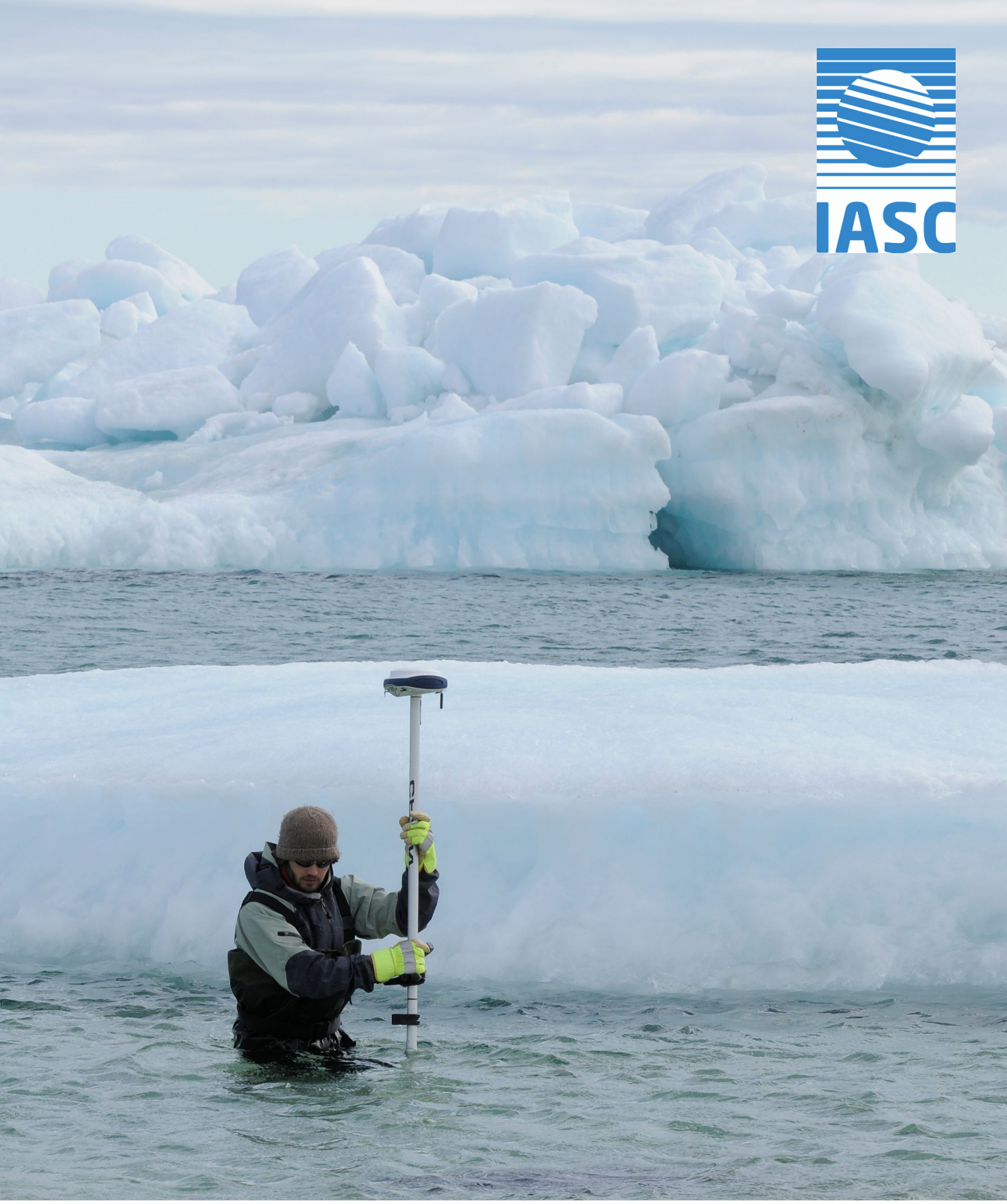

The International Arctic Science Committee´s

2021 STATE OF ARCTIC SCIENCE REPORT

Arctic Lands Acknowledgement

The circumpolar Arctic is the home to many different Indigenous Peoples. As researchers and others who are working in, or reside in, the Arctic we recognize these lands and waters as the mostly unceded traditional homelands of Indigenous Peoples. Wherever you may be reading this report, IASC honours and recognizes the place-based knowledge of Arctic Indigenous Peoples, and the ancestral and contemporary stewardship of their homelands. IASC encourages the Arctic science community to do the same.

It is the responsibility of each of us individually to learn, read, and gain better understanding of the Indigenous Peoples and cultures with which we engage. IASC encourages the Arctic research community to use their understanding to enhance engagement, partnerships, and co-production of knowledge with Indigenous Peoples.

IASC is also committed to recognizing that all knowledge and scientific systems (including Indigenous Knowledge, Traditional Knowledge and Local Knowledge), are equal and complementary, and should inform the work of IASC.

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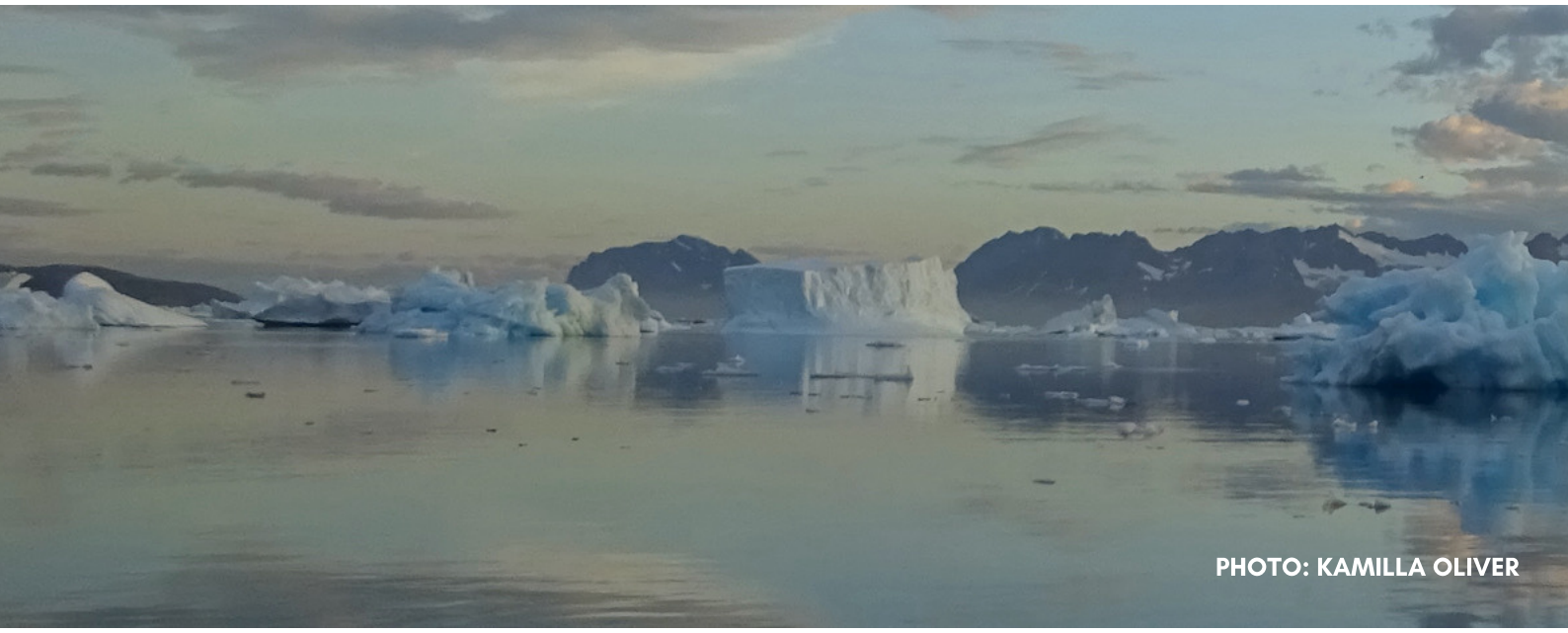


PHOTO: KAMILLA OLIVER

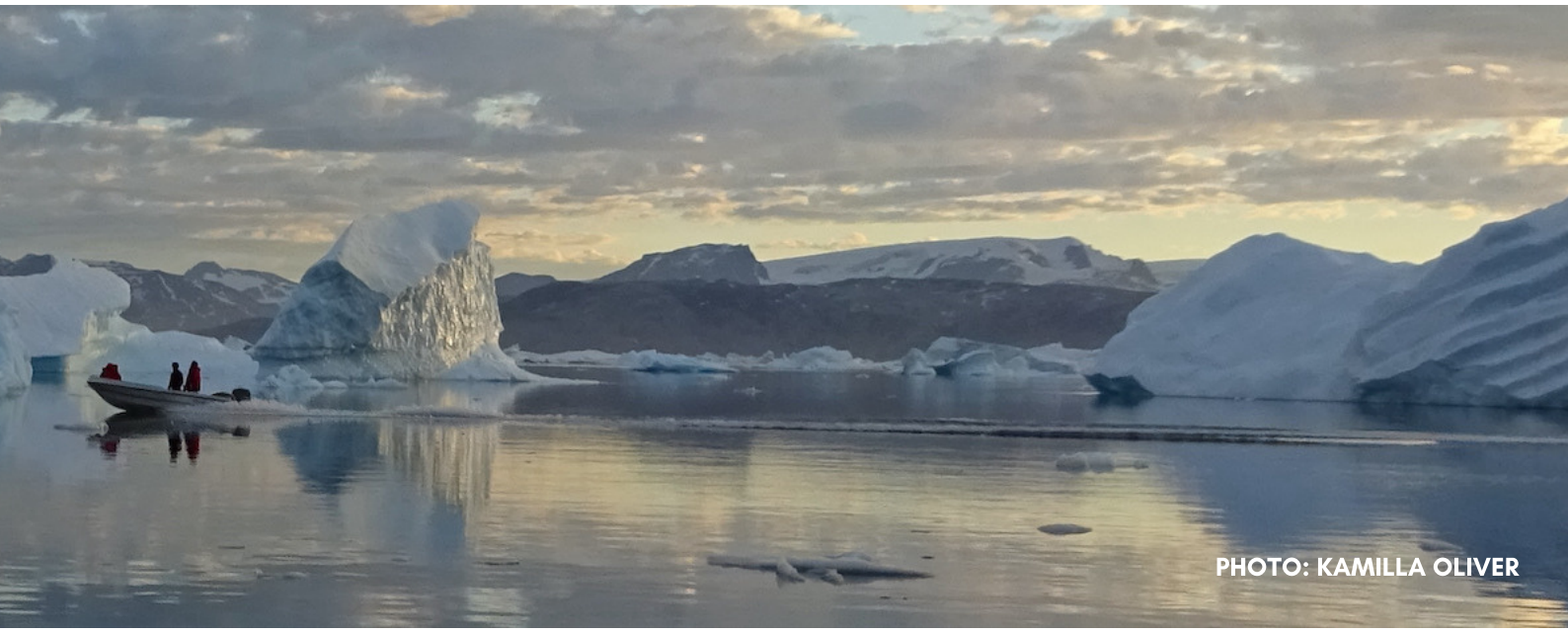


PHOTO: KAMILLA OLIVER

Introduction

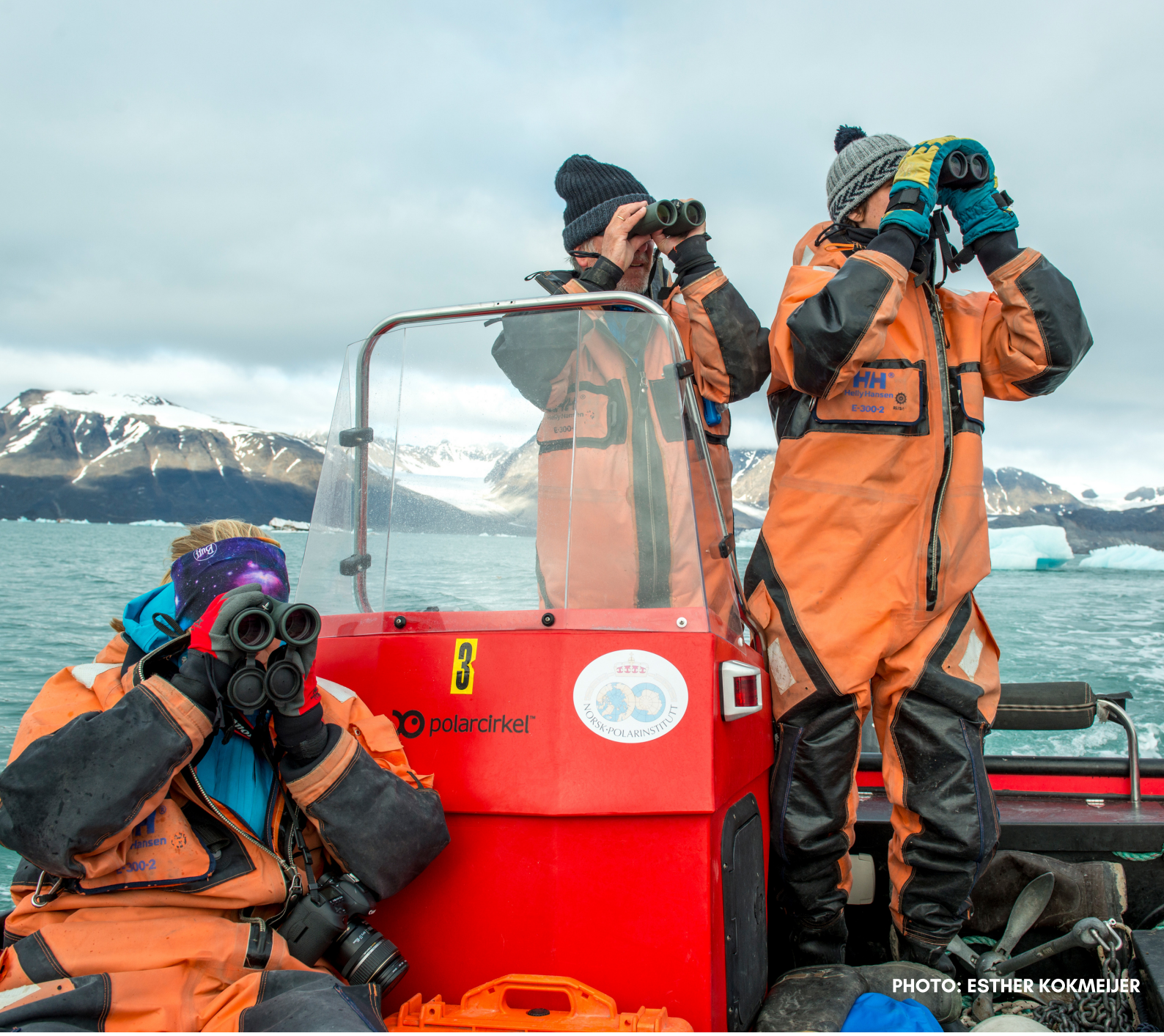
The International Arctic Science Committee (IASC) was founded in 1990 with a mission of encouraging and facilitating cooperation in all aspects of Arctic research, in all countries engaged in Arctic research, and in all areas of the Arctic region. IASC is a connector – connecting scientists and other knowledge holders across international, disciplinary, and cultural boundaries and connecting those who do research with those who apply the outcomes of research to inform solutions to Arctic challenges.

With rising temperatures, geopolitical interests, the initiation of the Arctic Science Ministerial meetings, and an increasingly active landscape of international Arctic (science) organizations, Arctic science is moving faster than ever. IASC is a network that responds to this rapidly changing environment and facilitates the collective voice of the international Arctic research community.

IASC is grounded in a community of scientists from its 23 member countries and aims to provide a consensus voice by reaching out to national communities, connecting internationally, and reporting out. The IASC State of Arctic Science Report presents a synthesis of a breadth of input and contributions. It was first published in 2020 and has now been updated for 2021 by members of the:

- **IASC Working Groups (WGs)** (Atmosphere, Cryosphere, Marine, Social and Human, Terrestrial) celebrating their 10th anniversary in 2021 (https://iasc.info/our-work/working-groups)
- **IASC Council** (https://iasc.info/about/organisation/council)
- **International Science Initiative in the Russian Arctic (ISIRA)** (https://iasc.info/our-work/isira)
- former **IASC Action Group on Indigenous Involvement (AGII)** (https://iasc.info/our-work/indigenous-engagement),
- **Arctic Data Committee (ADC)** (https://arcticdc.org/), and the
- **Sustaining Arctic Observing Network (SAON)** (https://www.arcticobserving.org/)

Every 10 years, IASC organizes the **International Conference on Arctic Research Planning (ICARP)** (https://icarp.iasc.info/), providing a forum for the Arctic research community to come together to discuss and identify priorities for international and multidisciplinary science. Initial planning has started for the fourth ICARP in 2025, and the IASC State of Arctic Science report series will provide an important resource for its planning process.



This report comes from the scientists themselves and is not exhaustive. There are many other NGOs, IGOs, institutions, non-profits, Indigenous Peoples' Organizations, companies, countries, and more working in the Arctic knowledge space that were not included in the preparation of this report. However, IASC´s intention is to include a wide range of stakeholders and knowledge holders in future versions of this report leading up to the ICARP IV in 2025.

IASC's State of Arctic Science Report is aimed at Arctic science agencies, Arctic science managers, and Arctic science users including a wide range of decision-makers and policymakers – e.g., national research councils and scientific foundations, Arctic ministers and ambassadors, international science bodies, and more. It is exciting to be able to learn from the insights of the Arctic science community, so please read on and also join IASC in thanking the community for their time and input.

Current Arctic Research Priorities

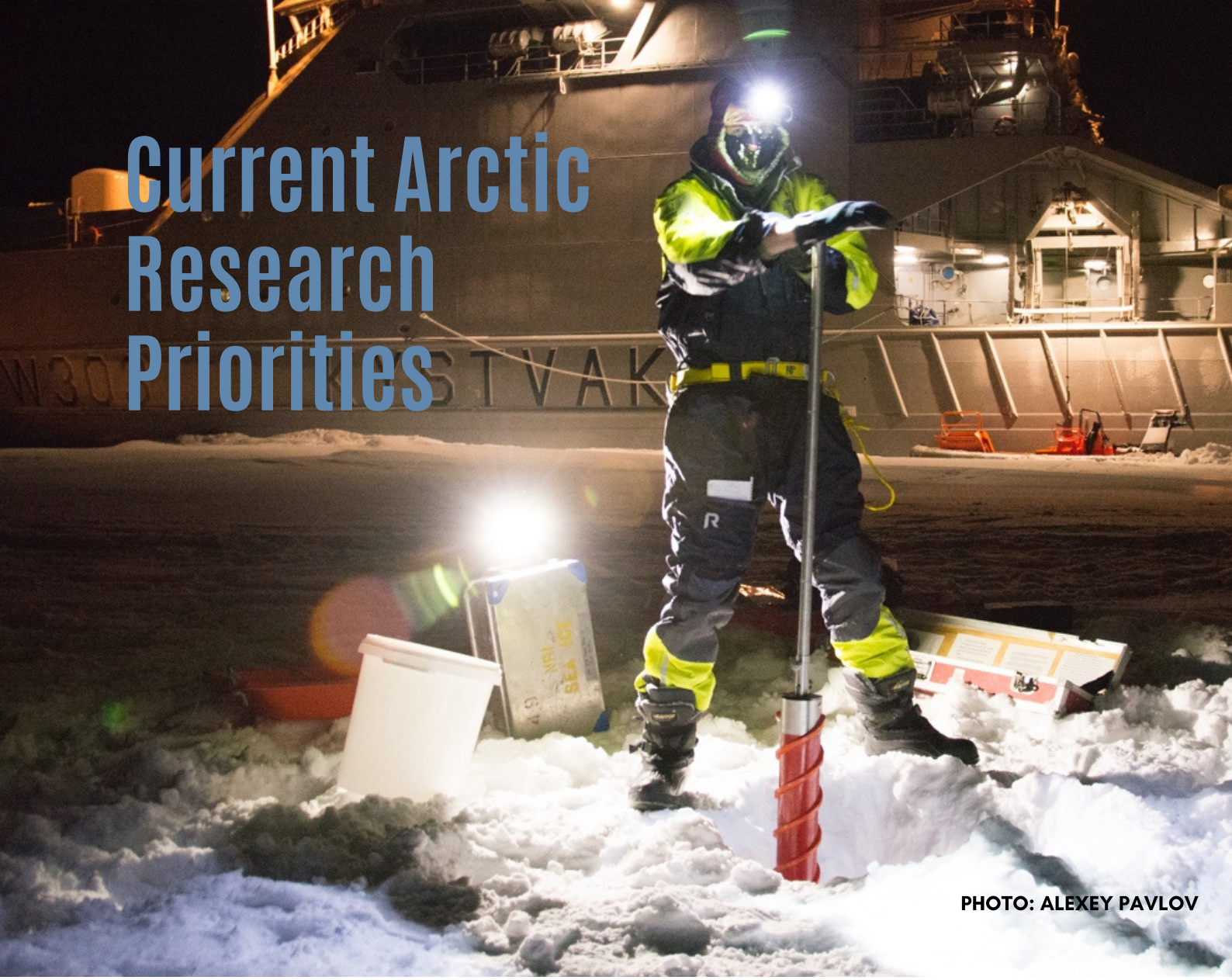


PHOTO: ALEXEY PAVLOV

Climate change is the predominant driving force for national research interests in the Arctic.

Research priorities can mostly be distilled into the following topics, with strong overlapping themes identified among nations. As organised below, IASC's research priorities are aligned with those outlined in its third International Conference on Arctic Research Planning (ICARP III) report "Integrating Arctic Research - A Roadmap for the Future." It is notable that themes are highly interdisciplinary not just at this summary level, but also at the IASC Working Group level. With the accelerating speed of natural and social changes in the Arctic, the research areas presented here update the ICARP III pillars to 2021.

It is interesting to note, though, that these priorities do not always flow from defined national Arctic research strategies. While some countries do have strategic plans, others do not have stated national Arctic research priorities or indeed are forbidden by law from doing so.

ICARP III Pillar 1: The Role of the Arctic in the Global System

- Improving understanding of connections between Arctic changes and mid-latitude & tropical weather, weather extremes, climate variability, and environmental processes
- Observing, understanding, and forecasting Arctic (environmental) change – especially using numerical coupled models.
- Improving understanding of Arctic amplification and Arctic climate feedbacks
- Climate change, including impacts on ecosystems (e.g., biodiversity, food webs, biogeochemical cycling, ocean acidification, permafrost thaw, sea ice loss, glacier melting, air temperature rise etc.).
- Developing new approaches to monitoring changes in the Arctic region
- Arctic radiation, energy, water, and carbon budgets – in particular, coupling between atmosphere, land, ice, and ocean.
- Contributions of Arctic ice sheets and glaciers to regional and global sea level
- Studying past environmental changes through the study of climate and environmental records (e.g., ice cores, lake and sediment records, etc.).
- Use of ecological and biological indicators to understand current and past Arctic changes.
- Resources (including minerals, energy, fish, subsistence, and more).
- Geopolitics, security, international law, and international relations in the Arctic.

PHOTO: SPENCER BROWN

ICARP III Pillar 2: Observing and Predicting Future Climate Dynamics and Ecosystem Responses

- Observing, understanding, and forecasting Arctic (environmental) change – especially using improved numerical coupled models.
- Sustaining and developing long-term data sets, including paleolimnological and paleoceonographical approaches to validate Arctic predictive models.
- Monitoring Arctic trace gases and aerosol-cloud interactions, motivated by the need to improve understanding of Arctic amplification and Arctic climate feedbacks.
- Investigate interactions and coupling processes at climate domain interfaces to improve understanding of Arctic amplification and Arctic climate feedbacks, and improve regional climate models.
- Monitoring long-distance pollution transport in the Arctic (metals, persistent organic pollutants, etc.).
- Monitoring of transports of heat and energy in the atmosphere and ocean into and out of the Arctic (warm air intrusions, cold air outbreaks, variability of Atlantic and Pacific water in- and outflow, sea ice and ocean freshwater export).
- Developing new observing systems and capabilities, including improving coordination with spaceborne Earth Observation programs (see New & Novel section).
- Monitoring future developments in the Central Arctic Ocean including but not limited to its sea ice cover, future fishing and transportation routes.
- Greening & browning of the Arctic (large-scale, as well as microhabitats)
- Life in (extreme) Arctic environments – disappearing ecosystems, resurrected ecosystems, and invasive species.
- The changing Arctic Critical Zone in the framework of geosphere-biosphere interactions and permafrost thaw.

PHOTO: SPENCER BROWN

ICARP III Pillar 3: Understanding the Vulnerability and Resilience of Arctic Environments and Societies and Supporting Sustainable Development

- Initiatives to better integrate Indigenous, Traditional, and Local Knowledge in research efforts and co-design/co-produce Arctic research strategies and projects with northern and Indigenous communities.
- Monitoring contaminants and pollutants (including plastics) in all parts of the Arctic environment.
- Improving understanding of the Arctic water cycle and its response to climate change.
- Understanding natural hazards and extreme weather (associated with climate change).
- Environmental sustainability, maritime technology, and shipping safety.
- Climate change, resilience, and adaptation.
- Health and wellness – community vitality, adapting to a new Arctic, (new) parasites, and holistic human-environment approaches.
- Gender and equality.
- History and archaeology.
- Coastal erosion and impacts on carbon cycling, infrastructure, communities, ecosystems, and more.

PHOTO: SPENCER BROWN

Major Ongoing & Upcoming Projects


PHOTO: ILYA ABRAMOV

International coordination is key for building impactful initiatives. Such collaborative projects currently ongoing or upcoming in the Arctic research community include, but are by no means limited to, the following:

- The expedition part of **MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate)** has been very successfully concluded. The one-year long drift with the Arctic sea ice on the research icebreaker Polarstern was a major multinational field experiment. It provides unprecedented multi-season datasets on high Arctic energy budgets, clouds, atmospheric composition, sea ice, ice-atmosphere interactions, ocean properties, ecology, biogeochemistry and more. The data analysis and inclusion in climate models has started and will continue for several more years. More information: https://mosaic-expedition.org/
- **T-MOSAiC (Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections)** extends the activities of MOSAiC to coordinate complementary activities relevant to coastal connections, terrestrial sciences, and Arctic communities. More information: https://www.t-mosaic.com/
- The **Year of Polar Prediction (YOPP)** aims to enable improvements in environmental prediction capabilities for the polar regions and beyond. More information: https://www.polarprediction.net/

- The **Synoptic Arctic Survey (SAS) and the Distributed Biological Observatory (DBO)** are projects coordinating Arctic marine observations for international and interdisciplinary benefit. More information: https://synopticarcticsurvey.w.uib.no/ and https://dbo.cbl.umces.edu/
- **INTERACT (the International Network for Terrestrial Research and Monitoring in the Arctic)** builds capacity and access to Arctic research stations. More information: https://eu-interact.org/
- **SIOS (Svalbard Integrated Arctic observing system)** aims to realize an international observing system for long-term measurements in and around the archipelago of Svalbard addressing Earth System Science questions. More information: https://sios-svalbard.org/
- **INTAROS (INTegrated ARctic Observation System)** is an EU H2020 project that aims to increase temporal and geographic coverage and usefulness of observational data in the Arctic. More information: https://intaros.nersc.no/
- **KEPLER (Key Environmental Monitoring for Polar Latitudes and European Readiness)** is an EU Horizon 2020 project that aims to prepare a roadmap for Copernicus (the EU´s Earth Observation Programme) to deliver improved capacity for monitoring and forecasting in the polar regions. More information: https://kepler-polar.eu/
- **EU-PolarNet 2** is the world's largest consortium of expertise and infrastructure for polar research. More information: https://eu-polarnet.eu/
- **Nunataryuk** is an EU Horizon 2020 funded project studying coastal catchments in permafrost areas, coastal erosion and impacts on carbon cycling, and science for socioeconomic adaptation. More information: https://nunataryuk.org/
- The Swiss-Russian-German expedition **ARCTIC CENTURY** onboard Akademik Tryoshnikov is planned for August and September 2021 and will involve 65 participants from Germany, Poland, Russia, Switzerland, UK and USA. An extensive interdisciplinary work program is to be carried out in the Kara Sea, the St. Anna Trough and in the NW Laptev Sea as well as with the support of helicopters to perform terrestrial investigations on Novaya Zemlya and Severnaya Zemlya. **ARCTIC CENTURY** will contribute to **SAS** and **T-MOSAiC**.

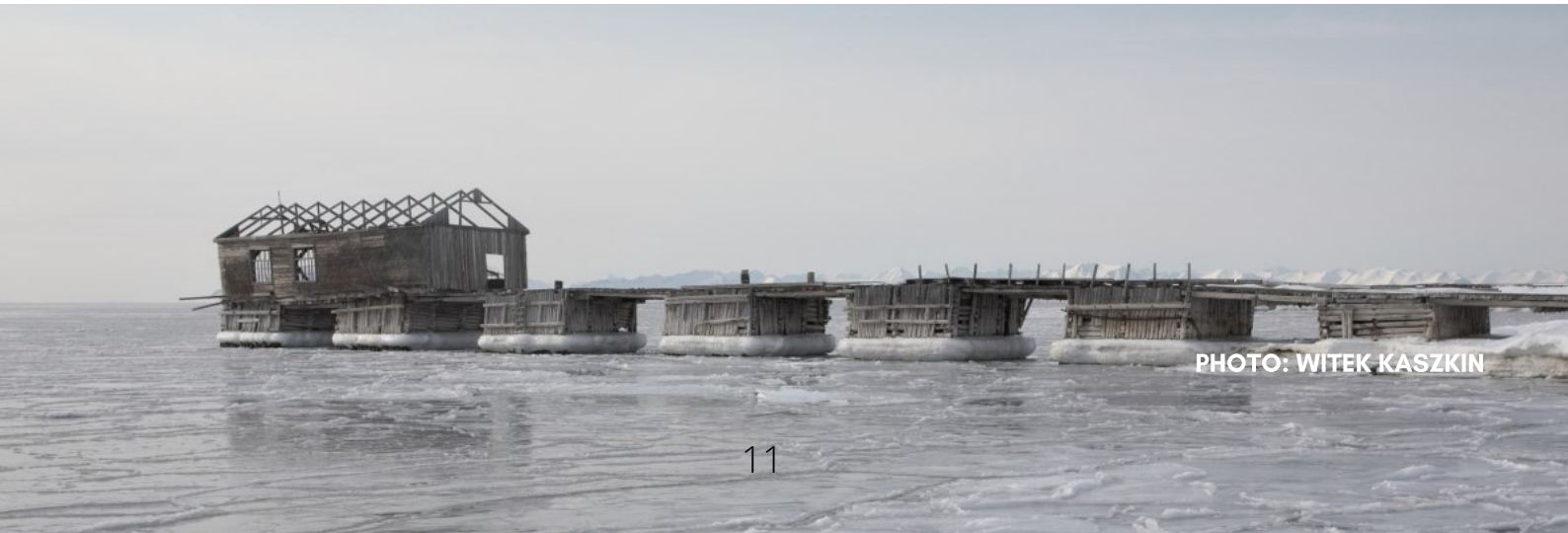


PHOTO: WITEK KASZKIN

- New international ice coring activities in Arctic and western Canada as well as Greenland provide deep climate change knowledge; these complement new projects in Antarctica, as well.
- Several new satellite missions (e.g. **NASA ICESat-2, EU Copernicus CIMR, CRISTAL, and ROSE-L, Jaxa AMSR3**) for monitoring Arctic environmental change and provide support for shipping and industry launched or under development.
- Several nations are undertaking model simulations for the forthcoming IPCC-AR6 as well as AMAP (the Arctic Monitoring & Assessment Programme) reports (e.g., projections of the whole Arctic region, Greenland Ice Sheet mass budget, atmosphere-ice-ocean interactions, and more). Many projects are also building insightful process-based studies to inform these models.
- The **International Tundra Experiment** studies effects of warming on vegetation and soil.
- **PolarRES (Polar Regions in the Earth System)** is a new EU Horizon 2020 project. It aims to provide new insights into key local-regional scale physical and chemical processes for atmosphere-ocean-ice interactions in the Arctic and Antarctic, their responses to, and influence on, projected changes in the global circulation.
- **CHARTER (Drivers and Feedbacks of Changes in Arctic Terrestrial Biodiversity)** is an EU Horizon 2020 project and aims to advance state-of-the-art knowledge on Arctic biodiversity change and social-ecological systems. More information: http://www.charter-arctic.org/
- **CRiceS (Climate Relevant interactions and feedbacks: the key role of sea ice and Snow in the polar and global climate system)** is an upcoming new EU Horizon 2020 project. It will deliver improved understanding of physical, chemical, and biogeochemical interactions within the ocean-ice-snow-atmosphere system that will lead to improved models that describe polar and global climate, enhancing the ability of society to respond to climate change
- The online **Polar to Global Online Interoperability and Data Sharing Workshop**, co-convened by the IASC-SAON Arctic Data committee is a bimonthly event that brings together polar researchers and Indigenous representatives to develop concrete guidance, standards, methods, and tools to make data FAIR (Findable Accessible Interoperable and Reusable). Significant progress is made towards an international standard for metadata sharing and catalogue federation.
- **JUSTNORTH** is a new EU Horizon 2020 project that investigates different dimensions of ethical systems and justice in the economic development in the Arctic. More information: https://justnorth.eu/
- The **EU Polar Cluster** is a network of EU Horizon 2020 and a Framework Programme 7 funded Arctic, Antarctic / Southern Ocean and Polar projects. More information: https://www.polarcluster.eu/

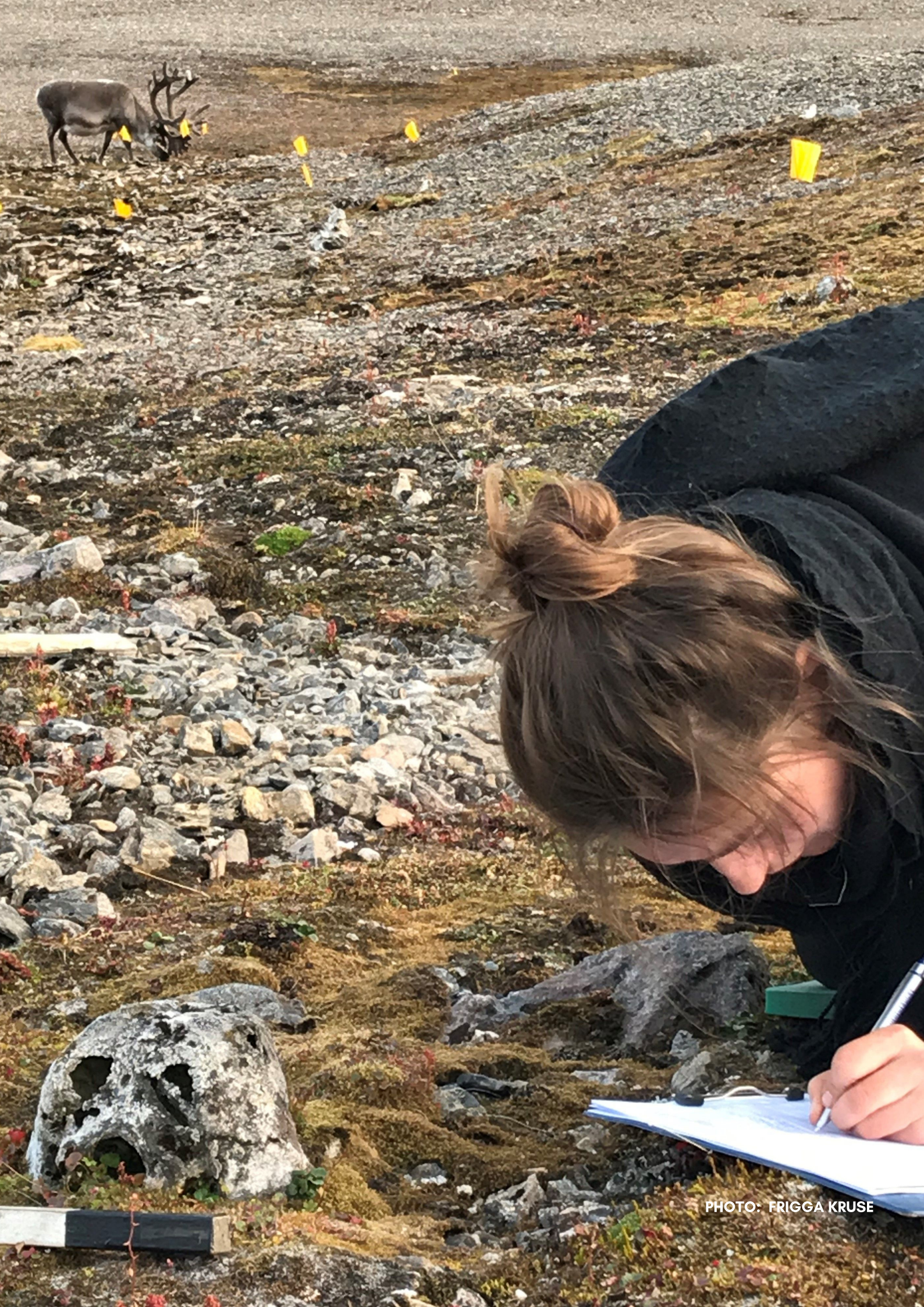


PHOTO: FRIGGA KRUSE

Long-term monitoring continues to be crucial to building improved understanding of the Arctic, and yet monitoring initiatives are still sparse in Arctic science. For example:

- Several programs at stations such as in Ny-Ålesund, Cambridge Bay, Zackenberg Station, Rif Field Station are studying atmospheric, ecosystem, Critical Zone, marine and climate variables.
- A special ice platform in Russia for long-term studies of atmosphere, sea-ice, and ocean interactions in the Central Arctic Basin is under development.
- Projects are monitoring migratory and native bird populations around the Arctic (e.g., Greenland, Svalbard, and Siberia) and around the world (e.g., Arctic Migratory Bird Initiative).
- The **Circum-Arctic Vegetation Map (CAVM)** is an international effort to map the vegetation and associated characteristics of the Arctic using a common base map, as an important point of reference for comparisons across the Arctic.
- The **Arctic Vegetation Archive (AVA)** is an international effort to consolidate and standardize vegetation plot data into a pan-arctic vegetation archive. This unique database will provide baseline data for species distribution and plant biodiversity analysis.
- Many monitoring projects in the Arctic harness polar-orbiting, globally observing satellites, this includes airborne and field calibration efforts at several Arctic test sites.
- **Greenland Ecosystem Monitoring (GEM)** is an integrated monitoring and long-term research program on ecosystems and climate change effects and feedbacks in the Arctic. The program has both a terrestrial and a marine component and is focused at two locations in West and in Northeast Greenland.
- Integrated **Carbon Observation System (ICOS)** providing high-quality European climate and greenhouse gas data – some sites in Scandinavia and Greenland

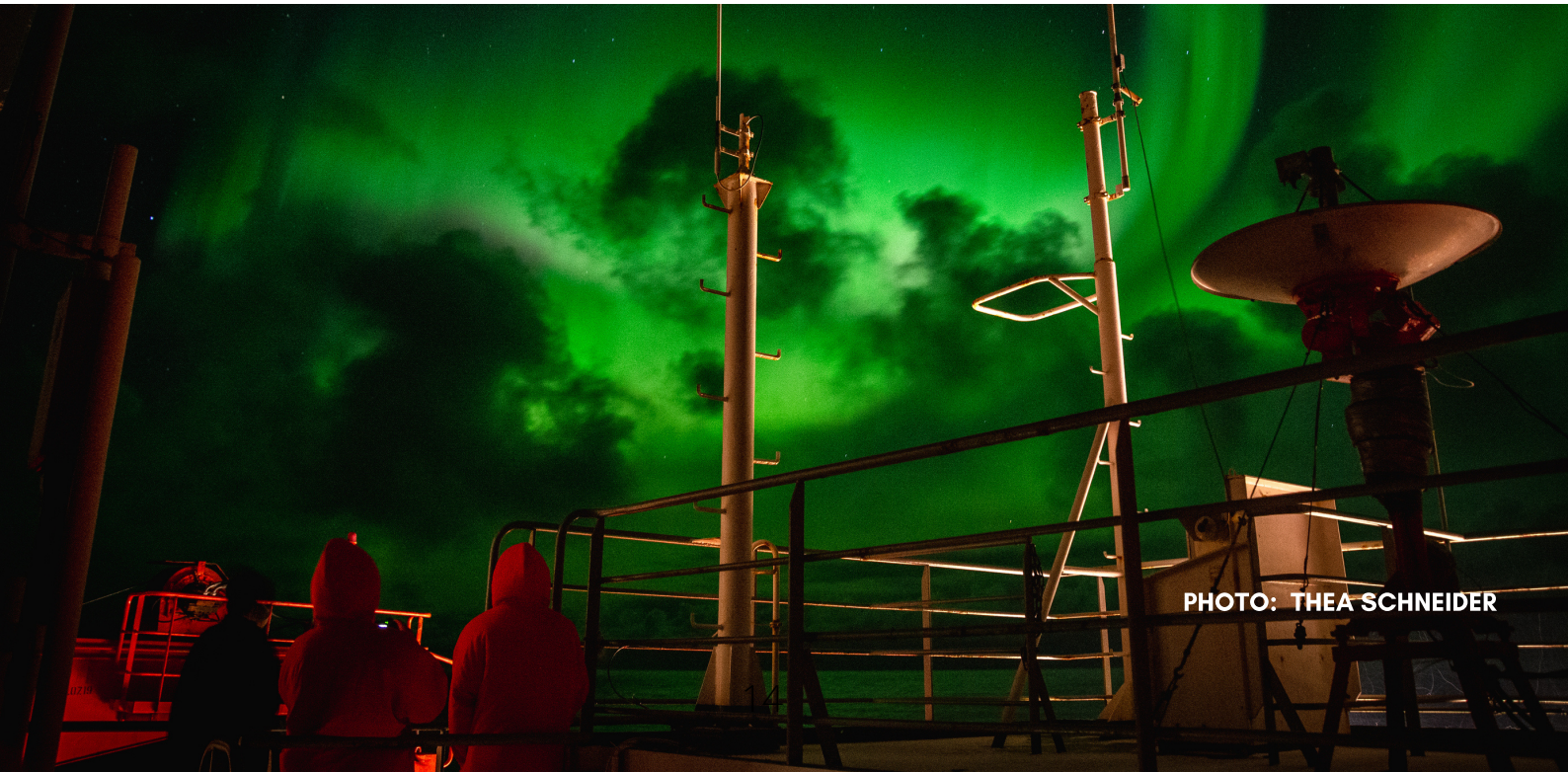


PHOTO: THEA SCHNEIDER

Members of the IASC Social & Human Working Group, in particular, highlighted a wide range of interdisciplinary projects and noted the increased demand for social and human perspectives in the work:

- There has been a shift in research project solicitations and funding streams towards more multi- and interdisciplinary scholarship (e.g., **Sustainable Cryospheres, the Horizon2020 funded project CHARTER and Face-It, and Navigating the New Arctic**).
- International, interdisciplinary projects focus on resource extraction, tourism, cross-border mobility, youth development, community & environmental sustainability, traditional economies, the roles of institutions in the Arctic, and more. **JUSTNORTH** is a Horizon 2020 EU project (2020 – 2023) designed to explore the multitude of ethical systems that coexist in the Arctic, as a starting point to assess the viability of new economic activities in the region.
- **Resource Extraction and Sustainable Arctic Communities (REXSAC)**, focuses on extractive resource industries in the Arctic as cultural, social, economic, and ecological phenomena, including what opportunities exist for transitioning toward post-extractive futures.

New & Novel Arctic Research

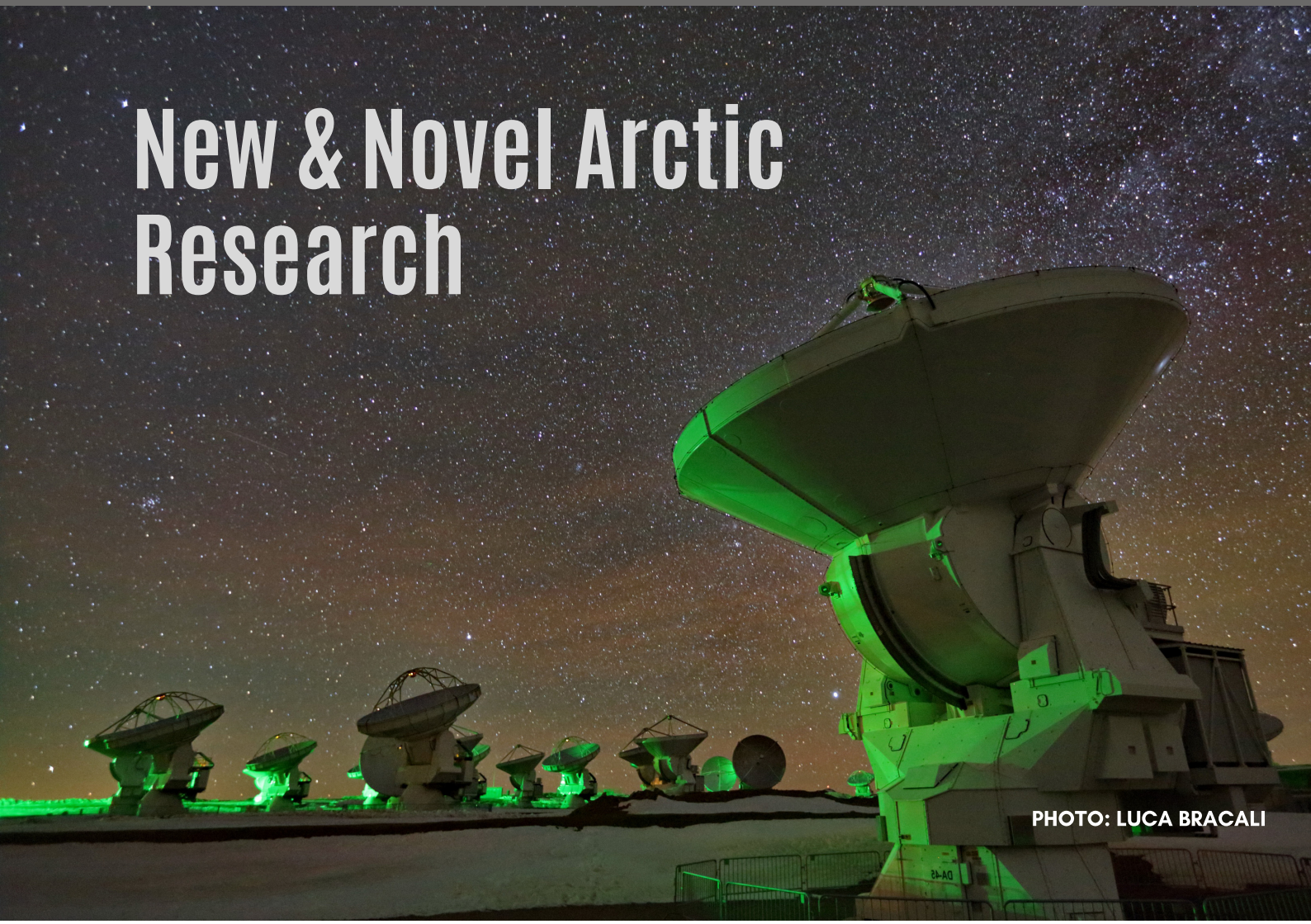


PHOTO: LUCA BRACALI

The most prevalent theme in novel Arctic research is the emergence and development of new technologies and capacities which facilitate more interdisciplinary efforts. For example:

- Using modern metagenomic and proteomic approaches to build better ecosystem and biodiversity understanding (both marine & terrestrial).
- Polar tree-ring dating, and climate studies are emerging tools which give insight into modern impacts of extreme weather events on terrestrial environments.
- Development of autonomous vehicles and observing platforms, like autonomous (under-ice) ocean monitoring with passive and active acoustics, gliders, drones and sail drones.
- The Arctic in winter can serve as a proxy for the frozen moons of Jupiter and Saturn.
- Novel isotopic measurement methods for trace elements such as mercury and osmium provide new insights for ice core climate studies as well as quantifying modern pollution.
- New, modern research stations in areas of northern Canada (Canadian High Arctic Research Station), Russia (special ice platform, Snowflake Station) will soon provide local logistical and laboratory support.

- Bioprospecting and biotechnology approaches are being applied to the Arctic.
- In Finland, the Aalto Ice Tank has been renovated to study wave propagation through sea-ice cover.
- In Svalbard, the establishment of new Critical Zone observatories for the interdisciplinary study of rock-soil-permafrost-water-biosphere interactions.

Remote sensing (both satellite and airborne) technology and techniques were highlighted:

- Historical archive data is being combined with current data to understand past changes.
- There is broad support for further development and use of unmanned airborne vehicles.
- Airborne laser ranging and high-resolution satellite stereo imagery are enabling studies of glacier mass balance and snow cover.
- Many countries are investing in new satellite platforms to improve observational and processing capabilities, which are complemented by on-the-ground measurements.
- Remote sensing of land- and sea-ice properties, in particular, were widely noted.
- Drone borne mapping and quantification of vegetation composition and biomass.

New methodologies and techniques are also enabling new science. For example**:**

- Methodologies for knowledge co-production in the Arctic: Arctic social sciences in collaboration with Indigenous and Local Knowledge holders and communities are well positioned to address this challenge and pioneer, transdisciplinary and post-disciplinary ways of thinking and knowing, but also about acting on that knowledge to co-produce and co-design sustainable and viable solutions for e.g., green transition under climate change. This entails more research focusing on developing start-ups, small scale entrepreneurship etc. in economic sectors such as culture, food, gastronomy, and tourism.
- All branches of sciences should be able to leverage Indigenous Knowledge in pursuit of new insights, respecting the Indigenous ownership of knowledge and the need for compensation of knowledge holders. It is also important to share research results to Indigenous and other local communities in an accessible format (including translations into the language spoken by the knowledge holders / community).
- Arctic social sciences in collaboration with Indigenous and Local Knowledge holders and communities.
- Convergent research: deeply interdisciplinary work focusing on addressing grand challenges and broad questions yields profound discoveries.

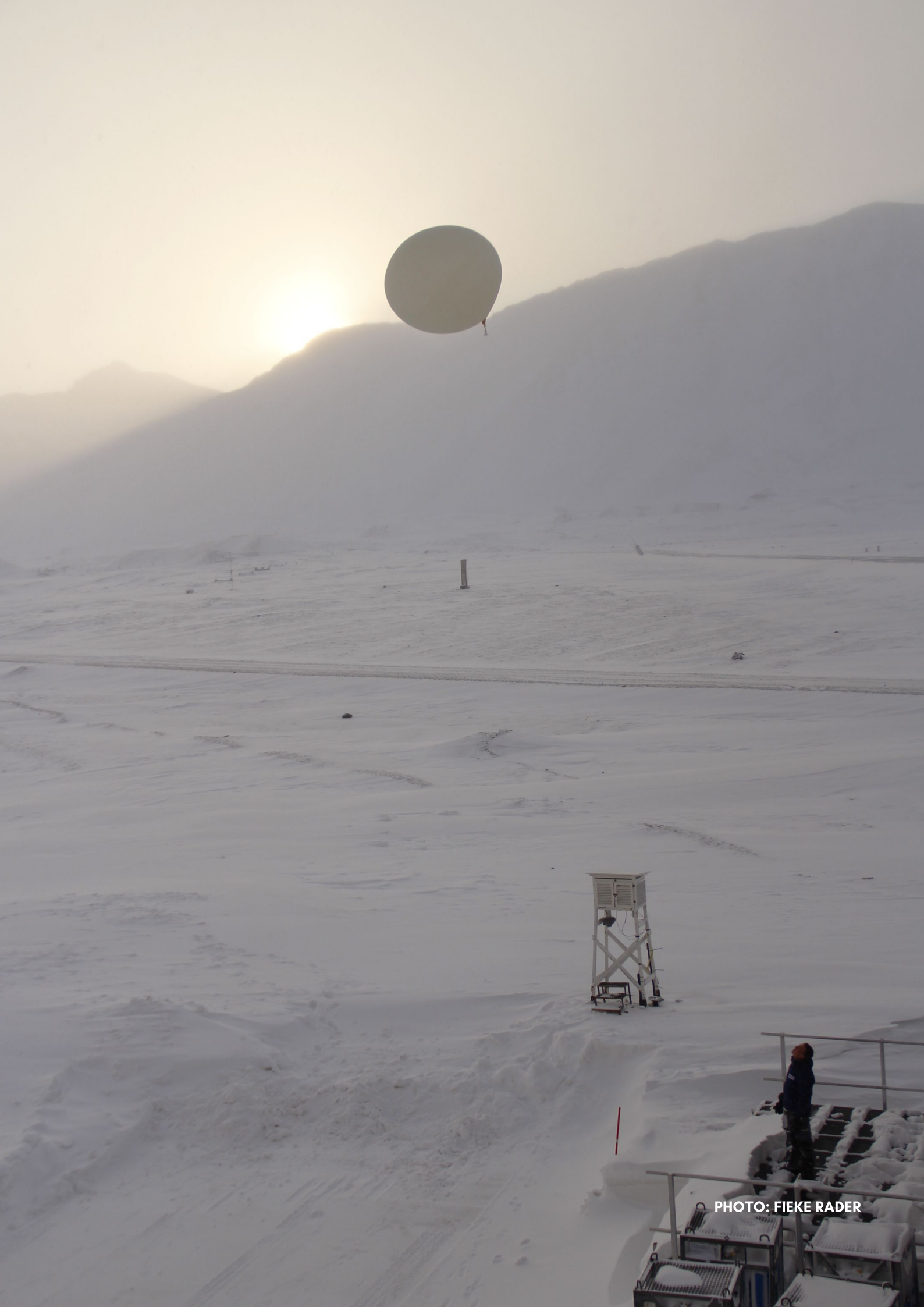


PHOTO: FIEKE RADER

- Uncertainty (emulation) statistical model analysis is being used to identify key weaknesses and uncertainties in climate modelling capabilities. This has applications, for example, to understand changes in the Arctic coastal environments and their relevance for safety and resilience of Arctic maritime transportation, offshore energy production, and fisheries; to improve prediction products; and to understand the value of additional Arctic data on quality of Arctic forecasts.

Emerging research themes include:

- **OneHealth:** a cross-cutting, interdisciplinary initiative recognizing the interconnection of human, animal, and environmental health has significant traction in the Arctic, especially within a context of sustainable development.
- Plastics in the (marine) environment.
- Research focusing on sea ice, particularly the shift from multi-year to first-year ice – and more generally, research on other transitioning systems.
- Investigations of the role ocean circulation plays in ice sheet mass loss in Greenland and its consequences for sea level rise.
- The growing influence of both Atlantic and Pacific inflows into the Arctic Ocean
- An emphasis on interdisciplinary approaches to understanding human-environment relations in the Arctic, with emphasis on assessments concerning economic systems.
- Air pollution in the Arctic, both as a driver of Arctic climate change and from the point of view of local sources and impacts – broadening the research on potential drivers of Arctic change and impacts on local communities.
- The effects of permafrost thaw and rising temperatures on the changes of the Arctic Critical Zone and corresponding impacts on natural resources.
- Intersectionality: focus on different/multiple experiences of marginalization to help elicit social inequalities in the Arctic.
- The role of extractive industries in society and resource extraction and sustainability
- Arctic Socioeconomic Amplification: feedback, amplification and loop effects between empowerment of Arctic communities & increased geopolitical/economic interest in the Arctic.
- Diverse other social science topics, including sustainable tourism and small-scale business development, mobility, connectivity, human rights, globalization, science diplomacy, and climate change effects on health in the Arctic.

Emerging Arctic Research Issues

PHOTO: THEA SCHNEIDER

Many of the areas of emerging Arctic research are nuanced and expanding upon the broadly stated priorities (above / ICARP-III).

Coupled Arctic Systems

- Arctic peoples are a key component of coupled Arctic systems, both as drivers of change and as persons who are impacted by the effects of Arctic change.
- Coupled Arctic systems include biogeochemical cycles and natural emissions; terrestrial-atmosphere carbon fluxes; relationships between atmospheric processes, ice, and ocean; coupling between the stratosphere and lower atmosphere; and understanding the role of Critical Zone dynamics and complex Arctic biological systems. Understanding how these interactions will respond in a warming Arctic is a priority.
- A better understanding of Arctic amplification is also emerging, both in the present Arctic and during past warming, as well as societal impacts of rapid warming.
- Improving knowledge of coupling between the Arctic and the large-scale global climate system, including mid-latitude – Arctic linkages, ocean and atmospheric heat fluxes, and tropical-Arctic linkages with respect to climate variability and via teleconnections

- Improved representation of interactions across system boundaries in regional and global models with a focus on the coastal zone.
- Understanding interplay of the biological pump, the marine food web, ecosystem stressors, and fish stocks (in the Central Arctic Ocean).
- Integrated ecosystem assessments - examining linkages between biodiversity and environmental change through space and time.
- Studying other processes like:
    - o Cryospheric controls on tundra nutrient cycling
    - o Fjord and ocean productivity
    - o Shifts in primary production in response to sea-ice and climate change
    - o Drivers and impacts of ocean acidification
    - o Drivers and impacts of permafrost thaw
    - o Coastal landscape transformation
    - o Impact of snow and ice dynamics on sea ice mass balance

Pollution: Sources, Sinks, and (Societal) Impacts

- Arctic aerosol and trace gases: Several nations have identified emerging issues around improving knowledge of Arctic aerosol sources and impacts in particular, including aerosol-cloud interactions, and in the context of local pollution sources and associated societal impacts. Wildfires as sources of Arctic pollution are also identified, as well as issues around the impacts and processing of mercury in the Arctic.
- In addition, the emerging issue of plastic contamination and litter in the Arctic and evaluation of the impact of plastics, emerging pollutants (such as UV filters in personal care products and pharmaceutical products), and pathogens were also mentioned by multiple countries.
- There are projects about air quality in the Arctic with observations of fine particulate matter (PM2.5).
- Expanded research in aspects of Arctic public health (e.g., pathogens & climate change).

Observing, Forecasting, Prediction, and Predictability

- Prediction of sub-seasonal to seasonal processes in the coupled Arctic system
- Supporting new and diverse Arctic research teams and participating in establishing new Arctic observing networks.
- Arctic scientists are making significant efforts to integrate different monitoring approaches and observing systems. Important coordination is promoted via the Sustaining Arctic Observing Networks framework and the Arctic Observing Summit.

- Machine learning and artificial intelligence for extracting information and identifying processes and feedbacks in big data sources associated with satellite observations and model simulations.

Societally Relevant Arctic Research

- The IASC Social & Human Working Group has a work plan that identifies scientific foci including Arctic residents and change; historical perceptions and representations of the Arctic; securities, governance and law; natural resource(s) / use / exploitation and development: past, present, future; and human health and well-being.
- Focus on resilience and adaptation of Arctic communities to climate change.
- Research ethics related to Arctic research – as well as data and metadata management.
- Healing processes, strategies for achieving spiritual strength, decolonization, reconciliation, and restorative justice, especially for Indigenous Peoples.
- Geopolitics and circumpolar governance, as well as Arctic legal governance.
- Gender equality in Arctic research.
- Arctic infrastructure including connectivity.
- Arctic economic and technological futures.
- Sustainability: Arctic sustainability in a global context, the UN Sustainable Development Goals and the Arctic, the politics of sustainability, just transitions to sustainability and sustainable Arctic cities.
- Societally relevant Arctic research results are provided to the working groups of the Arctic Council, their programs, and incorporated into their assessment reports.
- Building better dissemination channels of Arctic information to the public: for example, a growing number of citizen science projects with Arctic focus can help lead to a deeper understanding of the causes and consequences of climate and environmental change beyond the typical diffusion of scientific knowledge (e.g. the newly established International Arctic Hub in Greenland https://naalakkersuisut.gl/en/Naalakkersuisut/Departments/Forskning-Miljoe/International-Arktisk-Hub)
- Tourism and environmental effects of tourism in the Arctic.

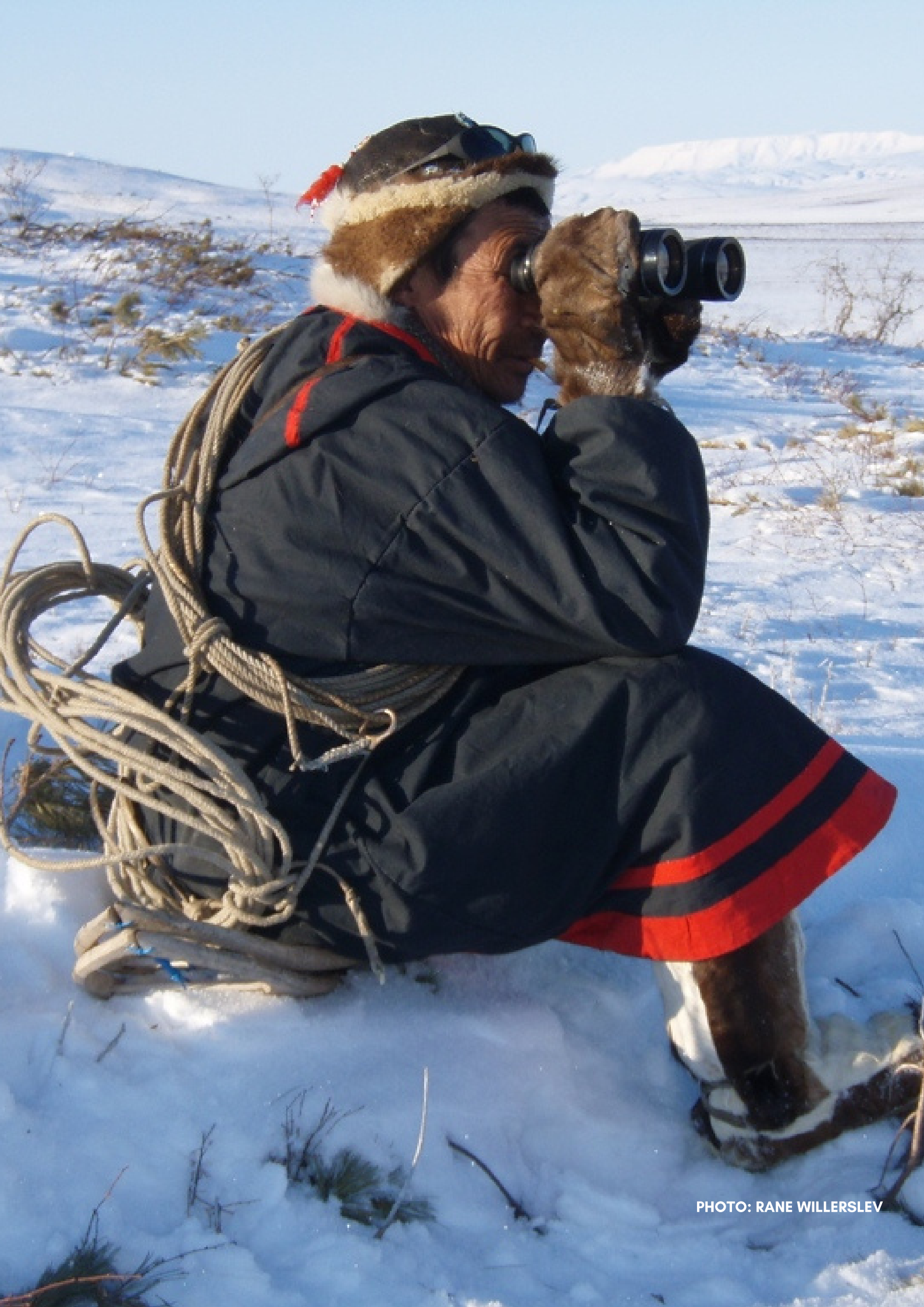


PHOTO: RANE WILLERSLEV

Current Gaps in Research and/or Data

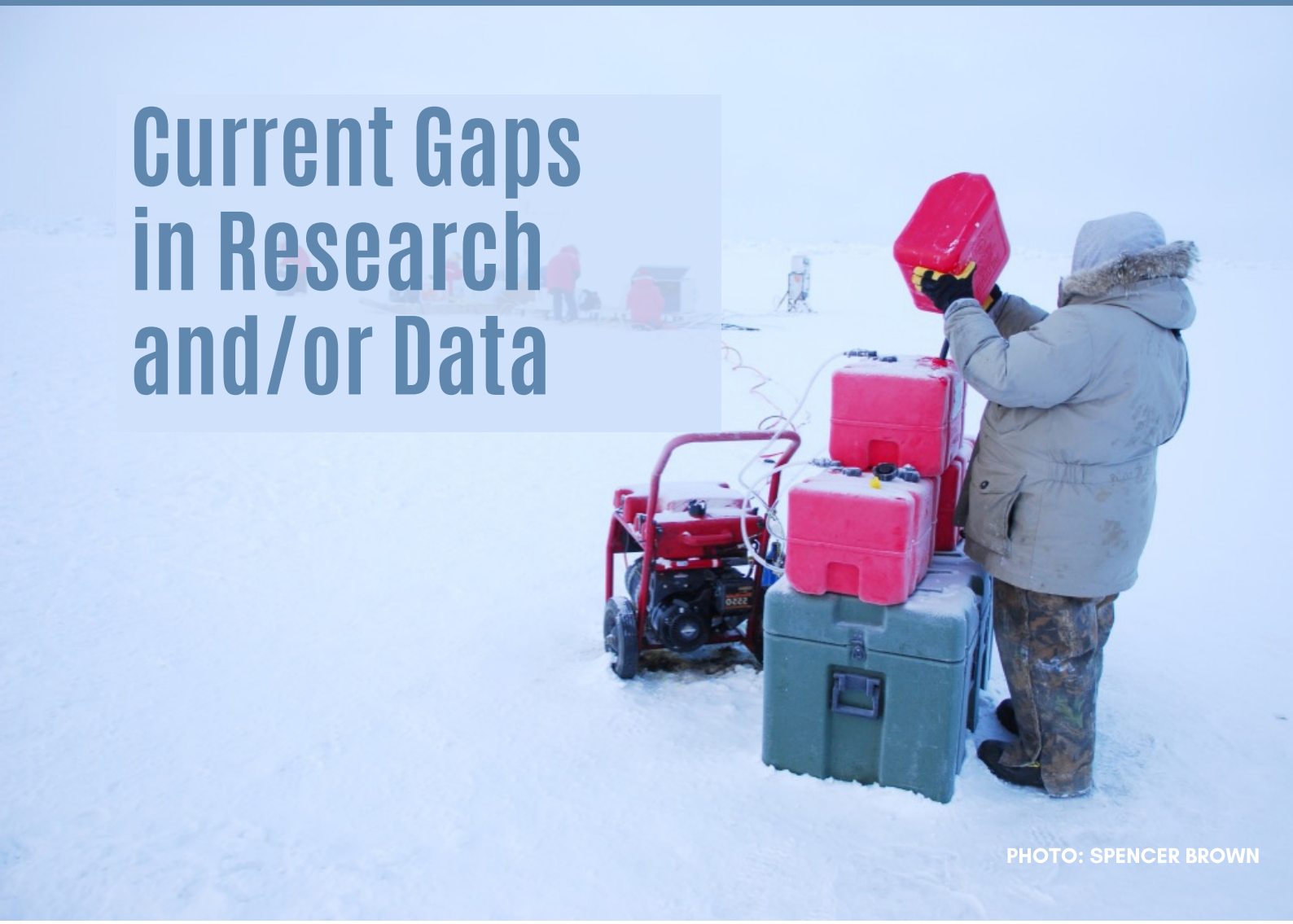


PHOTO: SPENCER BROWN

There is a recognized need to develop an integrated observing network for the Arctic and to make Arctic data and metadata more easily available internationally. There is a need to design or refine monitoring programs in support of societal benefit, including fundamental understanding of the **Arctic system. SAON´s Roadmap for Arctic Observing and Data Systems (ROADS)** proposes to develop broadly beneficial implementation strategies that are organized around **Shared Arctic Variables (SAVs)**. Such an approach is intended to merge the needs and extend the benefits of the observing and data system across Indigenous communities, researchers and decision-makers in the region and globally.

The **Arctic Horizons Report** (a community workshop report funded by the US National Science Foundation Arctic Social Sciences Program) points out that, "The Arctic is a testbed for interdisciplinary research, a 'critical region of inquiry.' ... This research takes place at multiple scales ... and requires that we work across disciplines and regions; the local and the global both need to be supported, and the places of their intersection located."

Spatial (and Temporal) Coverage

While field stations facilitate research, research infrastructure also limits Arctic science. Cross-site comparisons are needed to determine how generalizable individual findings are.

- Spatial coverage in ground-based network measurements is lacking. Data coverage and availability of data from the Russian Arctic, including Siberia are particularly lacking.
- Research gaps include the Central Arctic Ocean (and the related potential for fisheries), as well as other areas of the Arctic with limited data coverage, such as the East Siberian Sea and Canadian Arctic waters. More studies like MOSAiC are needed there that address the coupled atmosphere-sea ice-ocean system and feedbacks with the ecological and biogeochemical systems.
- The longer-term need to develop year-round sampling capabilities and sampling of the land-sea interface was also mentioned by multiple countries.
- Widespread and regular atmospheric vertical profile information is severely lacking.
- Limited coverage of some satellite observations at high latitudes. The area close to the North Pole (the so-called Pole Hole at typically 87-88°N) is not observed by most sensors but becomes increasingly important in an Arctic with less sea ice.
- There is a lack of cloud and lower atmosphere measurements (e.g., energy budget, aerosols) outside the summer 'fieldwork' season.
- It is important to bring consistency to the study of the heterogeneity of physical ground properties (soil, water, snow etc.), which increases the uncertainties of future projections of permafrost.
- There is a need for reliable measurements in order to predict on a sub-seasonal-to-seasonal basis sea-ice thickness at high resolution over large spatial scales.
- In glaciology, data are very limited for constraining ice motion at high elevations on the Greenland Ice Sheet, submarine melt rates at tidewater glacier termini, densification of firn, and seasonal cycles of snow mass and associated long-term, seasonally resolved measurements within glacial fjords and adjacent shelves.
- Long-term observations, research continuity, and comparative analyses in all disciplines are needed.
- Improved understanding of the spatiotemporal patterns of Arctic climate change, including meteorological observations, paleoclimate data, reanalysis products and climate models, is needed to quantify regional patterns (and drivers), as well as the impact of Arctic changes on global climate.

Interdisciplinary Data Exchanges

- There is a need for enhancing cross-disciplinary understanding and exchange of data across many disciplinary boundaries. Interfaces where improvements could be made include atmospheric and cryospheric disciplines, terrestrial and cryospheric research, oceanographic and cryospheric science, sea-ice science and biogeochemistry, permafrost science and microbiology, whole-system Critical Zone processes, and observations and numerical simulations, to name a few.
- Indigenous knowledge is an important component of cross-disciplinary understanding that contributes to interdisciplinary exchanges.
- It is important to improve collaboration of research groups studying (High) Arctic landscape system transformation related to climate change; coordinated ecological, cryospheric, atmospheric, and hydrological monitoring are necessary to improve understanding of Arctic change (e.g., tundra greening/browning and climate change).
- There are few hard-rock geoscientists in many Arctic science collaborative communities.
- There is a need for multi-component (land, ice, ocean, atmosphere) integrated observations and models of coupled coastal zone dynamics and processes.
- Research that is multi-, inter-, or transdisciplinary needs more time and adjusted funding schemes to mature than standard disciplinary projects. This is specifically true for projects that include Arctic communities or other stakeholders.
- In a decolonial research setting the ownership, control, access to and possession of data must be tackled in equity-based exchanges between Indigenous rightsholders and scientists.
- Information, data curation, management and the FAIR principles regarding data sharing are key. There is a need to save legacies of polar science and make them accessible by ensuring access to documents and data, developing databases of scholarship and scholars, and respecting data sovereignty.

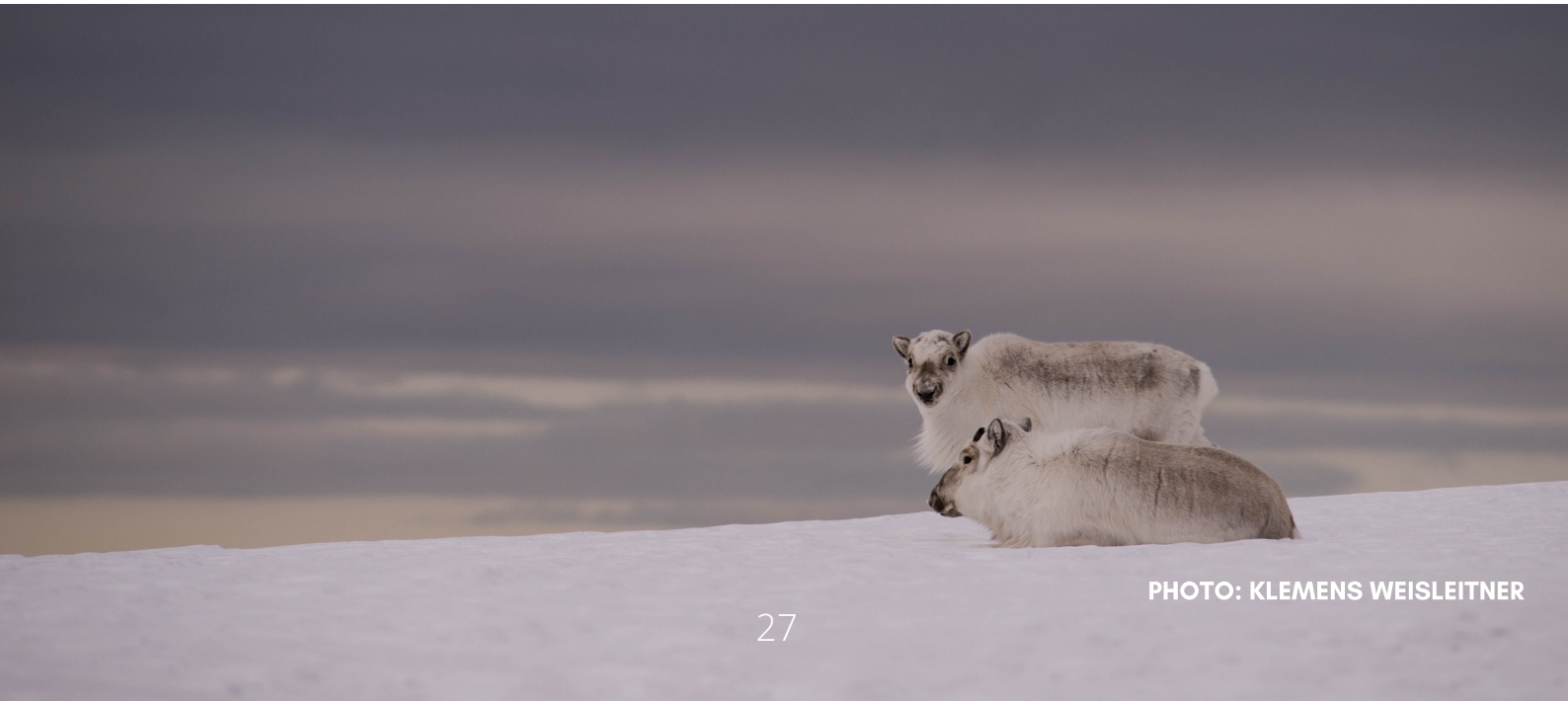


PHOTO: KLEMENS WEISLEITNER

International Data Sharing

- Special attention is needed for supporting international efforts to make Arctic data and metadata easily accessible, with the implementation of web portals and archives (e.g., within international networks such as **INTERACT,** permanent data archives such as **PANGAEA,** and research infrastructure such as **SIOS**) to facilitate data access.
- There is only limited consistent and one-point access for meteorological archive date, although Arctic reanalyses are now available (e.g. **Arctic System Reanalysis** and **European Copernicus Arctic Regional Reanalysis**).
- Data sharing and in-situ data access are not universally available across the Arctic.
- While coordination has improved in the data management community in recent years, there is a need for connecting the research community to those efforts and related activities.
- There are many efforts working to coordinate and align data (e.g., the **Polar Data Forum, the Arctic Data Committee, the recently EU-awarded Arctic GEOSS initiative, SIOS, INTERACT**, and many others) but insufficient funding and personnel relative to the scope of the task are available to be able to support implementation and follow-through.

Research Approaches & Infrastructure

- International scientific cooperation is underway in many research areas and there are numerous examples of joint and multi-lateral programs, but the need for infrastructure support (e.g., innovative technologies, new icebreaking platforms, etc.) remains clear.
- There is a lack of base funding, funding stability, and prioritisation of sustained baseline monitoring.
- Arctic scientists should further build cross-disciplinary, interdisciplinary, and convergent research practices.
- There is a further need for increased emphasis on co-producing research with Indigenous, Traditional, and Local Knowledge holders, for recognizing and validating the priorities of Northern residents and communities, and for more engagement of scientists in Arctic community vulnerability assessments. This will require a commensurate emphasis on research ethics and data sovereignty, but also on capacity building.
- Often, there is limited Northern infrastructure and capacity; many research projects still require equipment, labs, personnel, and training from lower latitude institutions.

Focus on Transitions in Arctic Natural and Human Systems

- Ongoing environmental change is a feature of the (modern) Arctic, and it can be anticipated that all of its spheres will be dramatically transformed within this century. It is an enormous challenge just to document these transformations – let alone to act on them in a manner informed by science. Although many countries prioritize Arctic research, the current levels of monitoring and research are clearly insufficient to meet these challenges.
- Increased connectivity in the Arctic transforms the research Arctic scientists can do, as well as the lives of Arctic residents (e.g., communication, mobility and telemedicine).
- Long term ecosystem monitoring and sustainability impact assessment of natural resources in a changing environment are important in the Arctic in order to understand the roles and functions of resources in supporting sustainable development and resilience in the Arctic.
- What impacts do new influences or technologies (e.g., expanded tourism, renewable energies, multimedia, digital communication, improved infrastructure) have in the Arctic? What is the impact of increased regional autonomy and Indigenous empowerment? How should these changes be contextualized by colonial pasts and present? What does a just transition to sustainability look like in Arctic communities?

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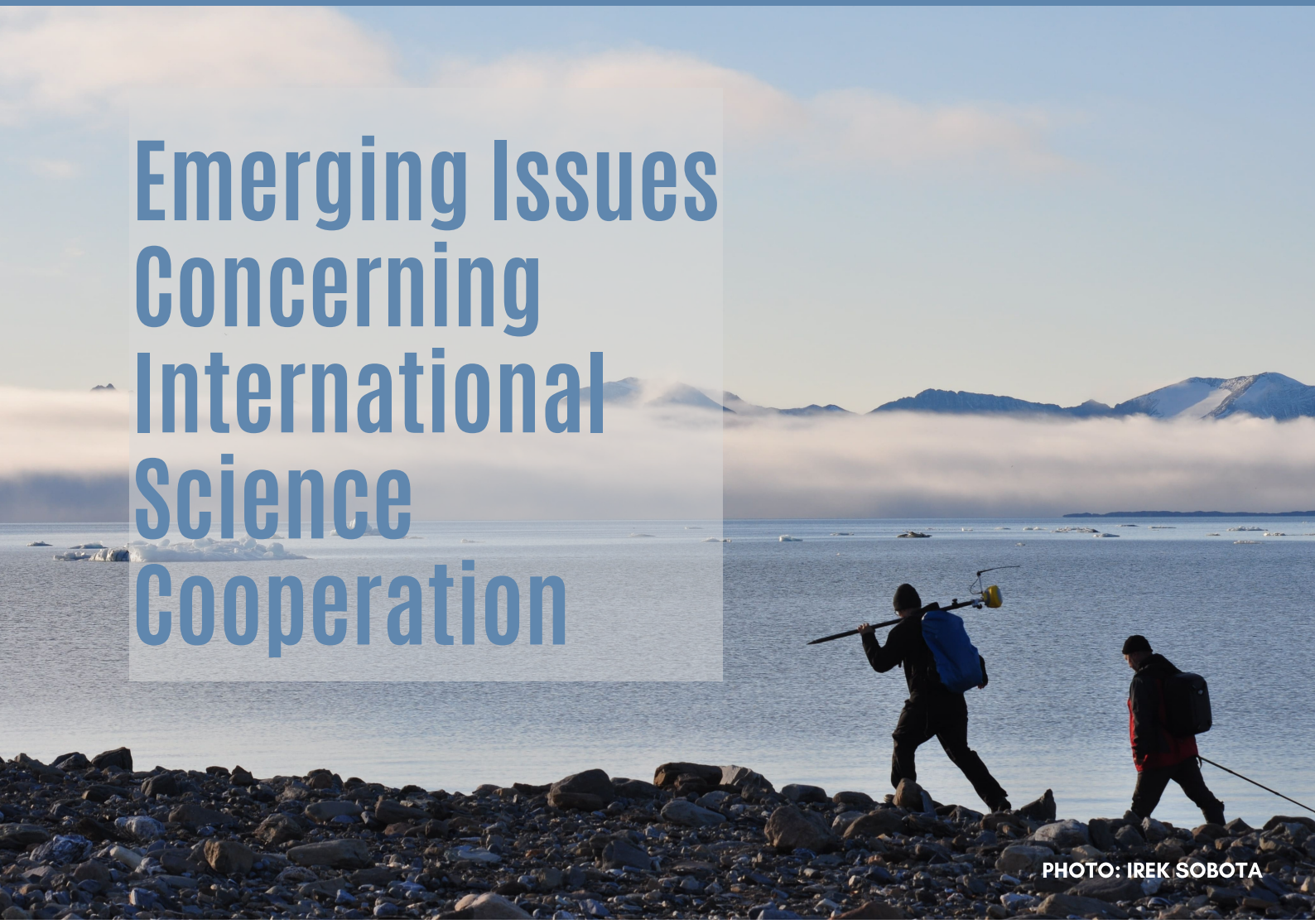


Emerging Issues Concerning International Science Cooperation

International cooperation is absolutely key to studying Arctic systems, many of which know no boundaries. Arctic systems involve the inhabitants of the Arctic who should be involved as stakeholders in international science cooperation, in particular Indigenous rightsholders' organisations. Arctic research does and should continue to involve extensive international collaboration, and barriers, including political boundaries and socioeconomic disparities overcome.

Science Planning & Coordination

- International cooperation is critical in developing widespread networks with comparable measurements. However, outside of the main long-term surface observatories, international cooperation often remains largely opportunity driven and less strategic.
- Institutionalized cooperation is rare and information at times hard to find.
- Improved collaboration among East Asian, European, and North American nations, as well as countries with emerging Arctic interests such as India and Singapore, are of value to maximize joint benefits and avoid duplicated efforts.

- **SAON** provides an on-going vehicle for collaboration on Arctic observing and data systems. It is now strategically partnered with several funded efforts to support the implementation of its 10-year Strategic Plan.
- Support for bilateral connections between non-Arctic institutions and field stations in Arctic countries is a promising place to start.
- **MOSAiC** is an important success story in developing a major multi-disciplinary and international field project to deliver unprecedented data and science from the bottom-up but ensuring that international critical mass and momentum is maintained is a major challenge.
- There is growing cooperation in international research initiatives via Horizon 2020 projects. **INTERACT** and the **Arctic Research Icebreaker Consortium (ARICE)** connect researchers around the Arctic. SIOS promotes integration along the Svalbard Archipelago. The **Pacific Arctic Group** is also an effective mechanism for improving international cooperation. Yet, other means of providing for cooperation among institutions in different countries are needed.
- The new **Roadmap for Arctic Observing and Data Systems (ROADS)** process was designed and developed by SAON as an approach to coordinate observations based on shared societal benefits and provide clear inputs to funding agencies as well as policymakers.
- Coordination organizations and research infrastructure bodies (polar clusters, polar boards, the **Forum of Arctic Research Operators, IASC**, etc.) are important for engaging the breadth of the Arctic research community and reduce the risks arising from fragmentation.
- Arctic inhabitants are not only facing rapid socio-ecological change but are relevant partners in international science activities in providing Local and Indigenous Knowledge to researchers for co-creating understanding changing Arctic systems. Such collaborations in both the natural and social sciences need to be actively improved.

Funding

- It is challenging, but crucial, to align national funding mechanisms to enable large multinational efforts. International collaborations are limited when there is a lack of international funding vehicles. The **EU framework** and **Svalbard Science Forum** are examples of effective mechanisms to support international programs. Joint funding calls from two or more national funding councils would be very helpful (such as the recently announced **UK-Canada Inuit Nunangat** and **Arctic Region Research Programme**). The Belmont Forum facilitates funding by using a framework guided by individual national needs, but it is also inherently limiting because such decisions on research priorities can lead to overly complex and elaborate approaches

- The nascent **Arctic Science Funders Forum**, an outcome of the 2nd Arctic Science Ministerial, is a multilateral discussion platform to coordinate, enhance, and initiate new collaborative scientific activities in the Arctic; it also aims to be a gateway for information about international funding calls for Arctic research.
- Funding for the engagement and participation of Indigenous people in research planning and executive is critical to equitable outcomes yet identifying funding mechanisms for this support continues to be an issue.
- ·Participation in strong international research networks has been and will continue to be essential for small nations and countries with developing Arctic research programs.
- Bilateral programs (e.g. the **UK-Canada Arctic Bursary program,** introduced in 2017, or the **UK-NERC Changing Arctic Ocean Program** with bilateral funding and projects between the UK and Germany) have been highly successful in stimulating research and collaboration. Through the German **Federal Ministry of Education** and **Research and the Russian Ministry of Research**, a number of joint research projects and expeditions on marine and polar research have been and are being funded.
- Recruiting and retaining diverse researchers is a critical challenge for Arctic science. One approach is creating knowledge exchange opportunities, such as Fellowship programs.
- Funding remains tight for the maintenance/continuation of (long term) observational networks despite being considered a high priority.
- The lack of funding for the inclusion of Indigenous rightsholders and for enabling co-production of Arctic knowledge must be tackled. Funding schemes must be established that transparently support the participation of non-academic stakeholders and Indigenous rightsholders in a transdisciplinary manner.
- There is a growing need to strengthen national funding efforts in relation to Arctic research.
- The lack of funding programs and streams within Arctic research funding structures that support international collaborations in social sciences, humanities, and/or interdisciplinary work. Without addressing this gap, advancing social sciences, health research, and humanities scholarship in the Arctic will be, at the very least, challenging.
- There is a need to continue to support excellence in scientific research, on Arctic/polar topics, as well as in related areas. This can be done by encouraging emerging sound practices, such as the sharing of data, field methodologies, and access to research stations, but most importantly by funding national and international projects based on open calls to which a broad array of research groups can apply, and which can be evaluated based on scientific criteria and merit.
- Apart from some topics that require major investments, it is vital to support small to medium-size projects that enable the development of innovative research questions.

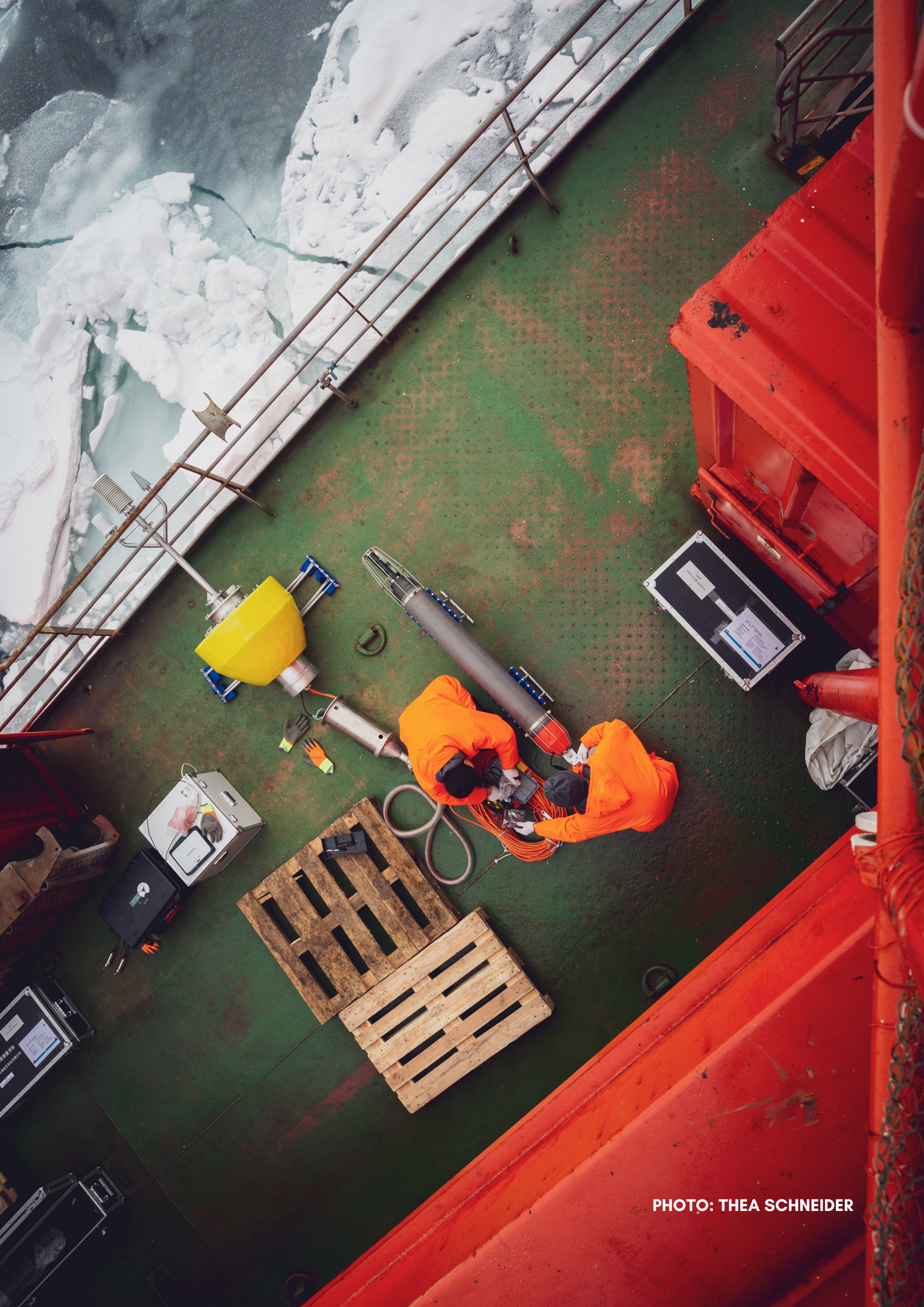


PHOTO: THEA SCHNEIDER

Access

- Access to data and objects, including acquisition, collection, transportation and repatriation of data, information, historical materials, archaeological artefacts, etc. is another key issue. Cross-border and sometimes intra-country mobility of data and objects can be difficult or impossible, which impedes knowledge discovery. Collaboration with Indigenous rightsholders has to be sought to conducts culturally appropriate research on these sensitive topics.
- Physical access to communities, and frequently a long-term presence, are necessary for most social science research; this remains difficult in many current funding structures.
- Open and timely data sharing is growing and critical. Yet, data management remains challenging. It is important to ensure common data policies and practices across nations, as well as to provide funding and resources to enable broad access to data.
- Providing platforms and protocols for scientific cooperation, including data and metadata sharing, facilitates research across the Arctic. This includes adhering to ethical and cultural protocols of data collection, accessibility and sharing in the context of research with Indigenous groups.
- The important roles of research infrastructure, networks, and field stations have been discussed earlier in this report.

Legal Framework

- Arctic researchers welcome efforts by **IASC, IASSA,** and **UArctic** to promote the recently adopted Agreement on Enhancing International Arctic Scientific Cooperation (**Arctic Science Cooperation Agreement**). The main leitmotif of this agreement is to improve access to data, places, and information, as well as to remove procedural obstacles to Arctic research. Scientists are especially interested in both how the agreement is applied to the states that are party to the agreement, and any impacts it has on researchers from non-party states.
- Current best practices include reaching out to Arctic countries and organizations to create memoranda of understanding and collaborative partnerships, following established procedures for applying to enter exclusive economic zones for shipboard research, and these efforts are in addition to implementing the **Arctic Science Cooperation Agreement**. Enhanced agreements to share infrastructure and logistical support could help to remedy some of the current obstacles.
- Given the diversity of the Arctic regions, cultures, and environments, Arctic scientists achieve the best results by working in international teams and consortia with scholars from multiple Arctic and non-Arctic jurisdictions, bringing together broad interdisciplinary experiences, expertise, and funding. The Arctic research community places high hopes in the implementation of the **Arctic Science Cooperation Agreement.**

- The **Arctic Science Cooperation Agreement** provides an unusual opportunity to promote and find support for inter- and transdisciplinary international research suited to understanding complex Arctic problems.
- There needs to be more widespread attention paid throughout Arctic and non-Arctic countries to ethical practices related to Arctic research, with international standards for policies/ethics/guidelines for research that will improve engagement with local and/or Indigenous issues/ communities (e.g. ITK National Inuit Strategy on Research).
- The marine research community emphasizes the importance of international access to exclusive economic zones, particularly in data-sparse Arctic regions, as a priority (part XIII of the **UN Convention on the Law of the Sea UNCLOS**).
- The **Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean** is also seen as an important milestone for Arctic environmental protection as well as an impetus for expanded research in the Central Arctic Ocean. It is protective of the Arctic as well as being a mechanism to stimulate additional internationally coordinated research.

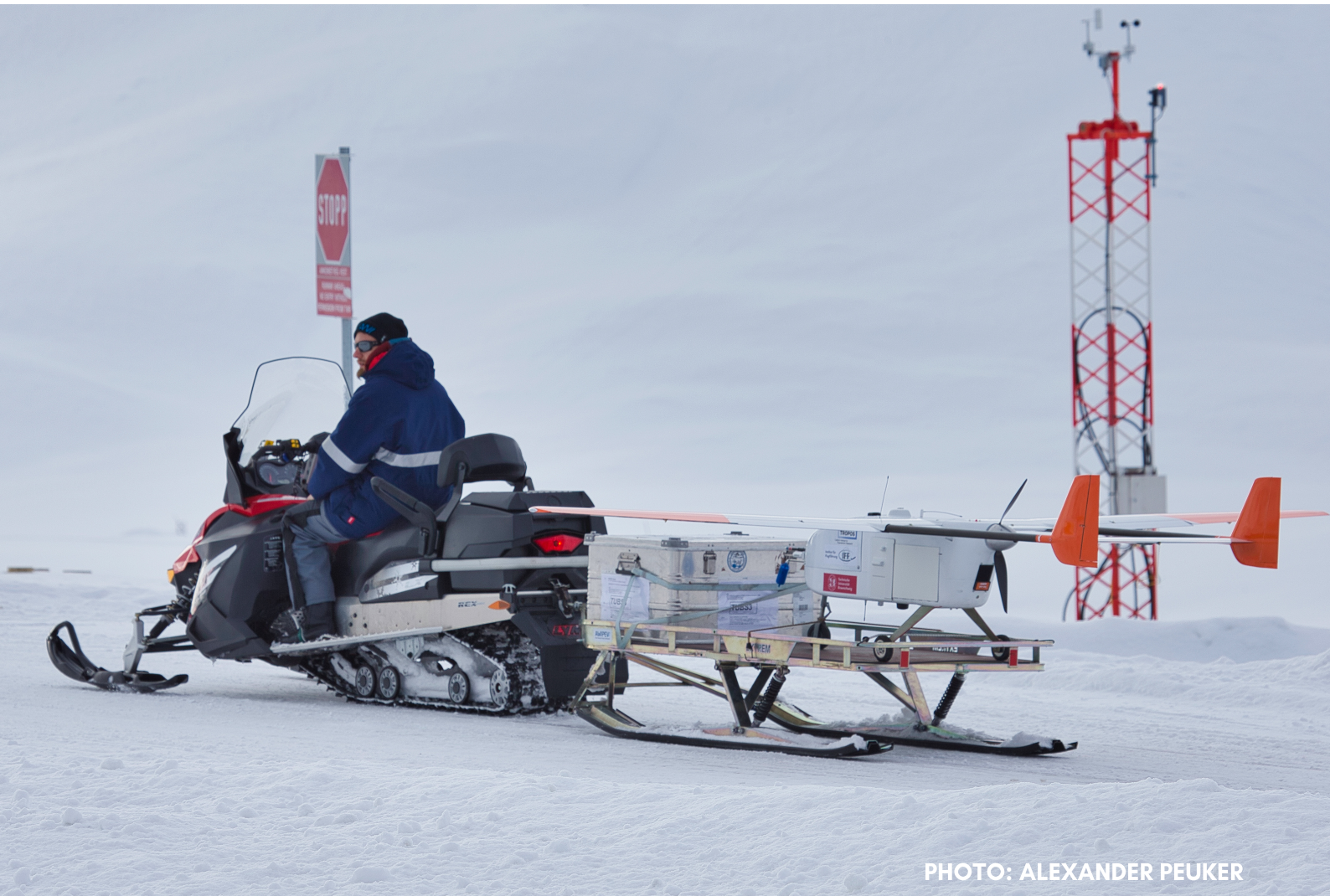


PHOTO: ALEXANDER PEUKER

Conclusions

The Arctic – a unique and globally important region – is also a rapidly changing region. More than ever before, we need to continue to build the understanding of the Arctic, including systems, and the connections between systems. Bigger than any one discipline or country can hope to address individually, IASC leads by bringing together science disciplines and international collaboration, prioritizing science over nationality.

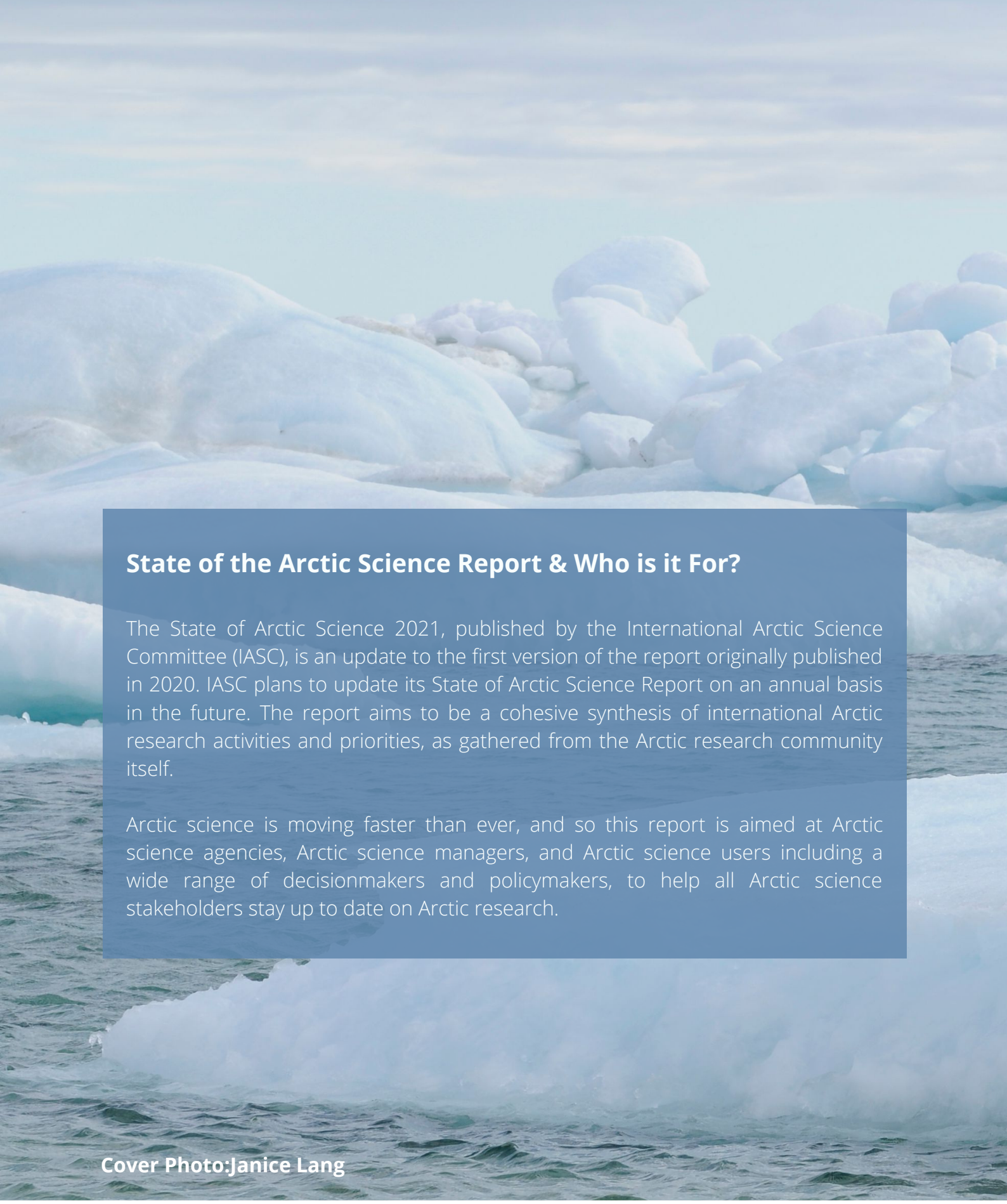
The State of Arctic Science 2021 is expected to provide benefits by identifying priorities, linkages, and gaps in the current work of the international Arctic research community. For example:

- Arctic research must be truly interdisciplinary, and indeed convergent, in order to meet both Arctic and global challenges.
- The Arctic research community must improve on its efforts to respect and implement the priorities, voices, and contributions of Indigenous Peoples and other Arctic residents.
- International and interdisciplinary cooperation are absolutely critical to studying Arctic systems and should be encouraged and expanded.
- Arctic data sharing, discoverability, access, and re-use continue to be difficult challenges, but improvements in these areas will be crucial for future success.
- Current levels of Arctic monitoring and research are insufficient to meet these challenges, despite the hard work and investments of both Arctic and non-Arctic countries.

The State of Arctic Science 2021 remains an initial effort to describe the status of the scientific endeavour at high northern latitudes. Building on a foundation of ICARPIII, IASC has compiled this report out of broad, bottom-up contributions from the IASC scientific community. Arctic change is accelerating, and Arctic science is vast, and so this report attempts to summarize - but just barely scratches the surface of - the tapestry that is Arctic research.

This report adds value and is a useful contribution for researchers, policymakers, and all research stakeholders by setting out the state of Arctic science. While this report is static, Arctic research is vibrant and evolving. Therefore, IASC will update this report on an annual basis in the future.

Email info@iasc.info and find out more about IASC at www.iasc.info.



State of the Arctic Science Report & Who is it For?

The State of Arctic Science 2021, published by the International Arctic Science Committee (IASC), is an update to the first version of the report originally published in 2020. IASC plans to update its State of Arctic Science Report on an annual basis in the future. The report aims to be a cohesive synthesis of international Arctic research activities and priorities, as gathered from the Arctic research community itself.

Arctic science is moving faster than ever, and so this report is aimed at Arctic science agencies, Arctic science managers, and Arctic science users including a wide range of decisionmakers and policymakers, to help all Arctic science stakeholders stay up to date on Arctic research.

Cover Photo:Janice Lang

IASC 2021 State of Arctic Science Report (SAS)
Eletronic version available at https://iasc.info/about/publications-documents/state-of-arctic-science

IASC Secretariat,
Borgir, Norðuslóð
600 Akureyri - Iceland
info@iasc.info I +354 515 5824