the data than it is about the ease of accessing that data. Availability concerns in this case include those related to people, technological and policy. In the past, many researchers have shown a hesitancy to openly share data when there is a perceived loss of value through sharing, concerns over misuse of data, and potential competition when the data are made more broadly accessible. When the value gained through data sharing from collaboration or new research opportunities is made clear, however, most are open to the idea so long as the advantages outweigh the disadvantages. Additionally, recent surveys have indicated that when proper assurances of credit are made for datasets, organizational support is increased, and that financial support is given, data-sharing interests further improve [25, Steiglitz S., et al., pp. 1–20; 26, Tenopir C., et al.]. Coordination with related climate observation sites to collocate select boreholes with weather stations could help improve monitoring or surface and subsurface conditions, to improve understanding of microclimate conditions, and provide a more comprehensive assessment of permafrost responses to climate change and by extent may empower the individual researchers and amplify the findings. On the technology side, scientific datasets have continued to grow in size as the ability to gather data at high resolution has rapidly increased. Low-cost sensors, an increasing number of open-access satellite systems, and the computational resources to generate massive datasets have fueled this growth, but computational power, storage resources, and network technologies have been unable to keep pace with the increase in data volume [16]. Making data available broadly, and freely to end users, requires continuing financial resources to support the assets needed to serve and distribute that data effectively over long distances, including storage infrastructure, network services, and staffing to support and maintain these systems. One of the few studies on long-term availability of research data indicates that datasets used in research may become unavailable at a rate of up to seventeen percent per year after publications are completed, indicating broader issues in the maintenance of long-term research data [27, Vines

[15] International Organization for Standardization (ISO). ISO Geographic Data. URL: Standard https://www.iso.org/standard/53798.html (accessed 2 June 2021).

[16] Business Wire. Data Creation and Replication Will Grow at a Faster Rate Than Installed Storage Capacity, According to the IDC Global DataSphere and StorageSphere Forecasts. URL: https://www.businesswire.com/news/home/20210324005175/en/Data-Creation-and-Replication-Will-Grow-at-a-Faster-Rate-Than-Installed-Storage-Capacity-According-to-the-IDC-Global-DataSphere-and-StorageSphere-Forecasts (accessed 2 June 2021).

H.T., et al., pp. 94–97]. This permanent loss of data results in gaps in long-term analysis in some fields, and costly reproduction of research in others. Efforts by the NSF and similar funding organizations hope to change this, but this would require broader adoption in the research and data relevant communities, similar to current efforts demonstrated by the NSF-funded Arctic Data Center [17].

Beyond technology and infrastructure, there also has to be a willingness to share that data openly on behalf of data owners and governments. The value of a dataset can go beyond its value to researchers, including strategic value from business or national perspectives. When it comes to permafrost data, large amounts of borehole data are gathered by private organizations and used for site-based risk or engineering design purposes. Without proper incentives to share this data, it may be seen either as proprietary, or an unnecessary financial burden. In other sectors, data gathered by government agencies may even be viewed as a national security concern if it relates to controlled sites, and/or offering insights to foreign competitors. While some grant-awarding agencies now mandate long term, such as the National Science Foundation in the US or the Natural Environment Research Council (NERC) in the UK, many agencies in countries such as Russia and China have no such mandate, leaving it up to the research team to decide [18]. A data-sharing mandate alone is not always sufficient without additional resources and tools being provided to researchers [28, Couture J.L., et al., pp. 1–13]. When strictly enforced and supported, though, data-sharing efforts can lead to not only higher data retention rates, but also increases in citations for authors and related journals [29, Garret C., et al., pp. 1–13]. NERC takes this one step further, and not only mandates data sharing, but provides this as a service to funded projects, outside of award funds, but few options like this exist on international scales, and are largely limited to specific projects [19].

Despite these challenges, prior efforts in data-sharing networks in fields such as oceanography, seismology and ecology have successfully highlighted the importance of multilateral data sharing, and what proved possible during the Cold War era for example [30, Km J., p. 19].

Success Stories in Related Disciplines

A number of successful projects have highlighted the importance of consistent multilateral data-sharing agreements in both security and non-security related realms. The Global Seismographic Network, a network of over 150 seismic stations in 80 countries, was established to help identify seismic events at regional to global scales, to monitor seismic events, their origins, intensi-

[17] Arctic Data Center. Data and Software from NSF Arctic Research. URL: https://arcticdata.io/ (accessed 2 June 2021).
[18] National Science Foundation. PAPPG Chapter XI—Other Post Award Requirements and Considerations. URL: https://www.nsf.gov/pubs/policydocs/pappg20_1/pappg_11.jsp#XID4 (accessed 2 June 2021).
[19] Natural Environment Research Council (NERC). Data Policy. URL: https://nerc.ukri.org/research/sites/environmental-data-service-eds/policy/ (accessed 24 April 2021).

ty, and to provide mechanisms for notification and further research. This network identifies over 30,000 seismic events annually and provides large amounts of data for scientific research [20]. It also allows follow on systems to warn of potential tsunamis, or for response to begin mobilizing for disaster response and recovery. Over 50 stations in this network are also used to support international peacekeeping efforts through monitoring of nuclear detonations as part of the International Monitoring System for the Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO). This network helps notify member states of potential nuclear tests or non-geological events. The testing network has improved over time and has led to advances in both detection of nuclear events, as well as improvements in seismic detection capabilities from research purposes.

Another perspective on the value of multilateral data sharing can be seen through the Argo buoy networks maintained and operated by a consortium of 30 countries. This network, which consists of over 4 000 buoys, is used to monitor a range of oceanic conditions, including temperature, salinity, pressure, biological nutrients, and other variables at depths of up to 6000 m, gathering vertical data profiles by descending and resurfacing at regular intervals [21]. Each country is responsible for purchasing, maintaining, and providing for the processing of data retrieved by these buoys. The data are then standardized and made freely available for those interested through a public data portal. The data have been used in the production of over 4,000 research papers to date and have been the basis for improved strategic planning and decision making [22].

The history of data sharing goes back to the 19th century and is widely recognized to be useful because of the importance of weather forecasting. This has accelerated in recent decades due to the exponential growth in travel and transportation by air and sea, exposure to hazards such as flooding, drought and sea level rise, and dependency on intensive farming methods to improve food security. In the late 1840s, a telegraph network was established in the United States with the help of the Smithsonian, which issued standardized equipment and helped organize the collection of observational data to develop early weather maps and forecasts [31, Miller E.R., p. 59]. Data collection efforts were often reduced or interrupted over the next several decades due to funding challenges or political conflicts. In 1950, the WMO was established as part of a concerted attempt to support international collaboration on meteorology, with emphasis given to the coordination of international exchange of observational data. During the 1957–1958 International Geophysical Year, the World Weather Watch (WWW) was established and they were charged with gathering and processing near-real-time observational data collected by a ring of stations around the world. The WMO's global observing system coordinates data sharing but it has been noted

[20] Gee L.S., Leith W.S. The Global Seismographic Network. U.S. Geological Survey Fact Sheet 3021. URL: https://pubs.usgs.gov/fs/2011/3021/pdf/fs2011-3021.pdf (accessed 2 June 2021).
[21] Roemmich D., Alford M.H., Claustre H., Johnson K., King B., Moum J., Oke P., Brechner Owens W., Pouliquen S., Purkey S. et al. On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array. *Front. Mar. Sci*. 2019. URL: https://www.frontiersin.org/articles/10.3389/fmars.2019.00439/full (accessed 2 June 2021).
[22] Argo Program Office. Argo Bibliography. URL: https://argo.ucsd.edu/outreach/publications/bibliography/ (accessed 2 June 2021).

that data sharing is under pressure due to increased commercial sensitivity towards weather data and a lack of investment and infrastructure suitable for long-term observation. In 2019, the WMO membership agreed to establish the Global Basic Observing Network and to create financial support for countries in the global South so that it was possible to collect and exchange surface-based observational data. In 2020, WMO held a data-sharing conference and reaffirmed the need for investment and continued support for data-sharing protocols.

What these 'success' stories reveal, however, is the intersection of scientific-technical and geopolitical orders in enabling data sharing. National governments and militaries valued geophysical and oceanographic data for surveillance and strategic power projection purposes. Further, scientists, some of whom worked for national security organizations, were often eager to encourage data sharing and international collaboration. Reconciling the impulse to hoard and to share was endemic during the Cold War, and thus researchers in oceanography and seismology were often caught up in protocols and practices establishing what was either classified or freely available data. To share or not to share was part and parcel of individual and collective calculations that were occurring all over the world. However, following the Soviet Union collapse, the exchange of information and international collaboration became possible between former Soviet and Western scientists. Of course, the digital revolution also contributed unprecedentedly to the opportunity and ability to share information.

Implications for National and Global Interests

Scientific and Political Histories of Permafrost

In his magisterial account of Red Arctic: Polar Exploration and the Myth of the North in the Soviet Union, John McCannon writes about the extraordinary efforts the Soviet Union made to exploit, develop and even conquer the 'frozen North') [32, McCannon J., pp. 15–31]. Much of his analytical account rests on a close reading of the intersection of institutional bodies and leading personalities charged with that developmental labor. It is not an environmental history of the 'Red Arctic', with substances such as permafrost meriting some but not detailed attention [33, McCannon J., p. 40]. What emerges is a complex story involving the Soviet Union and its repeated desire to industrialize its extensive northern territories through ambitious and aggressive resource exploitation, infrastructural investment and political prioritization. Two decades later, the field of environmental history addressing the polar regions has expanded greatly. In 2020, the environmental historian Pey-Yi Chu published The Life of Permafrost: A History of Frozen Earth in Russian and Soviet Science and offers a detailed reading of how Soviet scientists conceptualized permafrost [34, Chu P.Y.]. Nearly 50% of the Soviet Union was covered by frozen earth. She argues that Russian and Soviet framing of permafrost/frozen ground was informed by two historic and cultural currents; first, frozen ground was approached as an engineering challenge that needed to be managed even 'conquered'. Second, to connect permafrost to a holistic even planetary perspective

where the materiality of the Arctic was understood to involve the interchange of energy and matter.

In her auditing of Soviet permafrost science, Chu highlights the 'frustrating' quality of frozen ground. On the one hand, 'nature' was supposed to be a resource to be exploited and developed. The will of the Soviet people could not be allowed to be blocked by a recalcitrant nature. On the other hand, if frozen earth was a barrier to development, then someone had to be held to be responsible. Were there subversive elements in the Soviet North secretly undermining attempts to develop and exploit Soviet resources? The problem posed by permafrost was not one, as Soviet researchers later noted, could easily be 'defeated'. In his *The Conquest of the North (in the Region of Permafrost)*, the scientist Sumgin and writer Demchinskii wrote in 1938 that frozen earth was framed as a highly dynamic and challenging opponent [23]. Permafrost was dangerous because of its capability to manipulate the intersection of ice, water, soil, land. Could it be removed? Could it be thawed? How could the Soviet Union overcome it? It might be framed as a 'cunning adversary' by Communist Party officials, but what emerges is a more complicated story involving adaptation and concession. In Chu's survey, what emerges is Soviet scientists and planners moving away from 'conquest' to a series of pragmatic accommodations including de-icing roads, elevating buildings, and avoiding accidental thawing by an over-concentration of infrastructure.

The game-changer for permafrost science was the Cold War. Aided and abetted by the militarization of the Arctic, both Soviet and US administrations recognized the strategic importance of the earth sciences including glaciology, meteorology, geology, physical geography, marine biology. Permafrost, sea ice, and Arctic weather were topics of considerable importance to those charged with defending and developing northern territories. As the historical geographer Matt Farish observed, frozen earth was framed as a 'frontier engineering' challenge that carried with it a medley of implications for national security planning). What made frozen ground challenging and even discombobulating was that it has a dynamic materiality—alternating from frozen, thawed and refrozen. The depth and dynamism of 'active layer' carried with it a medley of implications for the infrastructural resilience of roads, pipelines and military bases, with concordant financial liabilities in the event of subsidence and slippage.

What has changed from the Cold War framing of permafrost to contemporary rhetoric is how the materiality of frozen ground has been explicated—from a frontier engineering challenge to an underground milieu that is more likely to be understood as a methane 'time bomb' and threat to communal resilience rather than exclusively infrastructural. Frozen ground is 'unreliably frozen' to echo the conclusion of the NOAA Report Card on the Arctic (2017) and this has led to repeated fears that permafrost thaw will scramble existing projections regarding not only the scale

[23] Sumgin M.I., Demchinskii B.N. *The Conquest of the North (in the Region of Permafrost)*. 1938. (in Russ.). URL: https://www.prlib.ru/en/node/411707 (accessed 2 June 2021).

and pace of anthropogenic change in the Arctic but also the wider world [24]. Land and sub-sea permafrost are being recognized as integral to how we assess and calculate 'locked up carbon' as well as how thawing brings the fore newer risks such as disease transmission (e.g., Anthrax) due to exposed and rotting animal carcasses [35, Hueffer K., et al., pp. 174-180]. By the end of this current century, it is predicted that the global coverage of permafrost could decrease by up to 30%–70% depending on warming trends with "potentially hundreds of gigatons" of total carbon release Thus, far, Arctic carbon (carbon dioxide and methane) emissions are comparatively under-counted in global carbon budget analysis [25].

One continuity that remains a shared one is the costs and challenges of adaptation for Arctic communities. If permafrost thaw and re-freeze placed additional cost pressures on those seeking to maintain Arctic infrastructure and buildings, worsening rates and extent of thaw is contributing to the imperilment of local communities in Alaska. As the Bering Strait Elders Group (2020) has highlighted recently through a series of short films, coastal villages have been buffeted by sea ice loss and coastal erosion and assaulted by landslides and slippages caused by permafrost thaw. In some cases, re-location becomes the only option as access to immediate higher ground is not available [26].

Actors and Interests Involving Permafrost Data Gaps and Sharing

As we have noted, permafrost data sharing has had to grapple with a series of long-term challenges that bedevil attempts to form a more comprehensive understanding of its current state and possible future trajectories. With approximately 14 million square kilometers of global permafrost, the vast majority of which is found in Russia, China, and North America including Greenland, there are geopolitical as well as geographical and scientific-technical reasons at play. As an example, one immediate parallel is the bathymetric data in and around the Arctic Ocean and the understandable reluctance of the US and Soviet navies to share what they had with civilian scientists because of national security concerns. Mapping and surveying the Arctic Ocean was integral to planning underwater surveillance operations and the tracking of enemy submarines [36, Doel R., pp. 605–626]. In both cases, an unwillingness to share can weaken shared understandings of the scale and pace of environmental change, foster decision making that is insufficiently attentive to current and future trajectories of change, and hinder planning for long-term investment in adaptation, dislocation and mitigation. Arctic communities in Alaska are facing a spectrum of challenges and the eventual consequences of ongoing warming trends range from adaptation measures (such as re-

[24] NOAA Report Card on the Arctic (2017). URL: https://arctic.noaa.gov/Report-Card/Report-Card-2017 (accessed 2 June 2021).
[25] Miceli R. Why Arctic permafrost is thawing and how its affects the planet National Academy of Sciences, Engineering, and Medicine 2020. URL: https://www.nationalacademies.org/news/2020/05/why-arctic-permafrost-is-thawing-and-how-it-affects-the-whole-planet (accessed 2 June 2021).
[26] Bering Strait Elders Group. URL: http://www.beringseaelders.org/ (accessed 2 June 2021).

treat to higher ground) to painful dislocation (e.g., abandonment) depending on cost and timeliness.

First, there are spatial gaps in data collection. Access to the Russian Arctic is harder for non-Western scientists and some of this is rooted in Cold War military and national security legacies, which ensured that there were simply forbidden zones or areas of restricted access (even for Soviet/Russian scientists). Permafrost research was informed by Cold War geopolitical agendas, with militaries being reluctant to share their own data in some of those restricted zones. Second, there are national variations in how borehole data are organized, collected, archived, and shared. Some of this might be simply down to the fact that there are a multitude of data collection agencies from energy and construction companies to local and state authorities as well as federal agencies. Data mapping might, for example, reveal where borehole locations are without giving any sense of what sort of data is being generated. Permafrost data might be open, partial and/or closed access, as a consequence. Third, if interested parties cannot access raw data then it not only complicates the work that climate change modelers might wish to undertake (harder to standardize data across vast geographical areas) but also makes it harder to account for any biases and limitations of data, such as relative distribution of borehole sites. Fourth, the role of traditional indigenous knowledge and citizen science in permafrost science has been arguably neglected. Native Alaskan communities have not only aided and abetted agencies such as the US Army Corp of Engineers and US Geological Survey for decades but also acquired first-hand experience and understanding of permafrost thaw and the implications for communal living and food security. Increased active engagement with indigenous peoples and national and regional commitments to develop and fund a collaborative network that actively looks to co-produce work that thinks about data in a pluralistic manner and sharing protocols. Pressing human security issues such as contamination to soil and water via increased concentrations of contaminants in the plants and/or disruption to animals relied on by community members for subsistence economies.

Impacts to Security

As early as 2012, US authorities began to provide focused assessments concerning climate change impacts to defense-related infrastructure. In one instance, the Government Accountability Office learned from Department of Defense officials that “the combination of thawing permafrost, decreasing sea ice, and rising sea levels on the Alaskan coast has increased coastal erosion at several Air Force radar early warning and communication installations.” Based on high and low forecasts from RCP8.5 and RCP4.5 and infrastructure modeling, Melvin et al. assessed, from 2015 to 2099, that after flooding “damages to buildings associated with near-surface permafrost thaw accounted for highest costs in most of Alaska [37, Melvin A.M., *et al.,* pp. E122–E131]”. More specifically, Karlovitch et al. discovered in 2020 that, at Eielson Air Force Base in Fairbanks, Alaska, construction issues related to permafrost cost approximately $164 million in the last three years, with $5 million alone going towards preventing permafrost thaw under critical ammunition storage fa-

cilities (2020). Growing awareness and analysis of permafrost thawing threats and impacts to both civil and military infrastructure continues to illustrate alarming vulnerabilities and challenges to the engineering aspects of changing conditions. Both the US Army and the US Air Force acknowledge a full spectrum of problems associated with permafrost thaw in their inaugural Arctic strategies, ranging from housing issues to critical defense installations [27].

Elsewhere, a recent Arctic national strategy of the Russian Federation established a requirement to establish a state system of monitoring and prevention of the negative impacts involving the degradation of permafrost [38, Putin V.V.]. In Canada, experts think that approximately half of the northern roads constructed in permafrost areas are at risk of becoming unstable, as a result of thawing [28]. In an assessment of the Circumpolar North by Hjort et al., the authors estimate that a mean of 69% of pan-Arctic fundamental human infrastructure is at potential risk in areas where near-surface permafrost is expected to thaw by mid-century [17, Hjort J., et al., p. 514]. The immediate connection to fiscal shocks and components of disintegrating security capabilities naturally becomes the leading tangible, as well as conceptual, struggle. Threats to human and national security remain inextricably linked. Governments continue to wrestle with how best to respond to the growing threat and where to focus funding. Finite resources and time further complicate issues, especially in areas where most of a national constituency lacks interest or tolerance in allocating public spending to problem areas in more remote areas of a national territory.

Permafrost Science Diplomacy

Science had been recognized and credited with building trust and establishing confidence building measures in global politics [39, Flink T., Schreiterer U., pp. 665–677]. Terms such as science diplomacy have been popularized to account and evaluate for the efforts made by governments and relevant actors to build networks and partnerships designed to encourage either the co-production and or circulation of authoritative knowledge [29]. Science and scientists are part of what are termed ‘epistemic communities’, with their own global codes, norms, values and scholarly rules for the production and circulation of knowledge. Scientific communities in the Arctic context have been widely recognized in identifying problems, shaping policy agendas, and advocating for greater coordination between Arctic and non-Arctic stakeholders. Notable reports such as *Arctic Environment Impact Assessment* (2005), organized under the auspices of the Arctic Council, have been lauded as significant examples of science diplomacy—reciprocal, non-hierarchical and multi-disciplinary in focus and delivery. It also helped to pave the way for subsequent reports such

[27] United States Air Force. The Department of the Air Force Arctic Strategy; USAF: Washington, DC, USA, 2020. URL: https://www.af.mil/Portals/1/documents/2020SAF/July/ArcticStrategy.pdf (accessed 2 June 2021).

[28] BBC. The Fragile Future of Roads and Buildings Built on Permafrost. URL: https://www.bbc.com/future/article/20210303-the-unsure-future-of-roads-and-buildings-on-melting-ground (accessed 21 April 2021).

[29] The Royal Society. New Frontiers in Science Diplomacy: Navigating the Changing Balance of Power; AAAS: Washington, DC, USA, 2010. URL: https://www.aaas.org/sites/default/files/New_Frontiers.pdf (accessed 2 June 2021).

as *Arctic Marine Shipping Assessment* (2009) and *Snow Water Ice and Permafrost in the Arctic* (2017), which foregrounded collaborative social scientific and scientific labor around a sensitive topic, namely accessibility of shipping lanes around the edges and through the middle of the Arctic Ocean [40, Berkman P.A.].

The 2017 Agreement on Enhancing International Arctic Scientific Cooperation (Fairbanks Agreement) was a notable milestone for the Arctic Council, coming as it did in the wake of US–Russian tension over Crimea, Ukraine and Syria. It reaffirms the importance of scientific co-operation within and across international boundaries and the urgent need to share information. What the Agreement is less specific on is how that appeal for science diplomacy will be implemented in practice, and how that might complement data diplomacy (Berkman et al. 2017). Additionally, organizations such as the Permafrost Young Research Network (PYRN), the World Meteorological Organization, the United Nations Environment Program, the International Permafrost Association (IPA), and the Intergovernmental Panel on Climate Change (IPCC) all represent important network bridges and enablers that can provide guidance on how and why to effectively share data through global cooperation.

Conclusion

Thawing permafrost, especially near-surface, increasingly presents alarming challenges to all academies of knowledge, including the sciences (natural and social), engineering, and medicine. Individually, nations continue to maintain or grow effective research and studies involving thawing permafrost problems. Evidence, both obscure and obvious, indicate that the degradation of permafrost is part of a global dilemma that requires international solutions. In order to facilitate multinational approaches in solving such issues, the relevant authorities need to collectively establish the most valid and trustworthy science-based information from which to unilaterally advise the decision and policy makers. However, potential competing scientific models could impact confidence in scientific recommendations—indicative of the current climate change circumstances involving so much uncertainty. Models provide a representative, systematic description of a phenomena in order to better understand and/or predict key aspects of the world. Models often focus on answering specific questions involving temporal, topical and / or spatial components where supercomputing power becomes more and more necessary to handle such complex interactions. Fragmented, even competitive, efforts to present authoritative models involving an accurate understanding or prediction of permafrost thaw and effects leave the scientific community vulnerable to marginalized consideration in policy development and implementation as well as frustrations affecting permafrost-related diplomacy.

To be sure, individual modeling endeavors do provide value, especially in support of achieving a consensus on best practices forward. However, part of the current problem of shared data involves restrictive national policies, and other parts include a lack of opportunity or motiva-

tion, where many experts simply continue to maintain career-supporting research within national systems. The authors suggest that the scale of the permafrost problem and the amount of data that exist urgently require that the global permafrost expert community transition to a collective enterprise involving shared data in order to pursue cohesive models. A surprisingly significant amount of permafrost data currently exists from which to conduct extremely robust analysis and computational modeling, including improved methods of monitoring. Clearly, such an undertaking would come at a cost, but the ability to advise national authorities and wider publics with increased accuracy, and relatively quickly given how much data currently exist, would seemingly pay for itself exponentially both domestically and foreign.

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