RATIC 2019 Workshop

RATIC / T-MOSAiC Connections and Opportunities

Arctic Science Summit Week 2019
NArFU Intellectual Center, Arkhangelsk, Russia
26 May 2019

An IASC cross-cutting workshop and an activity of the Rapid Arctic Transitions due to Infrastructure and Climate (RATIC)

Workshop Report to the IASC Secretariat
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Executive Summary

The impacts of climate change, infrastructure, and the interactions between them in vulnerable Arctic landscapes are both complex and urgent. The Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) initiative was created in 2014-15 as a forum to promote sustainable infrastructure as a key theme in Arctic research planning—one that requires multidisciplinary collaboration by scientists, local communities, governments and industry to be successful.

The 4th RATIC workshop was held at Arctic Science Summit Week (ASSW) 2019 at the Northern (Arctic) Federal University (NArFU) in Arkhangelsk, Russia. This full-day workshop brought together 51 participants from 11 countries to share their work and identify research priorities. Eight oral presentations and more than 10 posters were presented. The group also discussed opportunities to advance RATIC goals through participation in the three-year, circumpolar T-MOSAiC (*Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections*) project. The workshop was sponsored by the International Arctic Science Committee (IASC) as a cross-cutting activity of the Terrestrial, Cryosphere, and Social & Human Working Groups.

The workshop developed a short-term goal for 2019–2021of participating in T-MOSAiC as a new infrastructure action group. During the several workshop activities, the participants:

- Prioritized key scientific questions related to sustainable Arctic infrastructure in natural, social and built environments.
- Identified a range of data products that would help answer these questions, including a pan-Arctic geospatial database of infrastructure, a time-series analysis, and an update to the IPA circumpolar map of permafrost and ground-ice conditions.
- Developed a conceptual approach for pan-Arctic infrastructure research based on a new classification of infrastructure types to identify representative monitoring sites in collaboration with local communities, in places where access and resources exist.
- Identified key challenges for multidisciplinary teams studying the socio-ecological impacts of climate and infrastructure, which include the need to use mixed quantitative and qualitative methods and be responsive to local community interests while producing standardized data for use in circumpolar models and analysis.
- Agreed to form an Arctic Infrastructure Action Group under T-MOSAiC as the nexus for RATIC activities in 2019-2021. The scope of activities will include catalyzing projects to monitor and observe consequences and interactions between climate and infrastructure on Arctic landscapes and communities, especially coastal and near-coastal social-ecological systems in ice-rich-permafrost environments.

This document contains the agenda, workshop summary, and six appendices, including a list of participants, abstracts of talks and posters, key science questions from the Prague 2017 RATIC meeting, notes from the breakout and panel discussions, and an overview of the scope and membership of the T-MOSAiC Arctic Infrastructure Action Group.

Agenda

Rapid Arctic Transitions due to Infrastructure and Climate Workshop
Arctic Science Summit Week 2019
26 May 2019, 9:00–18:00
Room 502, NArFU Intellectual Centre
Smolny Buyan, 1, Arkhangelsk

Goal: Promoting sustainable Arctic infrastructure as a key research theme requiring a collaborative multidisciplinary approach involving scientists, local communities, governments and industry.

9:00 **Welcome and introductions**

9:20 **Presentations: Impacts and interactions of climate and infrastructure in the Arctic**
(15 min + 5 min Q&A *except as noted*)

- Response of permafrost environment to natural changes and human impact in the north of West Siberia (Yamal-Nenets Autonomous Okrug) (Leibman & Khomutov, Russia)
- Modeling circumpolar permafrost and permafrost thaw-related geohazards affecting infrastructure (Karjalainen, Finland)
- Impacts of climate change and infrastructure on reindeer herding in the Yamal peninsula (Laptander & Kumpula, Finland) (25 min + 5 min Q&A)

10:30 **Coffee and posters**

11:00 **Presentations: Approaches to research and adaptation** (15 min + 5 min Q&A each)

- T-MOSAiC and RATIC: Connections and opportunities (Vincent, Canada)
- Navigating the new Arctic: Landscape evolution and adapting to change in ice-rich permafrost (Walker, USA)
- Sustainable housing in rural Alaska (Garber-Slaght, USA)
- Infrastructure stability estimation: Usage of GTN-P data and permafrost forecasting (Sergeev & Utkina, Russia)
- Social science perspectives on Arctic infrastructure (Schweitzer et al., Austria)

13:00 **Lunch**

14:00 **Research directions: Prague workshop synthesis**

14:20 **Breakout groups: Natural and social/built environment perspectives on research needs**
What are the existing initiatives and projects in each sphere related to RATIC? What are some upcoming opportunities? What questions do we need to answer to achieve sustainable Arctic infrastructure? Which are most important? Which may be answered soon? Which will take longer or are unlikely to be answered in the foreseeable future?

15:30 **Coffee and posters**

16:00 **Panel 1: Research priorities (report from breakout groups)**

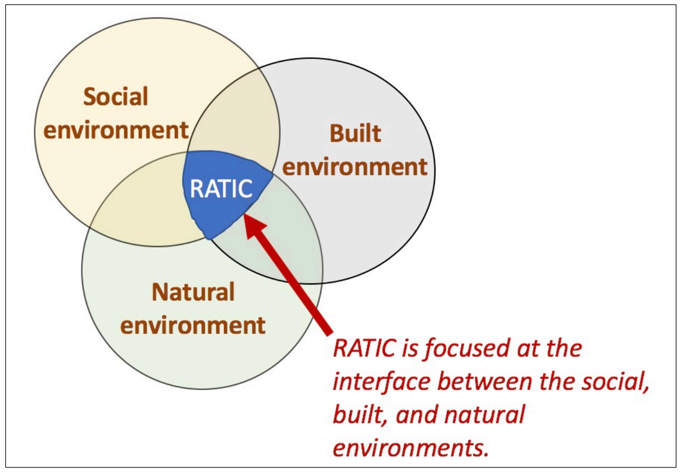
16:30 **Panel 2: Advancing RATIC through linkages with T-MOSAiC and other opportunities**
What are the opportunities for advancing the goal of sustainable Arctic infrastructure through participation in T-MOSAiC? What are some specific ideas for systems-level observation, monitoring and modeling related to infrastructure? What are the challenges from the social science perspective? How do we better engage indigenous communities, business and industry in this work? What T-MOSAiC data products can be used to answer some of the key questions identified earlier in the day?

17:30 **RATIC/T-MOSAiC: Planning the next steps**

18:00 **Adjourn**

RATIC 2019 Workshop Summary

RATIC beginnings and previous activities



The RATIC initiative grew out of a workshop and topical sessions at the Arctic Change 2014 conference in Ottawa, Ontario (8-12 December 2014) with support from IASC.

The workshop was organized so international scientists working independently in several areas of the Arctic on issues related to infrastructure could network with each other and share their findings. Presentations focused on case studies from the Prudhoe Bay oil field in Alaska, the Bovanenkovo gas field in Russia, and approaches to research, adaptation and policy making in northern Canada. It was supported by $10,000 from the International Arctic Science Committee (IASC) for Association of Polar Early Career Scientists (APECS) to attend. Around 40 participants attended.

Following Arctic Change, workshop participants began collaboration on a whitepaper that was refined at a RATIC writing workshop at ASSW 2015 in Toyama, Japan. As a result of these activities, the need for concerted international approaches to sustainable infrastructure development was adopted as one of the overarching messages from ASSW 2015. The final RATIC whitepaper was completed in July 2015 and submitted to IASC as a contribution to ICARP III, the Third International Conference on Arctic Research Planning, as part of Theme 3: Societies and Ecosystems.

Resolution adopted at ASSW 2015 in Toyama, Japan

Whereas:

- Northerners and Arctic socio-ecological systems are strongly impacted by changes in infrastructure;
- The drivers and consequences of infrastructure development in the Arctic are not adequately addressed by the Arctic research community; and
- The complexity of the Arctic infrastructure challenges requires a multidisciplinary and circumpolar collaboration approach involving all Arctic countries and implementation of an integrated social-ecological-system approach.

Therefore:

We propose that ICARP-III identify **sustainable infrastructure development** as a key research theme that requires a multidisciplinary collaborative approach involving scientists, local communities, governments, and industry.

Goals adopted at ASSW 2017 in Prague, Czech Republic

Participants at the Sustainable Arctic Infrastructure Forum in Prague at ASSW 2017 identified the following tasks to be completed over the next five years:

(1) Promote the topic of “sustainable infrastructure development” as a key IASC research theme;

(2) involve scientists, local communities, governments, industry and the general public in this research;

(3) publish a synthesis of sustainable Arctic infrastructure research findings in peer-reviewed scientific journals and more publicly accessible platforms;

pursue funding to continue the RATIC initiative; and develop a strategic plan for Arctic infrastructure research.

In April 2017, a “Sustainable Arctic Infrastructure Forum (SAIF)” was held as part of ASSW in Prague, Czech Republic, with IASC support. Participants at the Prague workshop discussed the cumulative effects and drivers of four major types of infrastructure systems: urban, village, industrial, and indigenous (camps, trails, corrals, etc.). “Corridors” and “nodes” emerged as an organizing framework for research to address these types of infrastructure. Key science questions related to each infrastructure type are included in Appendix C.

At Arctic Change 2017 in Quebec City (December), seven science talks were presented at a RATIC session chaired by Peter Schweitzer and Andrey Petrov. Topics explored issues of Arctic engineering, permafrost monitoring, adaptation, land use management, impacts on reindeer herding, cumulative impacts of oil development, and social issues related to uneven development.

Continuing the conversation in Russia: Linking RATIC and T-MOSAiC

The May 2019 workshop in Arkhangelsk, Russia, provided a forum to continue building on these previous activities and to bring new people into the conversation with a short-term goal defining the role of RATIC as the Arctic Infrastructure Action Group of T-MOSAiC. RATIC 2019 workshop participants were asked to come with thoughts on where they could most effectively plug into the four-year-old RATIC initiative.

Participants from across the Arctic

Fifty-one people from 11 countries attended the workshop, including permafrost and vegetation scientists, ecologists, engineers, human and physical geographers, anthropologists, and a mix of other natural and social scientists. (See Appendix A for a list of participants.) As in previous RATIC workshops, IASC Fellows, Association of Polar Early Career Scientists (APECS) members, indigenous people, and industry representatives were encouraged to participate. Early career scientists from many countries attended, with the largest contingent from the host country of Russia.

Oral presentations and poster session

Eight scientific papers were presented during the morning. The first group of three presentations focused on the impacts of climate and infrastructure in the Arctic, including impacts on natural (permafrost response in West Siberia), built (modeling of geohazards affecting infrastructure), and social (reindeer herding in the Yamal peninsula) environments. The second set of oral presentations focused on approaches to research and adaptation, with presentations from the U.S., Canada, Austria, and Russia. An informal poster session was held during coffee and lunch breaks. (See Appendix B for abstracts. Copies of most presentations and posters are available at www.geobotany.uaf.edu/ratic/workshop2019.)

Breakout groups identify research priorities in three areas

After lunch, workshop participants divided into breakout groups to look at RATIC-related research questions and priorities in three areas: Natural Environment, Social Environment, and Built Environment, with the Built and Social groups meeting together. Individuals chose a discussion group according to their background and interest. A multidisciplinary Russian language breakout was also provided.

To inform the discussions, a presentation summarizing the takeaways from the 2017 RATIC workshop in Prague was made, and groups were given a list of key RATIC science questions developed in Prague (Appendix C).

Each breakout group was asked to name a few existing RATIC-related projects in their area as a warm-up exercise and then to sort and prioritize research questions based on their importance and feasibility (How important is the research to achieving sustainable Arctic infrastructure is it to answer? How easy will it be to answer?).

Breakout groups had one hour to work. At the end of the hour, a panel was formed with one member from each group to share highlights of the discussions. See Appendix D for the full list of priority research questions and topics by breakout group. The following is a short list of overarching questions and products.

Key "umbrella" questions:

- How can we classify infrastructure types? How do we classify impacts and the intensity of impacts?
- How do we track changes in the extent of infrastructure? How do we track individual impacts over time?
- How do we research impacts of infrastructure and climate in ways that are responsive to local community needs, while standardizing data for use in statistical models, comparative analysis and synthesis?
- What are best practices for measuring cumulative impacts using both quantitative and qualitative methods?
- How do we maximize practical applications of our research for engineers, government, industry and other infrastructure owners and users?

- What buildings do people want to live in? What material properties of infrastructure help meet local needs? How can we make infrastructure more useful?
- How do we demobilize infrastructure and rehabilitate sites when the infrastructure is no longer useful? Which infrastructure should be removed? Who decides? How do we plan for demobilization?
- How will increased shipping traffic and coastal infrastructure from the opening of the Arctic Ocean affect social dynamics in the circumpolar north?

Products needed

- Pan-Arctic geospatial database of infrastructure that includes parameters needed for modeling
- Time-series database of Arctic infrastructure based on available historic imagery to establish a baseline and understand trends in infrastructure development
- Classification of infrastructure and impact types
- Updated International Permafrost Association circum-Arctic permafrost map, with multiscale maps characterizing ground-ice attributes and distribution.
- Key indicators for permafrost evolution (permafrost state and dynamics)

Panel provides ideas for strengthening multidisciplinary collaboration and advancing RATIC goals through T-MOSAiC

The last part of the day featured panel and full group discussions on working across disciplinary boundaries and advancing RATIC through T-MOSAiC. The Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAiC) is the three-year, land-based component of the international MOSAiC Arctic Drift Expedition. To kick off the full group discussion, four panel members were asked to respond to questions provided in advance. (The questions asked of each panelist are in italics followed by a bulleted summary of their comments)

Warwick Vincent: Opportunities within T-MOSAiC for advancing RATIC

MOSAiC is largely focused on observing/monitoring and modeling changes in natural systems using a systems-level approach. T-MOSAiC brings that observation and modeling on shore and adds a human focus. What are the system-level themes in T-MOSAiC that relate to infrastructure? What kinds of data will be developed that might be useful to questions related to infrastructure?

- T-MOSAiC has a very well-defined science plan and now an implementation plan. You can review both at www.t-mosaic.com.
- The three T-MOSAiC themes most relevant to RATIC are: **Connectivity** (e.g. rain-on-snow events as an example of atmospheric and sea-ice conditions affecting coastal areas and infrastructure); **Thresholds & Discontinuities** (e.g. roads vs. roadless areas, off-road vehicle impacts, expansion of road networks into the Arctic in Canada); and **Extreme Events** (e.g. flooding, wildfires, rain-on-snow and the need for adaptation strategies).

Vlad Romanovsky: Applying monitoring and observation methods to infrastructure

What does it mean for RATIC to become an Infrastructure Action Group under T-MOSAiC, which is focused on observation/monitoring and modeling? Thinking about the impacts of climate and infrastructure on social systems and the built environment, are there opportunities for observing/monitoring networks? What questions might lend themselves to modeling?

- T-MOSAiC emphasizes observation and monitoring. When we apply this to infrastructure it requires a paradigm shift for physical scientists trained to seek out undisturbed sites away from human activities. Because of this preference and training to study physical parameters in undisturbed conditions, there is a big gap in our knowledge when it comes to understanding impacts *from* and *on* infrastructure.
- There are advantages and disadvantages to monitoring environments where people and roads already exist. Logistics may be easier and less expensive, but we have no guidance or protocols on how to do it. Infrastructure owners do not always welcome observations by researchers from outside their organization and may not allow publication of the results of monitoring studies.
- Each piece of infrastructure is unique. We must come up with some system to classify infrastructure by type so we can use a small number of monitoring sites to upscale and extrapolate to other infrastructure. This would be similar to what we do for natural environments where we use ecosystem types and put observatories in each ecosystem (see Dmitrii Sergeev's presentation). Infrastructure types should be very specific so that generalization from the specific is possible.
- Many infrastructure owners and engineers do monitoring. How do we access this data? Some data will be public (e.g., government transportation and public facilities) and some proprietary (e.g., oil and gas infrastructure).
- Remote sensing can be used to collect data and monitor changes.
- Developing collaborative relationship with industry is needed. As a policy proposal, requiring data sharing as a condition of permitting would be best.

Olga Povoroznyuk: Strengthening collaboration with social scientists and local communities

What are the ethical or other considerations when applying observation/monitoring or modeling to the social/built environment? What should physical scientists know when collaborating on research with social components?

- As social scientists, we look first and foremost at the local scale, sometimes seeing the global forces behind it. How do we upscale our observations and research?
- How do we combine different types of knowledge—scientific, indigenous, local—in the study of infrastructure? How can we be more inclusive in moving toward a community-based research and looking at the interests of vulnerable and minority groups?

- How do we combine quantitative and qualitative data in a meaningful way? That requires different kinds of analyses.
- What can we gain by involving local indigenous people in the process of data gathering, analysis and research?
- How do we disseminate study results and translate scientific findings to local communities? As social scientists, that is our responsibility. Hopefully it also becomes a part of interdisciplinary projects with natural scientists.
- Infrastructure is a material object, but it also functions as a nonmaterial or symbolic object: the embodiment of particular ideologies, beliefs, and memories connected with its creation and the human resources and labor that went into it.
- Social science is more likely to view infrastructure as a theoretical lens, which can lead to different interpretations of the same phenomenon and potential contradictions. The challenge for social anthropologists is to think of how to make their theoretical findings more applicable to other kinds of research. Examples where natural and social science research cooperate well include social and environmental impact assessments, the RATIC initiative, and other initiatives in Arctic studies.

Roza Laptander: Involving local and indigenous communities in research

It has been hard to engage indigenous people in discussions about research priorities that take place at science meetings, because this is not where they congregate. What are better ways to include local and indigenous communities in setting research priorities and in planning, conducting and reporting on research that impacts them?

- I can only give my perspective from working with the Tundra Nenets in Yamal. The development of infrastructure in Yamal for indigenous people is a very sensitive topic. Having a trusted mediator between the indigenous people and the scientists can help.
- It's a challenge to ask people about what kind of impact infrastructure has in the life of indigenous people. People may be guarded and give different answers depending on who is asking the question. We can collect this data, but you can only trust it so much.
- At one level, it is just people expressing their opinion, but we should respect the opinions because local people are living with the infrastructure and must deal with the impacts in their everyday life.
- It's better to talk with local people in indigenous societies. If you give them a questionnaire to fill out, you should not expect the answers to be 100% correct. Personal communication is a very good source of information.
- Traditional knowledge is a sensitive topic. What indigenous people such as the Sámi can or want to share with people outside their ethnic group may be limited.
- It's important to talk with official representatives of indigenous groups who are authorized to speak on behalf of their local communities. You can inquire of them what kinds of traditional knowledge they are ready to share.

- Ethically speaking, what kind of questions should we ask indigenous people and what should we give back to them? Much of the data that is collected by scientists, that we need for our publications, is not really useful to them.
- When collecting stories, oral traditions, and other things, I always try to make copies of all the recordings and return them to their society. Stories of the past will probably be useful to them in the future: How was the tundra before? How did people live on it and work with reindeer? What differences were there in their relationship with the state?

Linking RATIC to T-MOSAiC: An Arctic Infrastructure Action Group

The following are highlights from the discussion of how to advance RATIC goals through participation in T-MOSAiC. Detailed notes from this full group discussion appear in Appendix E.

Strategic approach for linking T-MOSAiC and RATIC

Participants discussed how to link RATIC to T-MOSAiC and what the scope and product(s) of a T-MOSAiC infrastructure action group could be.

- MOSAiC will produce an unprecedented level of information regarding the ocean, atmosphere, and biota of the Arctic basin. We should proceed by linking infrastructure issues to MOSAiC themes. Sea ice, open water, winter atmospheric conditions all affect terrestrial environments and infrastructure in the Arctic. We should establish or continue observations on land that relate to the observations that will come out of MOSAiC. *What are the critical terrestrial and infrastructure questions related to the atmosphere over the ocean and sea ice? Should we specifically focus on coastal areas or along gradients or transects? How do changes in where there's open water affect terrestrial areas and activities (e.g. rain-on-snow events)?*
- We should also look at where RATIC science questions fit within T-MOSAiC themes and science plan. Key topics will be interactions between climate, permafrost, infrastructure, and their impact on the built environment and local communities.
- RATIC's original goal of bringing attention and funding to the issue of Arctic infrastructure development has already been partially realized. Recent calls by the Belmont Forum and NSF's Navigating the New Arctic initiative are addressing the questions of: *What are the effects of infrastructure in the Arctic? How is climate change affecting infrastructure and vice-versa?* Projects funded through these initiatives will provide a tremendous opportunity to advance the goals of RATIC and T-MOSAiC. *How can we synthesize the knowledge gained through disparate projects to answer infrastructure-related questions on a circum-Arctic basis?*

Monitoring and observation methods

MOSAiC and T-MOSAiC are largely focused on observation, monitoring and modeling. Building on ideas presented in the panel discussion, participants discussed how to approach such activities in relation to Arctic infrastructure on a multidisciplinary basis.

- A conceptual approach for a monitoring network could be to:
  - Use a stratified sampling approach as in ecosystem science and set up a monitoring network(s) for specific infrastructure types.
  - Prioritize areas where there are existing projects or resources.
  - Use a mix of natural and social science methods.
  - Set up projects that involve local indigenous people to assist with various kinds of observations.
- Creating a monitoring or observational network is complicated from the social science perspective. The only way to study infrastructure close to a community is in close cooperation with the community, which can only be successful if the community sees value in the research and is willing to participate.
- Standardized data sets will be difficult to achieve but are needed for comparative studies. What data parameters for buildings and other types of infrastructure will be needed by modelers to create geospatial or statistical models?
- How can we gain access to relevant data developed and used by engineers? Public data is currently available but scattered (e.g. Alaska Department of Transportation & Public Facilities, Transport Canada). For greater access to industry data, we may be able to leverage researchers' existing relationships (such as those developed through environmental assessment projects) to bring industry to the table and encourage data sharing.

Synthesis publications

Participants discussed what types of publications would be a reasonable goal for a action group. Suggestions ranged from a large assessment volume to a strategic plan for Arctic infrastructure research to individual synthesis articles on specific types of infrastructure or impacts.

- Action group members should develop synthesis articles that bring together knowledge developed through social science, engineering and natural science in the same documents.
- Ideas for synthesis publications include: 1) An article on the positive and negative impacts of roads, including ecological and sociological impacts; 2) an article on flooding that looks at the sociological, ecosystem-level, and infrastructure sustainability implications of major flooding events and identifies best practices from different parts of the world; 3) expand an article already in production, which looks at the impacts of oil and gas development in Prudhoe Bay, Alaska, to a circumpolar analysis of similar development.

    - An article on the positive and negative impacts of roads, including ecological and sociological impacts.
    - An article on flooding that looks at the sociological, ecosystem-level, and infrastructure sustainability implications of major flooding events, and that identifies best practices from different parts of the world.
    - An article already in production that looks at the impacts of oil and gas development in Prudhoe Bay, Alaska, could be expanded into a circumpolar analysis of onshore oil and gas infrastructure impacts.
- An Arctic infrastructure assessment report on the scale of the Arctic Monitoring and Assessment Porgamme (AMAP), the Ocean and Cryosphere assessment, or the Arctic Human Development Report would be valuable in establishing a baseline and setting out best practices for new activities. However, it is not a realistic goal for a three-year effort without staff or dedicated funding.
- Two funded initiatives that may still be useful as models are the Global Terrestrial Network for Permafrost (GTN-P) of the International Permafrost Association and the Permafrost Carbon Network, an activity of the SEARCH project. Both provide examples of researchers with multidisciplinary expertise collaborating to write high-impact synthesis publications.

Accomplishments and next steps

Creation of the T-MOSAiC Arctic Infrastructure Action Group

An Arctic Infrastructure Action Group has been formed under T-MOSAiC that will serve as the nexus for RATIC activities in 2019-2021. The workshop achieved several goals that help define the preliminary scope of activities for the action group and provide the first steps for a long-term RATIC strategy. They include:

1) a strategic approach to linking T-MOSAiC and RATIC through observations of terrestrial infrastructure change that result from MOSAiC observations in the central Arctic Basin;
2) a prioritized list of key scientific questions related to sustainable Arctic infrastructure in natural, social and built environments;
3) a range of data products that would help answer these questions; and
4) preliminary concepts for developing monitoring and observation methods that include thoughts on site selection, classification, and standardization.

Action group activities will include the identification of catalyzing projects to monitor and observe consequences of climate and infrastructure on Arctic landscapes and communities, especially coastal and near-coastal social-ecological systems in ice-rich-permafrost environments.

All RATIC 2019 workshop participants have been invited to join the new action group; eleven have volunteered to serve on the steering committee. The group's co-chairs are Peter Schweitzer and Skip Walker. The steering committee will meet in Fall 2019 to develop a list of specific goals and activities to be accomplished in 2019-2021. A draft scope of activities and list of steering committee members are available in Appendix F and at www.t-mosaic.com/infrastructure.html.

Next RATIC / T-MOSAiC session

Several workshop participants said they do not want to wait another two years to meet as a group, and that it's important to capitalize on the momentum created in Arkhangelsk. The participation of so many Russian scientists was especially valued.

Good opportunities coming up to host workshops, work sessions or topical science sessions on RATIC themes include:

- European Geosciences Union (EGU) 2020 in Vienna, Austria (3-8 May)
- ASSW 2021 in Lisbon, Portugal (19-26 March)

Other options include the International Conference on Permafrost (ICOP) in China in June 2020, and the annual American Geophysical Union (AGU) meetings.

Seeking greater involvement of industry, government and local communities

RATIC has identified the critical need for greater involvement and dialogue with local communities, governments, and industry in the topic of sustainable Arctic infrastructure. Hosting RATIC meetings exclusively at conferences primarily attended by scientists makes it difficult to achieve this. One area of continuing discussion at the Fall meeting of the T-MOSAiC Arctic Infrastructure Action Group will be how to promote greater participation by these groups.

Appendix A: Participant List

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Appendix B: Abstracts of Talks & Posters

Copies of most presentations and posters are at www.geobotany.uaf.edu/ratic/workshop2019

Oral presentations

Sustainable housing in rural Alaska

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Alaska contains some 300 Native villages scattered across 360 million acres ranging from temperate rainforests in the southwest to Arctic tundra in the north. Most are only accessible by airplane. There are few services and most of the food, fuel, and supplies are brought in by barge (in the summer) or plane. Alaska's coastal communities are feeling the brunt of climate change today.

The community of Newtok on the southwest coast has been battered by a changing climate for over 15 years. Because of melting sea ice that used to protect their shore, the village regularly floods during the fall storm season. They have lost their sewage lagoon and landfill to flooding, and every year they lose about 24 m of coastline. The closest homes are within five meters of the edge. Like many Alaska Native communities, Newtok was never a permanent settlement. But because permanent infrastructure was built there by outside agencies, it became permanent which has led to many of the sustainability problems we are seeing today.

CCHRC is working with the community of Newtok to provide housing that is more sustainable than what they currently have, in a location that is better suited for permanent settlement. This presentation will highlight CCHRC's work with rural Alaskan communities to develop a process for locally driven sustainable housing that is being used as part of the Newtok relocation.

Modeling of circumpolar permafrost and permafrost-thaw related geohazards affecting infrastructure

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Degradation of permafrost poses a threat to the current and future infrastructure of the north circumpolar region. Rapid warming of the Arctic has led to rising permafrost temperatures and the potential for severe damage to infrastructure. The thermal state of permafrost in the near future must be considered carefully when planning future societal and industrial development of the Arctic.

Our aim was to assess permafrost-thaw related geohazards at an unprecedentedly high spatial resolution (< 1 km^2) across the entire circumpolar region for a near–future scenario. The possible consequences for human activity were estimated by quantifying the amount of basic infrastructure at risk (roads, railways, airports, pipelines, buildings, human settlements, and industrial areas). We first performed statistical ensemble modeling of permafrost properties (ground temperature and active-layer thickness) under current conditions. Next, we predicted permafrost conditions around mid-century using climate forcing scenarios that considered different pathways of human-induced greenhouse gas emissions. Finally, we formulated geohazard indices employing the projections of permafrost thaw, changes in active-layer thickness, and soil and terrain properties affecting permafrost stability.

Considering a moderate scenario, around 70% of the current infrastructure exists in areas where near-surface permafrost has high potential for thaw by mid-century. Moreover, one-third of the circumpolar built environment is located in high-hazard areas where thaw-related instability may cause severe damage. Sustainable development of Arctic communities and utilization of natural resources requires that these issues are addressed in planning at regional and local levels. Our modeling improves knowledge about large-scale variability in permafrost-thaw related geohazards and facilitates targeting localized analyses.

Impacts of climate change and infrastructure on reindeer herding in the Yamal peninsula

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The traditional land use in the Yamal is generally based on the Nenets reindeer herding. However, the hydrocarbon industry is presently the source of most ecological changes in the Yamal peninsula and socio-economic impacts experienced by nomadic Nenets reindeer herders who move annually between winter pastures at treeline and the coastal summer pastures nearby the Kara Sea.

In the central part of the Yamal peninsula, which is a permafrost area, both natural and anthropogenic changes have occurred during the last 50 years. We have studied gas field’s development and natural changes, like increases in shrub growth, cryogenic landslides, drying lakes in the region and these impacts to the Nenets reindeer herding.

The Nenets with collective and private owned herds of reindeer have proven adept in responding to a broad range of intensifying industrial impacts, at the same time, as they have been dealing with symptoms of a warming climate and thawing permafrost phenomena.

The results of climate change together with the industrial development of the Yamal Peninsula have a serious impact to the Nenets nomadic reindeer husbandry. Their consequences caused the Nenets reindeer herders to change their migration routes and the way of working with reindeer. During several years, we were doing interviews with the Nenets reindeer herders about the influence of climate change and industrialization of the tundra on the quality of the Nenets' life and their work with reindeer. Reindeer herders said that the impacts of the industrial development have reduced their migration opportunities. Due to the concentration of a high number of reindeer in certain areas, nowadays the quality of pastures is quite poor. It has fatal effect during icing on the tundra in the winter. At the same time, in the summer reindeer have more food because of the increasing of green vegetation on the tundra.

Here we detail both the climate change impacts and spatial extent of gas field growth, landslides drying lakes, shrub increase and the dynamic relationship between the Nenets nomads and their rapidly evolving social-ecological system.

Response of permafrost environment to natural changes and human impact in the north of West Siberia (Yamal-Nenets Autonomous Okrug)

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Our main goal is studying natural permafrost environments and limited human impact caused by infrastructure development in the area close to gas fields, pipelines, railways, roads and quarries. Years of monitoring active layer, ground temperature and landslide activities at Vaskiny Dachi research station. Spatially we extended monitoring westward to include gas-emission graters (GEC), and eastward to Tazovsky and Gydan peninsulas, south of, and north of Vaskiny Dachi research station latitude.

Research topics were extended as well. The following have been added to the research: (1) field studies (organic matter fate and hydrochemistry in the lake and GEC lake water; distribution and rate of thermocirque growth; dynamics of GEC width and depth); (2) laboratory studies (ionic and isotope analyses of lake and GEC-lake water; methane concentration in lake and GEC-lake water; dissolved organic matter in the lake water. Remote-sensing studies (processing optical images for monitoring GEC, thermocirques, peat plateaus, mapping tabular ground ice, methane emission in the lakes, predicting natural hazards). We perform measurements of moisture content in the active layer, geochemistry of active-layer soils, bathymetry of lakes, including GEC lakes, snow survey and geochemistry of snow.

Results achieved so far are as follows. Since 2012 air temperature increase dramatically resulting in 20% deeper active layer, 0.5 ˚C higher ground temperature, activation of thermal denudation, formation of GEC transforming into lakes-successors.

It was revealed that the thaw depth increase in 2012 and 2013 reached the top of tabular ground ice and thermocirques were formed. In 2016, the growth of thermocirques speeded up.

Evidently, the presence of gas accumulations inside the permafrost caused by the increase in average ground temperature predetermined the release of gas formed during the dissociation of gas hydrates, with the formation of gas emission craters.

Human impact resulted in deeper active layer along the vehicle tracks, degradation of peat plateau crossed by the road, fast overgrowing of the quarries thanks to warmer summers.

Social science perspectives on Arctic infrastructure

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Infrastructure, while planned and built by humans, has in turn significant impacts on people’s lives. Arctic infrastructure development often has even bigger impacts than similar projects in temperate zones, as it affects fragile ecosystems and remote communities. Social scientists have started to study infrastructure later than engineers but can bring important perspectives to the field. By engaging concepts such as “infrastructural violence”, “enclaves” and “uneven development”, Arctic social scientists attempt to understand the socio-political conditions, problems and benefits of infrastructure development in remote regions.

Arctic marine shipping (AMS) is projected to increase significantly due to shrinking sea ice and increased resource extraction activities. This requires the construction of new port and subsidiary facilities, which will further transform the natural, built and social environments of the High North. The so-called Northern Sea Route (NSR) is the most productive passageway for AMS. Current and planned research – that combines ethnographic methods with the analysis of satellite images will allow to quantify growth and decline – will be introduced.

Corporate Social Responsibility (CSR) activities are becoming increasingly important practices in infrastructural (mega) projects. However, not all CSR types and ways of their implementation are beneficial, and some become issues of dispute between project proponents, locals and political actors. This section will address the nexus of social impact assessment, CSR and the social license and will raise further critical issues in the context of infrastructural development in the Arctic.

Infrastructure stability estimation: Usage of GTN-P data and permafrost forecasting

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The long linear structures are under the influence of local permafrost diversity of various landscapes and different microclimate variabilities. An example of the features of the evolution of the natural-technical system of a railway embankment under the conditions of the Vorkuta tundra demonstrates the complexity of the task of predicting future change.

A possible (although time-consuming) solution is to develop individual forecasts for typical combinations of landscapes and engineering structures. Such forecasts need special discussion about input data preparation rules. Possible sources of models' input are geological surveys (to clarify the local landscape features), regional GTN-P data from the monitoring of the undisturbed permafrost conditions (for calibrating the regional models of permafrost response to climate change) and regional climate models (for specifying the climate impact scenarios).

To ensure the comparability of the results of permafrost forecasting, a transparent description of the assumptions and setting boundary conditions is needed. In particular, the expected lifetime of the infrastructure affects the depth of research and the characteristics of the model. Forecasts with a duration of more than 50 years should be provided with data on direct downhole measurements with a depth of at least 300 m. It's important for setting the correct initial temperature field configuration.

It is recommended to use the various key indicators of the state and dynamics of permafrost, which are correlated with the specifics of making management decisions. It is recommended to use the indicator of the maximal depth of interannual temperature fluctuations to determine the depth of surveys and monitoring. It is also recommended to use the annual average integral fraction of liquid moisture in a ten-meter layer of soil to estimate the bearing capacity of the ground soils, and the depth of permafrost table. They are important information for designers.

T-MOSAiC and RATIC: Connections and opportunities

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MOSAiC (*The Multidisciplinary drifting Observatory for the Study of Arctic Climate*) is a multinational year-round study of the central Arctic Ocean to measure the coupling between atmosphere, sea ice, ocean and ecosystem processes. **T-MOSAiC** (*Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections*) brings that focus to land. It is an IASC pan-Arctic, terrestrial research program that extends the activities of the flagship MOSAiC program planned for 2019-2020. The objective of the T-MOSAiC satellite program is to coordinate complementary activities that will aid and benefit from MOSAiC by extending the work to the lands surrounding the Arctic Ocean and to the northern communities who live on those lands.

The defining focus of the RATIC initiative on the impacts and interactions of climate and infrastructure in the Arctic provides its own complement to the broad system-level focus of T-MOSAiC with its themes of connectivity, gradients, discontinuities and thresholds, feedbacks, extreme events, legacy effects and emergent properties. RATIC fills in the little "i" in T-MOSAiC through its goal of promoting sustainable Arctic infrastructure as a key research theme requiring collaboration across disciplines and geographic boundaries. RATIC workshops at IASC conferences provide a valuable forum for scientists to discuss research needs and priorities related to both RATIC and T-MOSAiC, to explore opportunities for international multidisciplinary collaboration, and to promote more involvement by early career scientists, local communities, governments, and industry. More information about RATIC is provided at www.geobotany.uaf.edu/ratic, and the Science Plan for T-MOSAiC can be downloaded at: www.tmosaic.com/science-plan.html.

Navigating the new Arctic: Landscape evolution and adapting to change in ice-rich-permafrost systems (NNA-IRPS)

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Much of the response to permafrost-related damage caused by both climate change and infrastructure has been incremental actions driven by the necessity to repair and stabilize existing roads and structures. There is an immediate need to develop more strategic approaches for mitigation and adaptation that is informed by science and engineering in collaboration with local observations, knowledge, and preferences. This paper presents a project that has been proposed as part of a new U.S. National Science Foundation initiative called Navigating the New Arctic (NNA). The proposed NNA-IRPS project offers a transformative view that places ice-rich permafrost (IRP) at the center of change to social-ecological systems in many areas of the new Arctic. Our ultimate goal is to understand ice-rich permafrost systems (IRPS) at local, regional and circumpolar scales. We are particularly interested in how differences in vegetation, water, and time influence the accumulation and degradation of ground ice, and how the loss of ground ice can radically change these landscapes, their components, and the infrastructure built on them. Our key questions are: "How are climate change and infrastructure affecting IRPS?", "What roles do ecosystems play in the development and degradation of IRP?", and "How can people and their infrastructure adapt to changing IRP systems?"

Our initial geographic foci are at Prudhoe Bay and Point Lay, Alaska, where permafrost temperatures are changing rapidly with large impacts to ecosystems, infrastructure, and communities. Both areas provide excellent examples of IRP-related issues relevant to many other areas of Alaska and the Arctic. We will develop three IRP observatories: 1) Roadside IRP Observatory in the Prudhoe Bay oilfield; 2) Natural IRP Observatory remote from infrastructure; and 3) Village IRP Observatory at Point Lay. The Prudhoe Bay region has the best long-term historical record of geoecological change associated with infrastructure within the Arctic with key legacy datasets and good collaboration between industry and science. We will revisit permanent plots and remap Prudhoe Bay vegetation and landscapes first studied in the 1970s.

Point Lay has received less research and agency attention than other climate-impacted communities, yet its thaw related issues are among the most severe. The Cold Climate Housing Research Center will work with the Regional Housing Authority, community residents, local high school students and regional planners to collaboratively produce adaptive housing strategies. A permafrost and infrastructure symposium hosted by the community will bring together US-Canadian science and engineering expertise to discuss a range of public infrastructure issues relevant to many Arctic villages. Our team's work with the Alaska Department of Transportation will advance knowledge on IRP-related impacts to roads and industrial infrastructure and contribute to best practice guidelines for road and airport construction. Science education and training components will reach K-12, undergraduate, graduate, and post-doctoral students.

Posters

Influence of the climatic factor on the mechanical properties of frozen soils (region of the Yuribey river, Yamal Peninsula)

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Throughout the existence of the Earth, cyclical climate changes took place: glacial epochs were replaced by interglacial periods. Today, climate warming is abnormally fast, one of the theories explaining global warming is the greenhouse effect.

In the Arctic regions, an increase in temperature is particularly dangerous due to an increase in permafrost temperatures and thawing of ground ice. The temperature change of permafrost soils affects their structure and mechanical properties.

This paper presents results of the research of the temperature influence on the strength properties of frozen soils of the area near the Yuribey River (middle Yamal). Strength properties (cohesion) determined by triaxial shear test at temperatures from -1 to -8 ° C.

When soil freezes cryogenic concentration occurs as a result of which salinity increases from top to bottom along the section from 0.05% to 1%. Along with increasing salinity down the section decreases the magnitude of cohesion. As a result of cryogenic concentration of salts at a depth of 20-23 m, cryopegs form, where soils in the cryopeg zone have salinity of 1%, and the minimum cohesion value appears at a temperature of -3 ° C.

Patterns of cohesion change with increasing temperature and increasing salinity in loam and sand. In the sands with an increase in salinity from 0.01 to 0.05, the cohesion decreases by half at a temperature of -1 ° C. Loams with a salinity of 0.5% have minimal cohesion at 0.17 MPa at a temperature of -2 ° C, and when the temperature rises -1 ° C the soils have no cohesion.

Thus, the work evaluates the effect of temperature and salinity on the cohesion values of soils in the study area Yuribey River. The important point is that frozen soils can significantly lose their strength without going into a thawed state.

The obtained data will be used for further experimental studies of the influence of changes in climatic and geocryological conditions on the properties of the permafrost soils of the Arctic zone.

Study of dynamics of ice wedge polygonal system of peatlands under climatic and technogenic factors

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Ice wedge polygonal systems of peatlands were studied in the North-Eastern part of the Pur-Taz interfluve in the north of West Siberia.

Very high-resolution satellite images and even more detailed UAV orthophoto maps were used to assess changes in the surface of peatlands. The analysis of multi-temporal satellite images showed that the changes that occurred for more than 10 years from 2005 to 2016 are comparable with the changes for the last 2 years from 2016 to 2018.

Ongoing monitoring of permafrost parameters showed that climatic fluctuations of 2012-2013 caused thawing of ice wedges at different rates depending on variability of environmental factors and degree of technogenic influence. Extremely warm conditions of 2016 contributed to the increased ice wedge thawing.

Ground-penetrating radar (GPR) studies revealed details of the spatial variability of the seasonal thawing depth and the configuration of the top of the permafrost in the cross-section. The impact on these difference on natural and technogenic factors were studied in detail using this method. GPR also enabled the development of basic principles of integrated study of the top layer of the permafrost and the relief of polygonal peatlands with ice wedges in the cross-section and their dynamics in time.

A new method for the study of aeolian sedimentation in the peat areas was proposed and tested. The decrease in the layer of aeolian deposits with the distance from the source of deflation (road embankment) occurs quite sharply. The process is described by a degree equation with decent approximation R^2 = 0.82 for natural processes.

Based on all conducted field and laboratory studies and remote sensing data we defined certain general patterns. They imply the influence of last year's climatic changes in combination with technogenic factors on dynamics of peatland polygonal ice wedge systems in the study area. As a result, it was possible to make an assessment map of the degradation degree of peatland ice wedges. Peatlands are classified according to the degree of potential degradation of the surface and the top layer of permafrost.

Dynamics of active layer depth and ground temperature under climatic fluctuations and technogenic impact

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The long-term observation series in Central Yamal (since 1993) reveals the regularities of active layer depth and ground temperature dynamics under recent climatic fluctuations. Increased summer air temperature total precipitation in 2012 and 2016 caused a significant active layer deepening in all types of surfaces as compared with the previous period of 1993-2011 (12-20% in 2012, 24-37% in 2016). Ground temperatures increased on all surface types during 2012 and 2016. And at 10 meters depth for 5 years of observations there is a constant increase in the average annual ground temperature. The total increase was 0.5 °C.

The observations series on the north of Gydan Peninsula and the Pur-Taz interfluve are short (since 2016). Therefore, the only limited conclusion that can be suggested is that the colder ground temperatures and thinner active layers correspond to colder climatic conditions in this region.

To assess the impact of all kinds of technogenic activities, monitoring of active layer depth was initiated across vehicle tracks and in rather a recent sand quarry. An increase of active layer depth within the areas with technogenic impact in comparison with natural conditions was revealed to be 10-20%. On the disturbed surface of the quarry the melting of the ice wedges continues. Portions of quarry where vegetation cover restores active layer depths tend to values characteristic of natural conditions.

Observations in Central Yamal also include measurements of seasonal subsidence (since 2007). Subsidence at Vaskiny Dachi CALM grid ranges between 0 to 70 mm depending on soil moisture, snow thickness and soil salinity. More moisture and more snow show maximum subsidence. Saline soils show subsidence 25-35% less than non-saline. Salinity acts directly, through increase in unfrozen water content and thus less ice in winter and less subsidence in summer. Moisture content and snow cover provide moisture for active-layer ice lenses in winter, at the same time, determining slower freezing in winter and more intensive frost-heaving with more heaving in the cold season and deeper subsidence in warm season.

Impact of dangerious cryogenic processes on the transport infrastrucure in the Arctic

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The Arctic is the territory of perspective development. Strengthening of anthropogenic influence and noticeable climatic changes affecting the state of permafrost are negatively manifested for linear technogenic systems (LTS). We conducted complex field studies, numerical modelling, forecasting of the LTS state under changing conditions in the Arctic regions and defined five main types of LTS: pipelines (aboveground, onground and underground), city waterlines, electric lines, autoroads and railways. Pipelines, paved on the permafrost are traditionally arranged on supports that are raised above the surface and frozen into the ground; the main problem in this case is uneven frost heaving in the active layer. Deformations associated with dangerous cryogenic processes - thermokarst and thermoerosion develop in the zone of discontinuous and sporadic permafrost, which intensity is increasing due to climatic changes of recent decades; revealed that 30-40% of such LTSs are substantially deformed or even destroyed after 5-10 years of operation. About 70% of underground communications in the largest Arctic cities of Russia are in poor condition. We have analysed the potential hazards for the first time for all regions of Eastern Siberia and the Far East (about 300 administrative areas: uluuses, kujuuns) for roads and railways associated with thermokarst, thermoerosion, thermoabrasion, icing, frost heaving, frost cracking, moving of the rock glaciers. Negative effects from dangerous cryogenic processes are manifested in the form of frost cracks, formation of ice, dips, sliding slopes, wavy deformations, strengthening thixotropy of soils, lowering the bearing capacity of frozen bases.

Fieldwork was supported by the grant. RFBR 18-05-60080 “Dangerous nivalglacial and cryogenic processes and their impact on infrastructure in the Arctic”.

Mapping and risk calculation performed within support of the grant of the Russian Geographical Society No. 15/17: “Current state and dynamics of hazardous natural processes affecting the existing and prospective transport network of Siberia and the Far East.”

Arctic infrastructure at high risk by 2050

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It is becoming ever more evident that perennially frozen ground, permafrost, is warming at a global scale. In addition to the impacts on ecosystems, hydrology and geomorphology of permafrost environments, degradation of permafrost involves serious societal aspects. One of these is a threat to man-made engineering structures posed by thaw of ice-rich permafrost and resulting potential for ground subsidence, mass movements, and loss of structural bearing capacity.

We used statistical ensemble modelling to assess the temperature and extent of current and future near-surface permafrost, and to project permafrost thaw-related geohazards potentially yielding damage to infrastructure. Our approach combined an Arctic-wide extent (land areas north of 30°N) and a high spatial resolution (~1 km), which allowed for performing the first quantitative assessment of infrastructure elements (e.g., transportation and industrial constructions) and human settlements at risk in the Northern Hemisphere.

We found that nearly four million people and around 70% of the current infrastructure in the Northern Hemisphere are located on ground with high potential for near-surface-permafrost thawing by midcentury. Further analyses of the geotechnical hazard potential of permafrost thaw revealed that about one-third of all infrastructure is in high-risk areas. This includes 45% of the hydrocarbon extraction fields in the Russian Arctic and long segments of oil and gas pipelines. Alarmingly, we found that achieving the targets of the Paris Agreement would not do much to reduce the hazard potential by midcentury.

Our results provide important insights into the broad-scale development of geohazards in the near future and allow for identifying high-risk regions where localized hazard assessments should be targeted to facilitate sustainable development of Arctic communities. Thereby, our findings contribute to successful management of the impacts of the ongoing climate change.

Assessment of nutrient concentration and availability in ice-wedge polygon successional stages in a coastal Arctic tussock tundra near the Jago River, Alaska

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Nitrogen availability strongly influences plant productivity and distribution in Arctic environments. Recently, the Arctic has experienced warmer temperatures and the resulting permafrost thaw along the coastal Arctic tundra has caused ground subsidence, ponding, and the release of solutes and nutrients, impacting vegetation distribution. In patterned ground (polygon) permafrost systems, nutrient cycling can vary substantially across ice-wedge polygon successional stages. A better understanding of fine-scale spatial and temporal nutrient cycling among these ice-wedge polygon trajectories will improve the ability to predict tundra response to warming. This study took place during July and August of 2018 in a coastal tussock tundra site in Jago, Alaska. The study aims to identify and quantify plant-available inorganic nitrogen and total dissolved nitrogen in the soil, water tracks, and ponds of various successional stages of ice-wedge polygons, and to quantify %N and C:N ratios in plant biomass in each successional stage. Water samples were taken from various inundated or water-logged ice-wedge polygon successional stages and water tracks flowing throughout the transect, and NO_3^- and NH_4^+ uptake at each site type were assessed with buried bag experiments (still in progress) and AgWestern ion probes. Biomass was clipped from each successional stage to compare functional group composition, mass, and C:N ratios (still in progress). Clippings of the common wet tundra sedge *Eriophorum angustifolium* was also taken from each successional stage to use as a benchmark species to compare C:N ratios across site types.

Preliminary results show that though there are relatively small concentrations of NH_4^+, and especially NO_3^-, at all sites sampled, there is a greater availability of NH_4^+ and TDN in sites that are experiencing some degree of degradation and inundation. A one-way ANOVA found significant differences in NH_4 ($p= 0.0046$), TDN ($p=0.00026$), and DON ($p=0.0002$; data not pictured) among sites. AgWestern soil ion probes suggest greater N uptake at sites that have experienced some degree of degradation, and %N by weight of plant tissue from *E. angustifolium* increases slightly across successional sites. Greater average C:N ratios in *E. angustifolium* are found in tussock tundra (polygon center) and undegraded ice-wedge polygon sites. This preliminary data suggests that when permafrost thaws, the soil organic matter and minerals within the permafrost become available for remobilization and uptake, and the resulting increase in water may play a key role in the storage and transport of nutrients, influencing vegetation response to the warming Arctic. Future work includes completing the assessment of the buried bag experiments to compare with the data from the AgWestern ion probes; analysis of biomass clippings from each ice-wedge polygon successional stage for vegetation functional group composition, mass, and C:N ratios; and further studies of nutrient availability in relation to ice-wedge degradation or stabilization and the impending effect on Arctic tundra vegetation in additional sites in the coastal Arctic tundra.

Cryogenic processes distribution, monitoring and prediction using remote-sensing data

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Manual processing and visual interpretation were applied to very high-resolution data (Qiuckbird, Geoeye satellites). Various types of anthropogenic landscapes are easily identifiable, such as geocryological relief forms within Vaskiny Dachi research station. Using this precise data, “Object density” maps of anthropogenic areas and thermocirques were created for years 2009 and 2013. After this, density growth rate was estimated and spatial correlation between changes in infrastructure and thermocirques was calculated. The correlation is weakly positive and equals 0.15.

Middle resolution data (Landsat, Sentinel-2) are more suitable for studying Earth’s surface through a complex of vegetation indices. For this purpose, a Landsat-derived database was created for Ob’ Bay region and an automatic querying and processing algorithm was developed. The algorithm includes a selection of scenes depending on date, spatial intersections and vegetation development rate through air temperature (phenology). The algorithm calculates NDVI, NDWI and SWVI and compares them between the two scenes.

On the other hand, Sentinel-2 data were used to examine relatively new objects such as gas emission craters (GEC). Hypothesis of GEC formation allowed us to develop prediction maps based on known triggers and controls interpreted on imagery by supervised classification.

In addition, UAV surveying was used as a compromise between field methods of monitoring and classical remote sensing. UAV survey provides information about landscapes (mostly vegetation patterns and DEM) through 3D models or orthophoto maps with resolution up to 0.02 m/pix. UAV survey was applied to old and new research objects: thermocirque edges in 2017 and 2018 were compared to precisely detect the rate of retreat. A peat plateau near Gaz-Sale was also surveyed by UAV and orthophoto maps were compiled. At the same time, a tacheometric survey was made to complement the UAV survey. The orthophoto maps appeared to be efficient and precise. Very high-resolution satellite imagery analysis established nonlinearity of peatland degradation process and destruction of inter-polygonal depressions.

Configurations of "remoteness" (CoRe) - Entanglements of humans and transportation infrastructure in the Baykal-Amur Mainline (BAM) Region

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The Arctic and Subarctic have gained a surprising amount of attention in recent years. What used to be the 'remote' backwaters of global economic and political currents have morphed into a new frontier of geopolitics, resource extraction, and developmental designs. New transportation infrastructure often plays a critical role in these transformations. But its effects – accessibility, the shrinking of social and physical distance, the increased speed of connection – are not uncontested. On the one hand, those for whom 'remoteness' has been an asset, are often among the opponents of such developments. New transportation infrastructures are often not built to make the lives of local residents easier but to move cargo. Thus, there are 'winners' and 'losers' of such infrastructural developments.

Our key research question: Given the technosocial entanglement of people and infrastructure, how do changes in remote transportation systems affect human sociality and mobility?

CoRe is located in North Asia, at the junction of eastern Siberia and the Russian Far East. We call the area the BAM region because it is defined by the Baykal-Amur Mainline (BAM) railroad and its sidetracks. In that region there are pockets with a long history of industrial development and resource extraction, while many parts of the area have been little affected by Soviet and post-Soviet modernization efforts. Current attempts to revitalize, improve and extend the railway network serve as the backdrop for our project.

Permafrost State and Permafrost Dynamics: Key Indicators for Infrastructure Stability

Dmitrii Sergeev & Irina Utkina[1]

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Permafrost responds to climate change. This creates unforeseen problems for designers, who are forced to provide special design solutions for future structures. On the other hand, this creates problems for existing facilities. There will be a high risk when the rising infrastructure finds itself in a situation that there will not be enough money to repair it or create the engineering protection.

It is necessary to use the correct indicators that will help investors, economists and design engineers to make the adequate decisions on the basis of modeling and permafrost forecasting. The indicators used now, such as the mean annual temperature of the grounds at the depth of penetration of seasonal fluctuations, the depth of seasonal thawing and the characteristics of the areal distribution of permafrost, are of little use in management decision-making. These indicators do not reveal all the features of the state and dynamics of permafrost. For example, the salinity of soils leads to a significant loss of their bearing capacity with increasing temperature of the frozen soil, although it remains formally frozen in negative temperature interval. Another example is the depth of penetration of seasonal temperature fluctuations, which dramatically decreases when the permafrost starts to thaw.

Thus, a methodical approach is required which would help to form the expanded list of regional indicators of the state and dynamics of permafrost. Such indicators should be objective, comparable and relatively easy to determine in the field. For example, the indicator “position of the southern boundary of permafrost” is difficult to determine, since it strongly depends on the scale of mapping and it is difficult to assure by the field observation.

The experience of work in the North of the European part of Russia and in Transbaikalia allowed developing a generalized approach to the compilation of regionally significant indicators of the state of permafrost. This approach provides in addition to standard types of analysis: 1) justification of areas with constantly thawed, partially frozen and constantly frozen conditions, 2) mapping of areas with different ice content, gas content and salinity of grounds, 3) fixation of representative areas which the depth of seasonal fluctuations of temperature has the tendency to change.

In planning the geocryological forecast it is necessary to take into account: 1) the inhomogeneity of the permafrost table position and the case of phase transition zone is deeper than the penetration of seasonal temperature fluctuations, 2) the presence of fluids that carry heat in the permafrost thickness, 3) the presence of the instable temperature field associated with the heat exchange history, 4) the presence of saline or gas-containing rocks in permafrost.

All these considerations can be summarized in the form of a list of indicators of the state of permafrost conditions applicable both for each source of field data (pit, borehole), and for larger zoning taxons. The list includes such indicators as the depth interval within the seasonal temperature fluctuations are observed; averaged air, surface and soil temperatures at different depths and averaged within a group of sites (related to the coldest and warmest landscape types), as well as areas with different ground ice content, depth intervals with partial freezing and thawing (with the establishment of a criterion for unfrozen water); the temperature of the onset of phase transitions at the bottom of the active layer; the sign and magnitude of the geothermal gradient below the depth of penetration of seasonal temperature fluctuations.

For these indicators it is recommended to build the special maps of the state and dynamics of the geocryological conditions that is important for economic development of the territory.

Vegetation along the 1700-km Yamal Peninsula–Franz Josef Land Eurasia Arctic Transect

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The study provides ground-based vegetation data for satellite-based interpretations of the western maritime Eurasian Arctic, and the first vegetation data from Hayes Island, Franz

Josef Land, which is strongly separated geographically and floristically from the rest of the gradient and most susceptible to ongoing climate change.

We addressed the following questions: How do plant communities on zonal loamy vs. sandy soils vary across the full maritime Arctic bioclimate gradient? What are the main environmental factors controlling the transitions of vegetation along the bioclimate gradient? How are plant communities of these areas related to existing vegetation units of the European Vegetation Classification? The Braun-Blanquet approach was used to sample plots (mostly 5-m x 5-m) at 14 total study sites at six locations, one in each of the five Arctic bioclimate subzones and the forest-tundra transition. Trends in soil factors, cover of plant growth forms (PGFs), and species diversity were examined along the summer-warmth-index (SWI) gradient and on loamy and sandy soils. Classification and ordination were used to group the plots and to test relationships between vegetation and environmental factors. Clear, mostly nonlinear, trends occurred for soil factors, vegetation-structure, and species diversity along the climate gradient. Cluster analysis revealed seven groups with clear relationships to subzone and soil texture. Statistical clusters of plots at the ends of the bioclimate gradient (forest-tundra and polar desert) had many highly diagnostic taxa, whereas clusters from the Yamal Peninsula had only a few. Axis 1 of a Detrended Correspondence Analysis was strongly correlated with latitude and summer warmth; Axis 2 was strongly correlated with soil moisture, percentage sand, and landscape age. Summer temperature and soil texture had clear effects on tundra canopy structure and species composition, with consequences to ecosystem properties. Each layer of the plant canopy has a distinct region of peak abundance along the bioclimate gradient. The major vegetation types are weakly aligned with described classes of the European Vegetation Checklist indicating a continuous floristic gradient rather than distinct subzone regions.

Appendix C: Key Science Questions from the 2017 RATIC Workshop

These research questions were developed by participants at the 2017 RATIC Sustainable Arctic Infrastructure Workshop at Arctic Science Summit Week in Prague, Czech Republic.

Umbrella Questions

- What is our capacity to predict and forecast impacts of climate change on infrastructure?
- To what extent can information on landforms and surface features inform the prediction and planning of infrastructure stability?
- Can we use an integrated systems approach to better understand the interaction between the infrastructure and the impacts of climate change?
- What are the thresholds and positive-feedback effects that amplify climate change effects on infrastructure?
- What technologies are needed to identify catastrophic events and on-going environmental change?
- How can we improve prediction of extreme effects (e.g., avalanche forecasting, sea level rise, flooding, loss of ice roads)?
- Can we develop improved 3-dimensional models (3 dimensions plus time) of heat transfer in permafrost?
- Is global snow modeling appropriate for the Arctic context since much of the science is based on alpine environments (e.g., avalanche research)?
- How can engineering solutions be adapted to different socio-economic systems?
- How do we more effectively involve local communities and government in this conversation?
- How much money is society prepared to pay to address impacts?

Corridors (e.g., pipelines, railways, roads)

- What are the permafrost-hydrology interactions in infrastructure corridors?
- What are engineering solutions to keep permafrost stable under railways and highways?
- How can we minimize thermal disturbance to permafrost with minimal cost?
- How do we predict the extent and cumulative landscape effects of expanding networks of roads and pipelines and their interactions with climate change?
- What are the impacts of road dust on water quality and pollution?
- What are the safety issues and what safety technology is available?

Onshore Oil & Gas Infrastructure

- What are the effects of increased ice-wedge thermokarst on wildlife, hydrological systems, and access for subsistence?
- How do different landscape settings, cultural settings, and historical factors affect the cumulative outcomes of oil and gas development?
- How do summer and winter infrastructure differ in their socio-ecological impacts and their interactions with climate change (e.g., ice roads vs. gravel roads)?
- How do we minimize landscape fragmentation by networks of roads and pipelines?
- How do we protect areas of high cultural and ecological value from expanding networks of pipelines and roads?
- Where is the concept of adaptive management working?
- How do we develop more effective planning tools for adaptive management?
- What are successful policy strategies for coping with climate change in oil & gas infrastructure systems?

Urban Infrastructure

- Can we develop an index of sustainability?
- Can we perform city-wide monitoring and develop data sharing and data management protocols so information doesn't get lost with ownership or contract changes?
- How can we study the complexity of urban infrastructure?

Remote Communities

- How do we improve the resilience and reduce vulnerability of communities to climate change impacts?
- How do we integrate multiple knowledge systems including local expertise and leadership in understanding the Arctic and developing policy?
- In evaluating human capital, how do we identify strengths and gaps?
- How can a co-design, co-production approach to answering science questions to improve our communication of results and empower decision-making?

Indigenous Infrastructure (e.g., corrals, trails, camps)

- How does seasonality as a very specific aspect of indigenous infrastructure vary in the context of climate change?
- How are different types of infrastructure valorized negatively or positively along a spectrum in indigenous perceptions:
  - Negative: Over-reliance on infrastructure or the feeling of being trapped by it
  - Neutrality: Indifference
  - Positive: “Making it ours”

Appendix D: 2019 Breakout Group Notes

Discussion Questions

Breakout groups at the RATIC 2019 workshop were given one hour to address the following topics:

1) What are some current or planned/funded projects related to Arctic infrastructure impacts and sustainability? (20 min)
2) What science or engineering questions need to be answered to achieve sustainable Arctic infrastructure? (i.e., what are our knowledge gaps?) (40 min)
   a) Which are most important?
   b) Which may be answered soon?
   c) Which will take longer or are unlikely to be answered in the foreseeable future?
3) If time:
   a) What are opportunities or strategies to address these questions?
   b) How can we work better together across disciplines and geographic boundaries?

Discussion Notes

I. Natural Environment Breakout Group

The Natural Environment breakout discussion was led by Skip Walker (USA) and Marina Leibman (Russia). Participants included Ivan Agapkin, Oleg Anisimov, Amy Breen, Howard Epstein, Ksenia Ermokhina, Olli Karjalainen, Artun Khomutov, Pavel Orekhov, Dmitrii Sergeev, Irina Utkina, Masaki Uchida, Goncalo Vieira, and Anna Virkkala.

Current RATIC-related initiatives and projects

- Permafrost state and permafrost dynamics: key indicators for infrastructure (Institute of Geoenvironmental Geoscience RAS, Moscow)
- Circumpolar CO2 flux network, established by Ted Shurr
- Land Cover and Land Use Change project on the Yamal Peninsula, Russia (Funded by the U.S. National Aeronautics and Space Administration)
- Navigating the New Arctic (NNA): Multidisciplinary research looking at interaction between natural, social and built environments in the Arctic (Funded by the U.S. National Science Foundation)

Priority research topics

Questions and recommendations have been categorized by class (I to IV) ranging from high feasibility and “low hanging fruit” (because data exists) to big science questions that are important yet difficult to answer with existing data.

Class I: Definitions & methodology

- What gradients/transitions should we use to separate the human-impacted environment from the natural environment?
- What is the circumpolar distribution of ground ice in permafrost?
- What is our criterion for defining environmental stability? When do we consider an environment changed from its original state?
- How do we track individual impacts?
- How do we track changes in the extent of infrastructure?
- Can we agree on a standard for classification of infrastructure types and impact?
- How do we define key indicators to describe permafrost state and dynamics?
- How can we improve cumulative impact assessment methods and promote use of their findings? Fiber optic cable on the North Slope of the Brooks Range in Alaska did not follow best practices that have been known since the late 1960s.

Class II: Products needed

- Pan-Arctic spatial database of past and future infrastructure projects. This can be used to ask how new projects overlap with permafrost thaw hot spots.
- Time-series analysis of past and current infrastructure to establish a baseline
- Establish indicators for permafrost evolution.
- Map ground ice distribution remotely at a fine scale (VHR-HR-LR imagery), use statistical modeling, and update the IPA ground ice map.

Class III. What is the impact of the natural environment on the built environment or infrastructure, and vice-versa? Identify rates of change, vulnerability and thresholds and how these vary across ecosystems and climatic gradients.

- What is the effect of infrastructure on natural environmental processes? Are there feedbacks to climate and back to infrastructure?
- How do climate fluctuations impact permafrost and the interaction between permafrost and infrastructure?
- How does the rate of impact change with respect to climate and other factors that change along climatic or other gradients (maritime/continental, vegetation type, soils, geology)?
- What is the footprint of different types of infrastructure on natural ecosystems?
- How much of infrastructure instability is due to poor design and research and how much to environmental factors (e.g., the types and presence of permafrost conditions)?
- What kind and intensity of impacts can different infrastructure or ecosystem types tolerate? In other words, where are the thresholds? How can we measure this?

Class IV: Big questions

- Is society prepared to pay the cost for adaption to environmental changes in the Arctic?
- How do we rehabilitate after infrastructure? Does this need to be addressed prior to developing infrastructure?

II. Social and Built Environment Breakout Group

The Social and Built Environment breakout discussion was led by Peter Schweitzer. Participants included Ranjan Datta, Magnus deWitt, Robbin Garber-Slaght, Natalia Krashnoshtanova, Stas Ksenofontov, Timo Kumpula, Roza Laptander, Olga Povoroznyuk, Barrett Ristroph, and Vasily Tolmanov.

Current RATIC-related initiatives and projects

- Sustainable Cities (George Washington University, USA)
- History and current interpretations of Northern Sea Route (Nikolaievna team, Tyumen Center for Arctic Research)
- Northern Sea Route project (Hohoko University, Japan)
- Mapping informal roads and how people use them (Vera Kuklina project, funded by the U.S. National Science Foundation)
- Glacial cryogenic processes and impacts on railways and pipelines (Moscow State University, funded by the Russian Foundation and Russian Geographical Sciences)
- Comparative circumpolar project on port facilities and maritime infrastructure (Funding being sought by Peter Schweitzer team, University of Vienna, Austria)
- Energy and infrastructure projects (University of Alaska Fairbanks, Alaska Center for Power and Energy, USA)

Priority research topics

Low Feasibility

- How can waste be disposed of in rural communities? (see work of Alaska Native Health Tribal Consortium)
- How can we preserve current infrastructure?
- How can scientific research be better applied at a practical level?
- Which infrastructure should be removed and how once it is in disrepair or little used?
- How can we measure the cumulative long-term impacts on infrastructure quantitatively and qualitatively?
- How can we better predict extreme weather events and prevent or mitigate the impacts?
- What are the limits of adaptation for non-human systems and for humans?

Medium Feasibility

- What buildings do people want to live in (and what are they willing to live in)?
- How can researchers better use indigenous knowledges?
- How can we improve the eqitable distribution and utility of infrastructure?
- How can negative impacts of industrial development on indigenous lifeways be reduced?
- How can we measure the impacts of different projects on communities at different time scales?
- How will increased traffic and infrastructure associated with the opening of the Arctic Ocean affect social dynamics in the circumpolar north?

High Feasibility

- Which vehicles will have less impact on the tundra and climate?
- How does permafrost melt affect rural infrastructure?
- What material properties of infrastructure could help meet local needs (e.g., by increasing flexibility)?

III. Russian Language Breakout Group (multidisciplinary)

The multidisciplinary Russian language breakout discussion was led by Nikolay Shiklomanov. Participants included Evgeny Babkin, Elena Babkina, Valery Grebenets, Rustam Khairullin, Andrey Petrov, and Anton Smolekov. (Not a complete list of participants)

Current RATIC-related initiatives and projects

- NSF-PIRE: Arctic Urban Sustainability (Funded by the U.S. National Science Foundation)
- Impacts of cryogenic processes on infrastructure in Russia (Funded by the Russian Foundation for Basic Research)
- CALM V (Funded by the U.S. National Science Foundation)
- Current status and dynamic of the natural hazards affecting the present day and potential transportation network of Siberia and the Far East (Funded by the Russian Geographic Society and Russian Foundation for Basic Research)
- Informal roads: the impact of unofficial transportation routes on remote Arctic communities (Funded by the U.S. National Science Foundation)

Priority research topics

- Development of affordable standardize methodology to monitor ground thermal regime on local and regional level
- Community-based monitoring and development of standardized scientifically-based engineering approach for individual housing
- Safe storage and utilization of industrial and domestic waste in cryolitozone

- Analysis of interactions between industrial and traditional economic activities
- Top-down megaproject-type development vs. local development based on traditional knowledge/innovation/entrepreneurship
- Boom and bust cycles and the need for sustainable infrastructure (un)development
- Forestry and related infrastructure: environmental and socio-economic impacts
- Energy infrastructure (renewables/nuclear)
- Relations between government social programs and infrastructure development (health care, demographic drivers)
- Analysis of legal/governance/tax regime(s)

Appendix E: 2019 Group Discussion Notes

Notes from the full group discussion at the end of the day have been loosely organized by topic. Comments made by individual participants have been summarized as separate bullet points. These do not necessarily represent a group consensus.

Developing a typology or classification of infrastructure

- Select regions where we have resources and that are representative of changes being seen in the Arctic, rather than trying to study everywhere. Using mixed methods, we can set up projects in these regions and involve local indigenous people to do various kinds of observations. This provides an efficient, productive way to channel our efforts.
- Studying climate impacts in areas that are already built upon allows us to get a truer socio-ecological perspective and understanding of the linkages between the natural and built environment. This contrasts with the usual natural science inclination to seek out undisturbed areas to study.
- How are we going to look at the interaction between infrastructure and the environment in oil fields, villages, and cities? How do we look at social systems? Is there a way to do it constructively on a global scale and standardize it? Creating standard data sets is a key issue.

Establishing a T-MOSAiC Arctic Infrastructure Action Group

Members

- Preference is for everyone at the RATIC workshop to come on board as members and then work in subgroups on specific activities.

Scope and strategic approach

- Goal of developing a strategic plan for infrastructure-related research by the end of year 3 and use the ASSW 2021 meeting in Lisbon or another meeting to advance it further.
- The Permafrost Carbon Network is a great model of people with disparate expertise getting together to write high-impact journal articles that have now been picked up by IPCC and others. However, that effort has funding from the U.S. National Science Foundation.
- NSF is just now funding tens of millions of dollars in RATIC-related research through its Navigating the New Arctic (NNA) program. These are supposed to have an international component and call for coproduction of knowledge with local indigenous communities. Sometimes NSF holds some money back or synthesizing activities. Even if they don't do that, there will be more research occurring that we can leverage.
- In part, RATIC has already succeeded in its original goals of bringing attention and funding to the issue of Arctic infrastructure development. We see that in the recent calls by NSF and the Belmont Forum for RATIC-related research. These address

the RATIC questions of: *What are the effects of infrastructure in the Arctic? How is climate change affecting infrastructure and vice-versa?* Is it possible to take advantage of that funding to answer some of these questions?

- T-MOSAiC and RATIC each have science questions, and a lot of information is out there. It's a matter of taking the T-MOSAiC science questions and tweaking the RATIC questions that fall underneath. It may change a little depending on who or what gets funded, but it's just a matter of articulating how RATIC is going to help T-MOSAiC answer those questions.
- MOSAiC is generating a new way of thinking about the Arctic ocean. It will produce an unprecedented level of sea ice information, but we can't wait three years for that data to become available. We can proceed by linking to MOSAiC themes. Sea ice, open water, winter conditions are all important in MOSAiC. We can target these areas and say, "these are the key questions we need with respect to infrastructure."

Monitoring and observation activities

- We should set up monitoring program(s) related to specific infrastructure types using a segregated or stratified sampling approach as in ecosystem science and data that may be currently available but scattered (e.g. Alaska Department of Transportation & Public Facilities, Transport Canada).
- We should tie monitoring activities to the MOSAiC expedition and what's going on with sea ice. We only have two years and there are a lot of directions we could go. We can't explore everything. Can we set up or continue observations related to the observations coming out of MOSAiC? What are the critical questions we can relate to infrastructure from changes in the atmosphere and sea ice? For example: *What's going on at the coast? What's going on along gradients or transects? Every year we see differences in where there is open water. How is that going to affect land areas?* Rain-on-snow events are one example of ocean and atmospheric conditions that affect local communities. More open water means more shipping, which will have many coastal impacts.
- Infrastructure monitoring data could be brought together in a database or article. People in this room have worked for industry as environmental consultants. We can potentially use those relationships to encourage data sharing.
- The observational network is critical. *How do we structure it? Do we do it along climate gradients or by vegetation type, geological characterization, or cryosphere criteria?* There are lots of examples (ITEX, LTER). Possibly the best is Zackenberg Research Station in northeast Greenland, because they started with a well-thought out plan for creating it from the ground up.
- The U.S. National Oceanic and Atmospheric Administration (NOAA) already has an observational network with respect to sea ice, land temperatures, and what's going on with vegetation. It's a tool we can use with T-MOSAiC.
- Creating an observational network is important but complicated from the social science perspective. With permafrost it's easy: you put in a borehole. With

infrastructure close to a community, the only way to study it is in close cooperation with a local community. The questions are: *What is to be observed? What do you look at on the health side or other behavioral parameters? Is it about subsistence activities?* There are a variety of possibilities that can only be actualized if the community is interested and is willing to participate. It's a very complex issue. It's doable, but much more difficult.

- Asking the same questions on a circumpolar scale is difficult because you need to respond to local needs and interests. You can suggest something, but if people say, "No, that is really not important for us," what is the point? Also, if you ask people about the impacts of infrastructure and climate change, they tend to combine them and see them as one thing.

Synthesis publications

- We should develop synthesis articles or publications that bring knowledge developed through social science, engineering and natural science together in the same documents to frame the questions at a bigger level. Possible examples include:
    - An article on the positive and negative impacts of roads, including ecological and sociological impacts, that once in the literature would have to be cited by every Environmental Impact Statement for road-related projects done in the North.
    - Article on flooding that looks at the sociological, ecosystem-level, and infrastructure sustainability implications of major flooding events and identifies best practices from different parts of the world.
    - A synthesis article already in production looks at the impacts of oil and gas development in Prudhoe Bay, Alaska. This could be expanded into a circumpolar analysis.
- Many things are already well understood and well-covered by data and models. The best thing would be to write a huge review paper or assessment report that establishes a baseline and sets out the next target for activities. Something similar to AMAP, IPCC's Ocean and Cryosphere assessment, or the Arctic Human Development Report. Are we targeted at this level or more specifically at promoting certain science projects and setting priorities for these projects?
- The aim is not to create another IPCC. We don't have the budget or the number of people to duplicate that. We have the target date of Dec. 31, 2019 to identify chairs or co-chairs, action group members, and a subset of projects to take place within a three-year window.

Appendix F: T-MOSAiC Arctic Infrastructure Action Group

Draft Scope

The Rapid Arctic Transitions due to Infrastructure and Climate (RATIC) initiative will assume the role of the T-MOSAiC Arctic Infrastructure Action Group during the 2019–2021 MOSAiC Arctic Drift Expedition. The action group will collaborate with T-MOSAiC to identify and promote activities and synergies that lead toward sustainable Arctic infrastructure, including those that:

- Monitor the consequences to natural terrestrial systems of unusual climate sea-ice, atmosphere, and ocean changes during the MOSAiC ice-drift expedition.
- Observe and monitor consequences to the built environment, including, roads, runways, railways, pipelines, and indigenous, village, and urban infrastructure.
- Examine the consequences of climate and infrastructure changes to Arctic social systems.
- Begin developing an Arctic infrastructure observing network, with a focus on coastal and near-coastal social-ecological systems in ice-rich-permafrost environments.

RATIC was born with the goal of promoting sustainable Arctic infrastructure as a key research theme requiring a collaborative multidisciplinary approach involving scientists, local communities, governments and industry.

Co-Chairs

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Permafrost
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Polar Ecology
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Members

T-MOSAiC organizers at the workshop invited all participants at the RATIC workshop to become members of the T-MOSAiC Arctic Infrastructure Action Group. Action group members will:

- Be listed as a member on the action group web page
- Be informed of upcoming workshops and meetings
- Be invited to collaborate on specific action group activities based on their interest and expertise
- Be given the opportunity to help direct the scope and focus of the action group

Workshop participants can opt-out of membership by emailing the action group coordinator at jlpeirce@alaska.edu.

Website

www.t-mosaic.com/infrastructure.html

Breakout groups: (Top row) Natural Environment, (middle) Social and Built Environment, (bottom) Russian Language.