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• **News & Views** •

Recent Ventures in Interdisciplinary Arctic Research: The ARCPATH Project※

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ABSTRACT

This paper celebrates Professor Yongqi GAO's significant achievement in the field of interdisciplinary studies within the context of his final research project *Arctic Climate Predictions: Pathways to Resilient Sustainable Societies* - ARCPATH (https://www.svs.is/en/projects/finished-projects/arcpath). The disciplines represented in the project are related to climatology, anthropology, marine biology, economics, and the broad spectrum of social-ecological studies. Team members were drawn from the Nordic countries, Russia, China, the United States, and Canada. The project was transdisciplinary as well as interdisciplinary as it included collaboration with local knowledge holders. ARCPATH made significant contributions to Arctic research through an improved understanding of the mechanisms that drive climate variability in the Arctic. In tandem with this research, a combination of historical investigations and social, economic, and marine biological fieldwork was carried out for the project study areas of Iceland, Greenland, Norway, and the surrounding seas, with a focus on the joint use of ocean and sea-ice data as well as social-ecological drivers. ARCPATH was able to provide an improved framework for predicting the near-term variation of Arctic climate on spatial scales relevant to society, as well as evaluating possible related changes in socioeconomic realms. In summary, through the integration of information from several different disciplines and research approaches, ARCPATH served to create new and valuable knowledge on crucial issues, thus providing new pathways to action for Arctic communities.

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"And this our life ... finds tongues in trees, books in the running brooks, sermons in stones, and good in everything" (As You Like It, Act 2 Scene 1).

※ This paper is a contribution to the special topic on the Ocean, Sea Ice and Northern Hemisphere Climate: In remembrance of Professor Yongqi Gao's key contributions.

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The Concept of interdisciplinarity

This offering to a journal issue to commemorate Professor Yongqi GAO's key contributions to his field focuses on the interdisciplinary nature of his final research project, "Arctic Climate Predictions: Pathways to Resilient Sustainable Societies" with the short title ARCPATH (https://www.svs.is/en/projects/finished-projects/arcpath). The project ran for six years (1 January 2016 to 31 December 2021). Various academic minds and researchers have suggested independent, albeit similar, definitions of the term interdisciplinarity. One example is: "Interdisciplinarity is the inherent ability to use knowledge from many different realms and augment that knowledge to open new inquiry and new ways of understanding for successive progression throughout learning, life, and society" (Babich, 2020). Interpreting the concept in its broadest sense it may be traced back to the writers and philosophers of ancient times and their discourses on the disparate qualities of body and soul, mind and matter, and heaven and earth (Kenny, 2010). As later thinkers continued the quest to explain the workings of the natural world, emphasis was placed on the separation rather than the fusion of different disciplines. Scholars in medieval and early modern Europe emphasized what came to be called "natural philosophy" which sought to understand the world through physical inquiry. With the advent of the "scientific method" in seventeenth-century Europe, came the focus on reproducible and factual evidence through observations, and the accompanying development and testing of hypotheses. Put simply, this excluded systems of knowledge that did not rely on "hard data" and laid the foundation for the schism between the natural and social sciences. Part of the value of an interdisciplinary approach is to recognize that there are many different ways of perceiving and understanding the world, and these can be complementary, with one system not necessarily having more value than another.

In recent times it has become clear that interdisciplinary research is crucial to address the urgent challenges of climate change, and in this respect, climate science is a post-normal science (Bray and von Storch, 1999). The level of the required interdisciplinary research goes far beyond conventional cooperation between oceanographers and meteorologists, or among physicists, mathematicians, and climatologists. One step further into integrative research is "transdisciplinarity". This term refers to the inclusion of different knowledge systems, information from stakeholders, and other local and traditional knowledge holders, as well as the co-designing of research and co-production of knowledge (Berkes, 1993, 2017; Newman, 2021). The term "cross-disciplinarity" suggests seeing one discipline from the perspective of another (Chambers et al., 2021). Integrated research drawing on these concepts is even more crucial when it comes to research in Arctic regions (ARCUS, 1997; AHDR, 2004; ACIA, 2005) This is because the Arctic is of fundamental importance in the climate system, encompassing key atmospheric and oceanic processes. Furthermore, global warming has caused intense changes in Arctic climate, with a rise in temperatures during recent decades that is close to twice that of other regions (NOAA, 2022). Related to this, the loss of sea ice is critical, with a direct and immediate effect on Arctic communities and ecosystems (Bravo and Rees, 2006; Malinauskaite et al., 2022a). These rapid changes are a challenge to human welfare that is already at risk from socioeconomic, as well as climatic drivers (IPCC, 2022). Together they bring manifold challenges to planning responsible development in the Arctic. This has been a key focus of the ARCPATH project.

The ARCPATH project

Professor Yongqi GAO recognized the need for interdisciplinary research to address the challenges of the High North. Thus, in his final project, he led an endeavour that took him away from his traditional arena of expertise as a climatologist with a particular interest in understanding the variations in large-scale ocean circulations in the North Atlantic. His specific contributions to the project were primarily related to this latter research. ARCPATH was very much in line with the recent focus on interdisciplinary and transdisciplinary research, recognizing that climate change is only one of many societal drivers. ARCPATH resulted from a successful application to form a Nordic Centre of Excellence. Mindful of the fact that addressing global challenges requires a global perspective, the international project team was made up of colleagues, not only from the Nordic countries but also from Russia, China, the United States, and Canada. The importance of an interdisciplinary focus was made clear in the original call from the funding body NordForsk with its emphasis on "Responsible Development of the Arctic: Opportunities and Challenges" with the corollary "Pathways to Action" (https://www.nordforsk.org/programs/responsible-development-arctic-opportunities-and-challenges-pathways-action). Professor GAO's co-lead was Astrid Ogilvie, an experienced proponent of an interdisciplinary approach with a focus on climate history, and current Arctic issues. In addition, the core project team included expertise in the social sciences (Einarsson, McGoodwin), interdisciplinary studies in sustainability and the environment (Daviðsdóttir and King), marine biology (Rasmussen), as well as in climatology (Counillon, Gulev, Keenlyside, Fan, Koenigk, Yang). A further novel and highly interdisciplinary aspect of the project was its collaboration with a well-known Scottish environmental artist, Elizabeth Ogilvie, who facilitated project outreach through her books and films on sea ice (https://www.elizabethogilvie.org/). The contributions of numerous other colleagues involved in this very large project are highlighted in a description of the completed project (https://www.svs.is/en/projects/finished-projects/arcpath). For a general overview of the project see Ogilvie et al. (2021a). Results and insights from the project were disseminated at numerous conferences and outreach presentations during its six-year duration and came to the

attention of policymakers as well as academics and stakeholders, e.g., the published Nordic Council summary https://curis.ku.dk/ws/files/240333312/FULLTEXT01_2_.pdf, pp. 8–9, Ogilvie (2019), and Keenlyside et al. (2023).

ARCPATH focused on three main goals: (1) To improve Arctic climate prediction by using innovative methods to capture both anthropogenic and natural factors in global and high-resolution regional models; (2) To increase understanding and reduce uncertainties regarding how changes in climate interact with multiple societal factors including the development of local and regional adaptation measures; (3) To supply this knowledge as potential "pathways to action" to the specific Arctic regions singled out for special focus in the project. Thus, ARCPATH was a ground-breaking project that was designed specifically to synthesize results deriving from a variety of traditionally very different and separate academic disciplines (King and Ogilvie, 2021). While focusing on the Arctic region in general, main emphasis was on the developments in specific local communities in Iceland (e.g., Húsavík and surroundings), Greenland (e.g., Ittoqqortoormiit, formerly Scoresby and Qeqertarsuup Tunua, formerly Disko Island and Ilulissat, formerly Jakobshaven), and northern Norway (Skjervøy and Tromsø), as shown in Fig. 1.

Interdisciplinarity and synthesis

Because of its interdisciplinary focus, the ARCPATH project was specifically designed to integrate results and achievements derived from very different and traditionally separate academic disciplines, as represented by its team members. These included: climatology (global modeling; dynamical downscaling; historical climatology); environmental science (marine and fisheries biology); socioeconomic sciences (fisheries management systems; anthropology; economics; governance systems); and the broad compass of social-ecological systems theory. Thus, ARCPATH could provide a holistic analysis of impacts related to climate change and other social and ecological drivers, encompassing key implications for society,economy, and human well-being. This goes beyond the approach used in the IPCC Assessment Reports (IPCC, 2022; The Core Writing Team et al., 2023) which focused primarily on the detection, attribution, and mitigation of climate change, and adaptation to its consequences.

These various academic disciplines typically use different methods of analysis. Thus, bringing together and melding such disciplines is a long-term process and requires clear communication and a strong willingness among researchers to work together to seek solutions. One barrier is that sufficient observational data (e.g., from the social sciences) are not always available in a form that is easily comparable to numerical meteorological variables. Conversely, climate time series

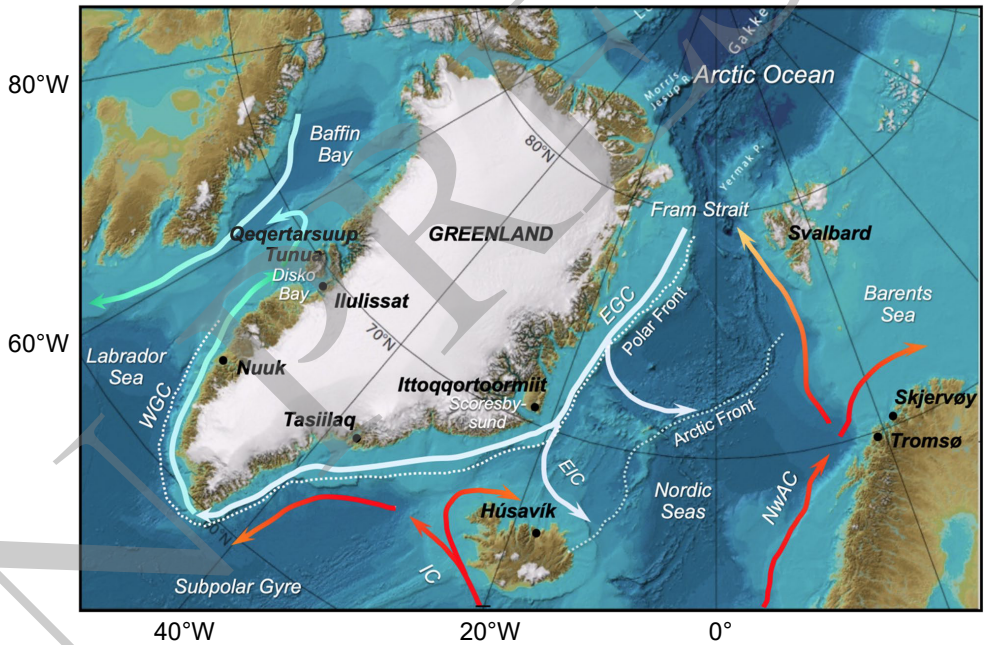

Fig. 1. Geographical settings and locations of ARCPATH primary focus areas. Major temperate warm (warm colours) and cold (cold colours) ocean currents are shown, including the East Greenland Current (EGC), West Greenland Current (WGC), East Icelandic Current (EIC), Irminger Current (IC), and the Norwegian Atlantic Current (NwAC). The Polar Front indicates the modern mean limit of polar waters and sea ice of Arctic Ocean origin. The bathymetry was sourced from the International Bathymetry Chart of the Arctic Ocean (IBCAO) see Jakobsson et al. (2012). This figure is courtesy of Dr. Martin MILES, NORCE Norwegian Research Centre, and the University of Colorado Boulder.

cannot automatically be integrated with social and economic information. A further element in ARCPATH research was the inclusion of local and Indigenous knowledge, with fruitful partnerships being forged with local partners in our study areas (Chambers et al., 2021).

The processes, structures, and actions required to synthesize emerging findings throughout the lifetime of the project were identified early on in the project. These included initiating synthesis by developing appropriate processes and structures from the design phase of the project, regular communication among project partners, joint authorship, and project meetings on topics that required input across the project. They also included means of harvesting and integrating findings, identifying policy relevance, and co-creating and mobilizing findings to ensure their applicability to the problem addressed by the research (King and Ogilvie, 2021).

Contributions to atmospheric sciences

Analyses of changes in both Arctic and global climate formed a significant and highly successful component of ARCPATH. One major aspect was an improved understanding of the mechanisms that drive climate variability in the Arctic. Historical observations and palaeoproxy records have shown that Arctic climate has varied on multi-decadal timescales (Ogilvie, 2010, 2022; Miles et al., 2014; Docquier and Koenig, 2021; Ogilvie et al., 2021b; Svendsen et al., 2021). The analysis of historical records of climate change, in particular the past sea-ice record for Iceland, in terms of a link to the North Atlantic Oscillation (NAO) index and Atlantic and Pacific multi-decadal variability, is a significant example of collaboration between climatologists and climate historians. Increasing knowledge of past climate beyond the period of systematic instrumental observations is extremely valuable, and is especially relevant to the study of low-frequency variability. In this respect, one of the challenges for ARCPATH was to demonstrate that oceanic variations in both the Pacific and Atlantic contributed to these variations through changes in the northward meridional heat transports—the major driving mechanism in the Arctic climate system. In particular, it has been demonstrated that up to 50% of the Arctic surface temperature warming during the 1940s may have been driven by changes in the Pacific Ocean (Svendsen et al., 2018). Furthermore, in contrast to previous work by others, ARCPATH research has shown the importance of the role of natural climate variability in providing additional contributions to greenhouse gas warming and aerosol cooling (Svendsen et al., 2021; Omrani et al., 2022). The magnitude of such natural climate variations, with operating timescales of years to a few decades, can be even larger than anthropogenic climate signals, thus forming the so-called “grey range” of climate predictability (Meehl et al., 2021). Furthermore, future socioeconomic planning requires information at this timescale (Street, 2016).

Meeting this challenge, ARCPATH was also able to provide an improved framework for predicting the near-term variation of Arctic climate, to include spatial scales more relevant to society (Yang et al., 2021). These advances focused on the joint use of ocean and sea-ice data combined with advanced statistical schemes in the dynamical prediction system to enhance prediction skill (Kimmritz et al., 2019; Dai et al., 2020; Tian et al., 2021). This led to better predictions of regional Arctic sea-ice extent on seasonal-to-decadal timescales. The findings have indicated that an improved representation of oceanic processes will facilitate predictions in this region, thus confirming that ocean–atmosphere interactions and teleconnections act to shape Arctic regional climate change (Docquier and Koenigk, 2021). Research of this kind serves to meet the demands of the societies and stakeholders in the ARCPATH focus region for a more nuanced picture of how rapidly their climate will shift up to 2030 as a basis for community planning.

Marine changes and ecosystem services in the Arctic

The ARCPATH project had a specific and integrative focus on marine changes in the Arctic, in particular with regard to the linkages among environmental changes, variations in cetacean populations and migrations, and the development of whale-watching tourism. Over the life of the project, social, economic, and marine biological research and fieldwork were carried out in Iceland, Greenland, Norway, and the surrounding seas. A combination of historical research and anthropological fieldwork documented the use of marine resources, focusing on past and present activities, including whale hunting and the contemporary emphasis on whale-watching activities (Kristjánsson, 1980; Einarsson, 1987, 2009; Cook et al., 2022b).

A novel aspect relating to the interdisciplinarity of the project was the focus on ecosystem services (ES). The rich data collected for the project allowed this to expand from ES identification and valuation to information on governance and co-production. This work was greatly enhanced by engagement with different stakeholders, ES users, and co-producers that revealed aspects of Arctic marine resource governance that would not otherwise have been known. While focusing initially on whale ES, the concept was also applied to previously unexplored areas in this regard, such as glaciers and volcanic areas (Cook et al., 2022a). This work went beyond just classifying and valuing ES monetarily but further investigated how these important services may be formed, governed, and potentially affected by future climate change. The data collected for this research extended beyond ES resources and also provided interesting information concerning the risks pertaining to, and the resilience of, Arctic coastal communities and how they relate to their local marine ecosystems. Furthermore, it was established that by considering different local cultural contexts, sophisticated ES assessments can be highly useful for evaluating multiple

uses of marine mammals and provide informed policy advice (Cook et al., 2022a, b; Malinauskaite et al., 2022a, b; Win et al., 2023).

In tandem with the ES work, ARCPATH investigated future projections of sea-surface temperature (SST) changes in the Nordic Seas region using a large ensemble of climate-model simulations following different future emission scenarios. The area of focus was on the region north of Húsavík in Iceland, where SSTs are expected to increase by at least 2°C in all emission scenarios up to 2050. This implies a critical impact of what is termed "Arctic Atlantification" (e.g., Polyakov et al., 2023), not only on Arctic Ocean climatic regimes but also on marine organisms that tend to move northward. The potential consequences of Arctic Ocean warming are significant for cetaceans. If whales leave these waters in search of colder regions the impacts on both the local and national economy could be far-reaching. Malinauskaite et al. (2022b) documented a significant negative correlation between minke whales and SSTs for the years 1995–2018. The same relationship was also documented by Lechwar et al. (2023). In close connection with such potential developments, it has been noted that blue whales have increasingly been moving north. They currently come into Skjálfandi Bay, adjacent to Húsavík, every summer in June. However, when a photo-identification catalog of 148 different individuals was compiled, it resulted in a match of many of these whales in waters off Svalbard as well as Húsavík. This possible shift may be linked to warming Arctic waters. Madsen et al. (2019) further describe these exciting findings and discuss future work. Although the "staple" of the whale-watching industry is now the humpback whale, the novelty of the presence of blue whales is of great interest and the loss of these magnificent creatures could negatively impact the Húsavík tourism industry.

Climate, fisheries, and marine governance past and present

ARCPATH had a major focus on fisheries and fisheries governance systems. As such, linkages between historical and contemporary data have been a significant element in the project. Correlations were found between fisheries and temperature changes in the North Atlantic back to ca. A.D. 1700. These data allowed for the occurrence of extreme weather events, such as increased storminess, and human adaptation responses in our study areas in the past (Ogilvie, 2024; Ogilvie and Sigurðardóttir, 2024)[a]. Clearly, a correlation exists between ocean temperatures and marine stocks. Therefore, although other factors were involved, it is highly likely that climate was of importance for the fisheries in several respects. If the weather was particularly stormy, for example, many lives were lost at sea, and more fishermen drowned during unusually cold and stormy periods (Ogilvie, 2024). The question as to whether current and future changes in climate will bring higher wind speeds and increased storminess was investigated (Sühring et al., 2023). Model simulations of future climate do indicate a slight increase in the number of days with greater wind speeds. Whether this could have a significant impact on fisheries and whale-watching tourism in the future is currently unclear. However, ARCPATH findings suggest that storms are an understudied climate-change factor for Icelandic fisheries that needs to be better understood in terms of their impact and consequent adaptations at the local level (Sühring et al., 2023). Although the presence of sea ice off the coasts of Iceland in the past had primarily negative effects (Ogilvie, 2010; Ogilvie et al., 2021b) some evidence suggests that ice fast to the coasts, as well as ice at sea, can ameliorate the destructive effects of storms (Semenov et al., 2019; Níels Einarsson, pers.comm.). These results are relevant for IPCC-related wave-modeling activities (Erikson et al., 2022; Morim et al., 2022) that focus on better prediction and diagnosis of changes in marine storminess.

Marine governance has had a focus on contemporary fisheries that included investigating the social and economic impacts of Individual Transferable Quotas (ITQs) systems in coastal communities. ARCPATH research found serious flaws in the design of this form of marine resource governance due to significant social, economic, and ecological externalities that are not sufficiently dealt with in policy design, implementations, and assessments. A major publication in the *Proceedings of the National Academy of Science* (Young et al., 2018) demonstrated that ITQs are panacea solutions to fisheries governance that need to be reviewed and potentially revised due to a range of negative social equity issues as well as a lack of flexibility and sophisticated ecosystem understanding. In fisheries management, or more generally, environmental governance, regulatory arrangements that are thought to be helpful in some contexts frequently become panaceas or simple formulaic policy prescriptions. When this happens, negative side effects are common.

One of the key goals of ARCPATH was to produce empirically based knowledge that could be of use to society at large, but in particular for stakeholders in fisheries and other marine-resource use sectors, as well as coastal communities based on making their living from the sea. As noted above, regarding marine tourism, ARCPATH focused on the expanding sector of whale watching. This is an enterprise that requires an interdisciplinary approach. It is highly sensitive to global processes, both in terms of biophysical forces, such as climate change, as well as the social and economic processes of globalization and cultural change. The project highlighted the need for a paradigm shift when it comes to valuing nature in terms of the ecosystem services of whales, and this new understanding has significant policy and management implications for future developments in the fisheries.

[a] Ogilvie, A. E. J., and R. Sigurðardóttir: Living with Ice, Fire, Sand and Floods: Responses to Natural Hazards in Early Modern Iceland. *The Oxford Handbook of Climate Resilience*, Dagomar Degroot, J.R. McNeill, Amy Hessl, Eds, Submitted.

Current and future interdisciplinary research

ARCPATH not only revealed the range of ecological, economic, and societal consequences caused by the rapid warming of the Arctic but also developed knowledge and capabilities to address these challenges. We deepened understanding of intricate social–ecological–climatic interactions and the need for interdisciplinary approaches. ARCPATH also improved the capability to predict climate on relevant timescales—seasons to a decade ahead. All of these aspects help to provide a basis for operational climate and ecosystem services to aid in climate adaptation and mitigation and achieve sustainable societies. Current projects continuing the ARCPATH ethos include NORSEACC[b], which is investigating the role of knowledge and governance in promoting resilience and adaptation to rapid environmental and social change in northern coastal communities. The JUST-NORTH project has considered how sustainable development can be met through the theories of justice and equity. The film and documentary INTO THE OCEANIC contributed to outreach work on climate change by illustrating marine changes in a novel way (https://www.intotheoceanic.org/outreach).

Continued progress requires an improved assessment of climate variability related to internal mechanisms and external forcing. The PARCIM project at the Bjerknes Centre for Climate Research addresses this by extending climate reanalysis back several centuries using palaeoclimatic proxy data. Historical archives can be used with these novel data to gain deeper insights into climate-ecological and social relations. The ICEHIST project takes ARCPATH historical climate research one step further in that, as well as focusing on historical data for Iceland and Greenland, the project will include auxiliary data, such as instrumental oceanographic measurements from coastal and shelf regions on timescales of one hundred years or more, e.g., in northern and eastern Iceland with the aim of testing the hypothesis that Great Sea-Ice Anomalies (GSIAs) were recurring events. A related project is ICEWHALE which considers social-ecological linkages between the presence of sea ice and whale strandings off the shores of Iceland in the past (https://www.svs.is/en/projects/ongoing-projects/icewhale).

Of critical importance is the need to continue improving climate predictions. More advanced methods that include machine learning are being developed to make better use of sea-ice data. Projects with this focus are based at the Danish state-funded National Centre for Climate Research and through the bilateral China-Norway project (4ICE). Theoretical approaches based on weather-climate interactions are being developed to advance the development and evaluation of climate predictions, through a Russian Megagrant in collaboration between Noel Keenlyside and another ARCPATH colleague, Vladimir Semenov. The use of large ensembles of predictions to provide information at regional scales using dynamical downscaling and machine learning is another key area that is being investigated in a large EU project (Impetus4Change) involving several ARCPATH partners.

When considering the legacy of ARCPATH and future directions in interdisciplinary research it will be crucial to continue to develop climate-marine ecosystem models and to co-develop associated services. This requires combining numerical climate predictions with marine ecosystem models, which is not only technically challenging but requires a more complete understanding of biophysical interactions. Such research has already begun in the Norges forskningsråd (Norwegian Research Council - NFR)-funded *Arven etter Nansen programme* (the Nansen Legacy Project) and the EU-funded TRIATLAS project. The development of useful services requires collaboration between natural and social scientists and interaction with stakeholders from both the private and public sectors. Promising initiatives in this regard have also begun at several centres around the world, including through the NFR-funded Climate Futures project and TMS-funded Bjerknes Climate Prediction Unit.

The interdisciplinary approach used in ARCPATH could be extended to a variety of linkages among human populations, climate change, and Arctic environments; for example, those associated with suggested social indicators such as: Health and Population; Material Well-being; Education; Cultural Well-being; Contact with Nature; and Fate Control (ASI, 2015). An example of this approach is the international Belmont Forum-funded RACE project, which focused on the impacts of rapid climate and environmental changes in the Arctic on infrastructure and pan-Arctic and regional population dynamics. RACE highlighted the need to understand the feedback between climate and environmental factors, infrastructure, and social indicators (such as the "climate–poverty-development (CPD) nexus" (Charles et al., 2019). This is vital for developing adaptation strategies and for the alleviation of major climatic and socioeconomic impacts on Arctic communities.

Summary

In summary, the combined expertise of ARCPATH team members (Fig. 2) created new knowledge on crucial Arctic issues by integrating information from several traditionally different disciplines. In seeking to synthesize results from such separate disciplines encompassing very different research methods, ARCPATH emphasized the need to go beyond the multi-

[b] The new and current projects mentioned here are referenced in the Acknowledgements.

Fig. 2. ARCPATH team members at the ARCPATH annual meeting held in Reykjavík, Iceland in October 2017. Yongqi GAO is in the front on the far left. Photograph courtesy of the Nordic House, Reykjavik.

disciplinary approach in which different aspects of a project are conducted separately, focusing instead on interdisciplinarity, where different research elements are integrated to provide greater insight into research questions and results where the whole is greater than the sum of the parts. Transdisciplinarity was also ensured through the inclusion of local partners and stakeholders. From the very start of the project, synthesis was an important goal of the research (King and Ogilvie, 2021). Communication was not always easy, but through perseverance and a willingness to listen and learn, by all members of the research team, the project resulted in an extremely successful example of the value of interdisciplinary research. In short, the highly successful ARCPATH project forms a testimony to Professor GAO's enthusiasm for embracing the spirit of interdisciplinarity. Although he was a natural scientist, in his final project, he found himself working not just with colleagues from his own field, but with new colleagues from many different disciplines along with research topics that were also novel. This willingness to accept new challenges may be seen as a measure of the man. Professor GAO's legacy will continue, not least through the numerous new and exciting interdisciplinary and transdisciplinary research endeavours inspired by ARCPATH.

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