T-MOSAiC

Terrestrial **M**ultidisciplinary distributed **O**bservatories for the **S**tudy of **A**rctic **C**onnections

Science Plan

INTERNATIONAL ARCTIC
SCIENCE COMMITTEE

IASC

December 2018

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Executive Summary

Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAiC) has been formulated as a research and synthesis project to provide an integrated, cross-disciplinary evaluation of how the changing Arctic Ocean affects terrestrial environments, from the coastal zone to the continental interior. The project will connect studies taking place throughout the Arctic and across disciplines in order to generate new insights into northern geosystems, ecosystems and human systems. Key aspects to be addressed include connectivity, gradients, discontinuities, thresholds, extreme events and emergent properties, with specific questions that bridge sites and disciplines. Data sets will be made available via open access repositories, with the intention to create merged, interoperable data compilations. T-MOSAiC will run in parallel to the ocean-based project Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), with temporal overlap in 2019-2020 and exchange of data sets such as climate observations from land and ocean stations.

Introduction

Large regions of the Arctic are currently warming at rates that are more than twice the global average, and current projections (*IPCC 2018*) indicate that amplified Arctic warming and associated impacts are expected over the course of this century. The most conspicuous impact to date is the major contraction of Arctic sea ice area and volume, with the increasing likelihood of ice-free summer conditions within the next few decades (*Overland et al. 2014*). This regime shift in the Arctic Ocean is likely to have wide-ranging effects on land.

Changing sea ice conditions will have direct impacts on the Indigenous communities that live on northern coasts. Many of the traditional, culturally and nutritionally important foods harvested by these communities are marine species that depend on cold, ice-containing waters (*Hoover et al. 2016; Huntington et al. 2016*). Diminished ice conditions are opening up the region to increased marine transport, providing new opportunities for tourism and other commercial shipping activities across Arctic seas and at coastal ports, with the concurrent risk of accidents (*Milesky et al. 2018*). Greater wave exposure combined with warmer temperatures is causing rapid coastal erosion at some sites (*Fritz et al. 2017*). There are also potential effects on the stability of permafrost (*Cai et al. 2018*), which underpins northern lake and river catchments, terrestrial biogeochemical processes and engineered infrastructure such as roads, runways and buildings (*Vincent et al. 2017*). The changing sea ice regime and Arctic Ocean climate appears to be affecting terrestrial ecosystems in a variety of ways, including via impacts on plant dispersal, animal migration and vegetation gradients (*Post et al. 2013; Forchhammer 2017; Macias-Fauria & Post 2018*). Loss of sea ice may result in an increased frequency of extreme warming events (*Screen et al. 2016*) and is paralleled by loss of Arctic lake ice (*Alexeev et al. 2016*). The melting of ice on Arctic lands, notably the Greenland Ice Sheet, has complex, reciprocal interactions with the ocean (*Straneo et al. 2016*), and the increased duration of open Arctic seas is likely to affect cloudiness and precipitation (*Bintanja & Andry 2017*) in the terrestrial as well as oceanic environment.

Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections (T-MOSAiC) has been formulated as a research and synthesis project to provide an integrated, cross-disciplinary evaluation of how the changing Arctic Ocean affects terrestrial environments, from the coastal zone to the continental interior. It aims to build an improved understanding of how northern lands and seas are connected, and to thereby inform policy development and decision-making in the face of the massive changes that are now occurring across the region, and that will continue to intensify over the course of this century. The project takes a systems-level approach to connect diverse studies at multiple

scales, including legacy effects of past conditions, the local impacts of rapid warming, and reciprocal interactions between the Arctic and the rest of the world.

T-MOSAiC has been catalysed and inspired by the ocean-atmosphere project **Multidisciplinary drifting Observatory for the Study of Arctic Climate** (MOSAiC). This large-scale project is the result of many years of planning under the auspices of the International Arctic Science Committee (IASC), and it is culminating in 2019-2020 in the deployment of 600 science personnel in the central Arctic Ocean via the freeze-in and drift of the icebreaker Polarstern, with support by other vessels, aircraft, ice camps and satellite remote sensing. In essence, MOSAiC is focused on the question "What are the causes and consequences of an evolving and diminished Arctic sea ice cover," with strong emphasis on an improved understanding of energy exchanges between the atmosphere, sea ice and ocean. T-MOSAiC, also under the auspices of IASC, asks the related question: "What are the implications of changing sea ice, oceanography and climate of the Arctic Ocean for the surrounding land-based geosystems, ecosystems and human systems?" T-MOSAiC aims to help support improved models, projections and policy decisions, and to extend new insights from MOSAiC to the lands and people around the Arctic basin.

The T-MOSAiC Science Plan is the result of a series of international workshops funded by IASC and partner organisations. This document first describes the genesis of T-MOSAiC, the development of its research themes and its conceptual relationship to MOSAiC. It then outlines the central hypotheses of the project, along with the overarching systems-level themes and working group subject areas. Finally, the steps towards implementation are described, including sources of funding support and other resources. The 'T-MOSAiC Implementation Plan' will be produced in 2019 after community-wide consultation.

Development of T-MOSAiC

T-MOSAiC began as an initiative of the Terrestrial Working Group of IASC at the IASC business meeting of the Arctic Science Summit Week (ASSW) in Prague in April 2017. Members of the working group agreed to explore the possibility of coordinated, complementary activities that would both 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. A poster presentation within the IASC MOSAiC workshop outlined potential areas of research activities (*Canário et al. 2017*), which formed a basis for the present Science Plan:

- Synthesis of atmospheric monitoring data from remote stations, along with measurements and models of permafrost, snow and glacier mass balance across different scales;
- Estimates of past changes in land and inland water systems, measurements of current states (e.g., via transects, drones); and
- Analysis of how changing precipitation and temperature regimes are affecting the wide range of Arctic ecosystem services: provisioning, supporting, regulating and cultural.

This established the potentially broad sweep of topics to be covered in the project, from the atmosphere and cryosphere (snow, ice, permafrost), to elemental cycles, vegetation, food webs and people. A first workshop was organized in Quebec City in December 2017, co-funded by IASC and the Canadian projects ArcticNet, CEN and Sentinel North, and was attended by around 70 people from many nations. It led to the linking of existing projects described below, as well as to the formulation of system-level hypotheses and themes, and the establishment of a Steering Committee (including many representatives from the Association of Polar Early Career Scientists, APECS) and an Executive Committee (ExCom) that lead the ongoing development and coordination of T-MOSAiC (Appendix 1). The second T-MOSAiC workshop took place in Davos in June 2018 and provided an opportunity to launch the T-MOSAiC website and secretariat, and to identify projects and themes that would be linked within the T-MOSAiC consortium. Participation of MOSAiC representatives in this workshop allowed the relationships between the two projects to be much better resolved, with the joint production of a conceptual diagram that summarized the linkages (Figure 1). A meeting of the T-MOSAiC ExCom in Lisbon in September 2018 further developed the systems-level objectives of the Science Plan.

Relationship between T-MOSAiC and MOSAiC

The two IASC projects T-MOSAiC and MOSAiC share certain similarities: both address systems-level questions about the structure and functioning of the Arctic and its reciprocal interactions with the rest of the world, and both lie within the priority areas for future research as defined by the IASC roadmap (ICARP-III, Box 1). However, there are fundamental differences, and the two projects are independently funded and executed with little overlap of personnel (but ongoing exchange) between the two. MOSAiC is a marine based project that centers on the freeze-in deployment of a highly equipped research platform, the PolarStern, which will drift across the North Polar region over the winter of 2019/2020. In contrast, T-MOSAiC links together observations from several hundred monitoring sites and field stations distributed around the circumpolar North, with more than 50 of the core stations operating within the EU Horizon 2020 network INTERACT.

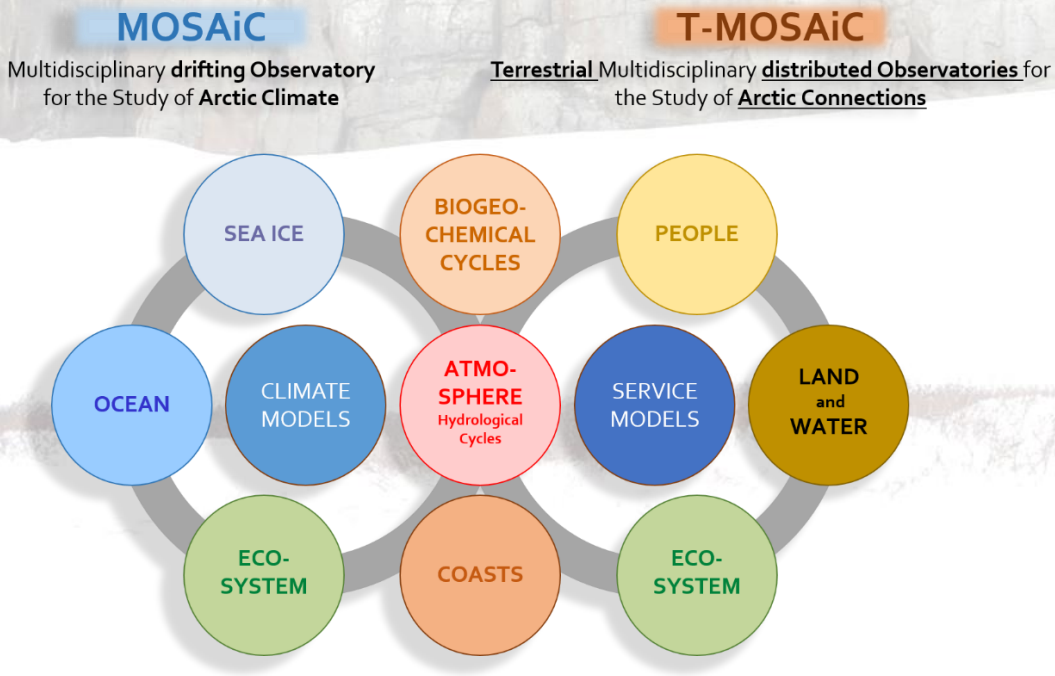

Figure 1. Schematic diagram showing the conceptual relationships between the MOSAiC and T-MOSAiC research projects

MOSAiC and T-MOSAiC interface across a number of theme areas, notably Atmosphere and Hydrological Cycles, Biogeochemical Cycles, and Coasts (Figure 1). With its focus on the central Arctic Ocean, MOSAiC will undertake studies on Sea ice, Oceanic and Marine ecosystem processes, while T-MOSAiC, with its focus on land, will collect, integrate and synthesize information related to human activities, the atmosphere, landscapes, land-based ice and snow, and terrestrial/freshwater ecosystems including biodiversity and ecological processes.

Modeling is a major activity in MOSAiC, with the aim to better parameterize and constrain atmosphere/sea ice/ocean energy exchanges, and to thereby improve global projections as well as local weather forecasting. Modeling will also be a component of T-MOSAiC, with the aim to produce ‘Service Models’ that support scenario analysis in environmental assessments of the terrestrial, freshwater, and coupled socio-ecological systems. These will include conceptual and qualitative models as well as statistical and dynamic simulation approaches.

Model outputs from MOSAiC will be used to generate scenarios of how regional climates will change in the coastal Arctic, while T-MOSAiC insights will be used to project the impacts of such climate change on permafrost and ice-rich landscapes (including glaciers), terrestrial ecosystems (including hydro-ecosystems such as lakes, rivers and wetlands) and northern communities (including infrastructure). T-MOSAiC research will take place on land and often in close association with the Indigenous communities that live there; attention to Indigenous questions and priorities (Box 2) will be encouraged throughout the program, including joint research and knowledge exchange with northern communities.

Box 1. T-MOSAiC and ICARP III

The International Arctic Science Committee (IASC) is required to undertake periodic evaluations to "review the status of Arctic science, provide scientific and technical advice, and promote cooperation and links with other national and international organizations." The most recent of these reviews took place via the 'International Conference on Arctic Research Planning III' that culminated in a final meeting in Toyama, Japan 2015 (ICARP III). The resultant roadmap sets out Arctic science priorities for the subsequent decade. The T-MOSAiC Science Plan fits within the three pillars of ICARP III:

- **The Role of the Arctic in the Global System**, especially 'assessing and understanding rapid Arctic climate change and Arctic amplification';

- **Observing and Predicting Future Climate Dynamics and Ecosystem Responses**, including 'the development and deployment of new technology to improve our understanding of the physical, ecological and social environments of the Arctic';

- **Understanding the Vulnerability and Resilience of Arctic Environments and Societies and Supporting Sustainable Development**, including 'the impacts of extreme weather events' and 'the diverse impacts of climate change and human activities on Arctic biodiversity and its consequences'.

The full report is available at:
https://icarp.iasc.info/

Box 2. Indigenous Partnerships and Priorities

Arctic and Northern Indigenous Peoples currently face the combined pressures of rapid socio-economic change and the regional and local environmental impacts of climate warming. There is an established need to prioritize Indigenous research objectives, which are clearly articulated in the planning documents and reports of Indigenous organizations. For example, in North America, both the Inuit Circumpolar Council and the Inuit Tapiriit Kanatami have laid out pathways forward for Inuit self-determination in research.

Following recommendations made in Canada as a guideline (ITK 2016; ITK 2018), T-MOSAiC will encourage Indigenous led projects where possible and where desired by Indigenous people. T-MOSAiC will contribute to Indigenous objectives by recognizing Indigenous rights in fundamental science and research, partnering with Indigenous organizations wherever possible, respecting and supporting Indigenous Knowledge, incorporating Indigenous observation and monitoring systems, training and supporting Indigenous students, and openly sharing data and information with Arctic Indigenous People. T-MOSAiC will provide data and information freely to support resiliency in Arctic communities, to support climate adaptation, and to understand emerging threats to infrastructure and food and water security, among other Indigenous priorities (see for example: Inuit Circumpolar Council-Alaska 2015). Partnership with Indigenous organizations and communities will guide and further refine T-MOSAiC efforts.

Above is one example of a community partnership that guided project selection and research activities – an Integrated Regional Impact Study (IRIS) for the eastern and central Canadian Arctic. This partnership and consultation with northern communities at all stages, from project formulation to reporting, led to specific recommendations for action in research related to housing, food security, education, health, employment, water quality and the impacts of climate change and resource development. The Inuktitut version is illustrated here, with versions also available in Inuinnaqtun, Siglitun, Uummarmiutun, French and English (ArcticNet 2015).

T-MOSAiC and MOSAiC take a special interest in winter properties and processes, because these are poorly understood in both the marine and terrestrial environment. Most sampling campaigns take place in the summer period, but there is increasing evidence that processes during the winter months exert a controlling role on many Arctic system properties, including the set-up conditions for processes in spring and summer.

Most importantly, T-MOSAiC and MOSAiC consider the Arctic as a highly coupled system in which changes in one component can have cascading effects that alter the overall functioning of the Arctic and its responses to future change. Both projects will pay special attention to the interactions among system components, including the importance of emergent properties and emerging issues that derive from these collective interactions and that cannot be predicted from the behaviour of individual components.

Overarching Hypotheses

T-MOSAiC is based on land but looks toward the atmosphere and ocean as environmental drivers of terrestrial change. Gradients inland from the coastal boundary of Arctic seas are therefore of special interest to T-MOSAiC (Figure 2).

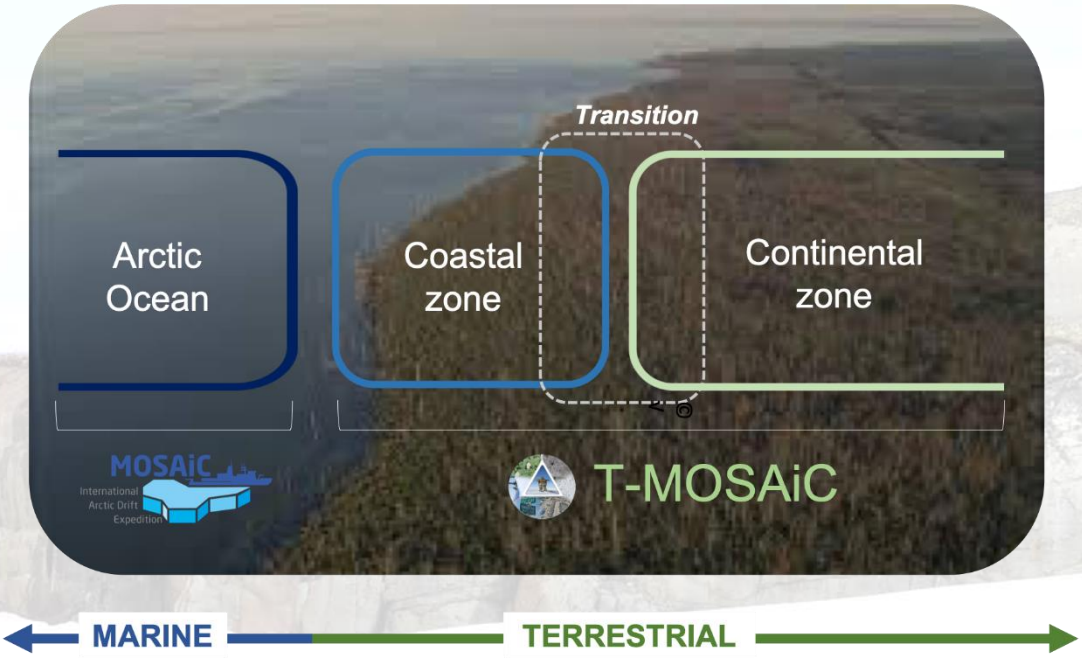

Figure 2. The terrestrial zones considered by T-MOSAiC.

T-MOSAiC will address a series of hypotheses that relate to marine influences on the coastal land environment, specifically:

- All system properties in the 'coastal terrestrial zone' are influenced by Arctic Ocean sea ice, climate and marine processes, and;
- There are discontinuities in terrestrial system properties in the 'transition zone' to the 'continental zone'.

The observations and analyses will also extend along transects inland to test the hypotheses that:

- There are strong gradients of system properties in the continental interior, and;
- These are also affected by the Arctic Ocean dynamics.

The Arctic system: Themes and Questions

T-MOSAiC will take a systems-level approach (see *Vorosmarty et al. 2018*). Special attention in all projects will be paid to the following thematic areas and relevant research questions that cut across all components of the Arctic system, from geosystems to ecosystems and human systems:

- **Connectivity** – What are the specific linkages of terrestrial systems to the marine environment, and the linkages among components of the terrestrial system, as indicated in Figure 1. What is the nature and strength of those linkages?

- **Gradients** – How do terrestrial system properties, processes and sensitivity to climate change across coastal gradients and across north-south gradients, as indicated in Figure 2.

- **Discontinuities and thresholds** – Are there abrupt changes in properties and processes, over time and space, and if so of what magnitude and duration? These encompass physical discontinuities such as loss of multi-year ice, loss of winter bed-fast ice, transition of snow to rain, as well as biological step-changes, such as the arrival of an invasive species or pathogen.

- **Feedbacks** – What are the negative feedbacks that may dampen environmental changes and support resiliency, versus positive feedbacks that amplify the effects of perturbation? The ensemble of processes giving rise to 'Arctic amplification' is an encompassing example of the latter.

- **Extreme events** – What are is the nature and effects of anomalies, such as unusual warming or precipitation? Such events include fires, floods and landslides, with implications for humans and wildlife, as well as for landscapes.

- **Legacy effects** – How is the current behavior of the Arctic system influenced by its past? Examples include modern day glaciers, ice caps (including the Greenland Ice Cap) and permafrost, all of which are legacies of cooling in the past.

- **Emergent properties** – What aspects of system behavior cannot be predicted from that of any single component? For example, the net methane emission from Arctic inland waters is the result of complex interactions among a myriad species of microorganisms that produce organic matter, hydrogen and CO_2, as well as among those that produce or oxidize methane.

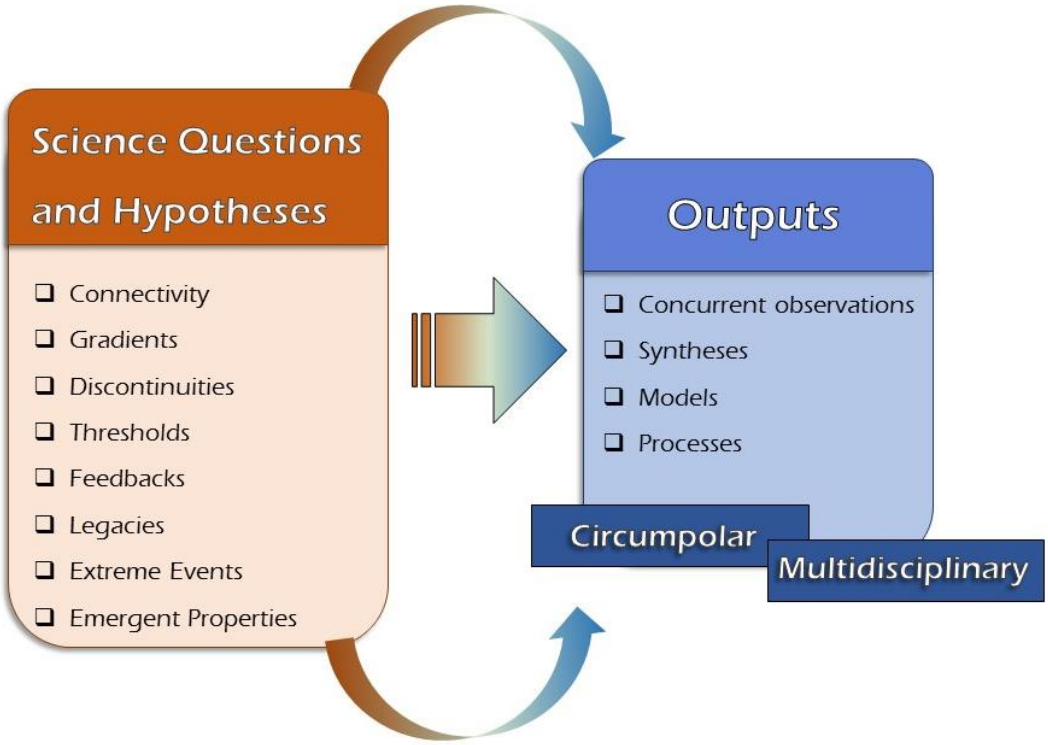

Figure 3. T-MOSAiC aims to consider systems-level themes to achieve a wide range of outputs across disciplines and locations in the circumpolar North.

T-MOSAiC Studies

T-MOSAiC will encompass a broad range of potential subject areas (see Box 3 below). One of the goals during the implementation planning phase will be to identify specific questions and objectives that bridge sites and disciplines, and that will focus collaborative research activities within the systems-level framework. For example, these could include: how did the climate regime of the MOSAiC-T-MOSAiC observation period in 2020 compare with long term records from land-based stations and paleoclimate records across the region; can land-based stations be used to improve radiation models and remote sensing products for Arctic seas and the surrounding lands; will future shifts in precipitation from snow to rain be more severe at the coast than in the continental interior, and what will be the impacts on permafrost, hydro-systems, ecosystems and infrastructure; are extreme events related to record minimum sea ice conditions; will increased coastal access by ships cause abrupt changes in terrestrial systems, and to what distance inland; what is the circumpolar variation in terrestrial sensitivity to changes in Arctic sea ice and climate. Specific questions and objectives from Indigenous representatives and communities will be welcomed.

Collaborations from research teams, holders of archived data or samples, as well as individual researchers will be welcomed, and requests for formal endorsement by the T-MOSAiC Executive Committee will be considered relative to the following criteria: collaborations (local, national and/or international); systems-related (incorporating one of more of the Arctic system themes presented above); interdisciplinary (where possible); output focused (synthesis paper, data compilation, new or refined models, validation of remote sensing data, new sets of observations or experiments); and data management plans. Consideration should be given wherever possible to outreach/education opportunities and collaboration with local communities.

MOSAiC takes place during 2019-2020, and T-MOSAiC will therefore strive to achieve as much overlap as possible, with the main 12-month period from January to December 2020 identified as the main period for new and concerted observations. Projects such as the synthesis of environmental monitoring records and paleoclimate studies will provide a valuable opportunity to place the 'MOSAiC-T-MOSAiC observation period' in a much broader temporal context.

Box 3. Potential research topics in T-MOSAiC

Atmosphere & hydrology Climate stations records – IASOA and other stations as available; Long term records; Paleoclimate records to provide a Holocene context for interpreting change; Energy fluxes, with use of land-based station data to validate models and remote sensing.

Coasts Coastal zone stability and erosion; Interactions with the sea.

Biogeochemical cycles Carbon and other elemental cycling; Permafrost carbon lability; Land-Water-Atmosphere gas fluxes; Sediment–nutrient fluxes; Oxygen dynamics in aquatic ecosystems; Contaminants including heavy metals.

Ecosystems Biodiversity of plants, animals & microbes (including viruses); Vegetation (including via satellite and UAV observations); Wildlife population dynamics; Land and freshwater food webs.

Land and water Permafrost (including GTN-P, ADAPT and other monitoring records); Ground ice; Lake and river ice; Snow properties; Snow/water ratios in precipitation; Landscape processes; Geomorphological dynamics; Hydro-systems and water fluxes/levels; Glacial processes and ice balance.

People Engineered infrastructure including roads and houses; Zoonoses - diseases that can be passed from animals to humans; Health aspects – contaminants; Country food access, habitat change; Drinking water security; Food security; Tourism; Maritime transport; Cultural heritage; Adaptation to climate change.

Service models Socio-economic models; Cultural and traditional knowledge models; Climate projections/weather models; Implications of changing sea ice for land; Wind, precipitation, temperature, humidity, precipitation, cloud models; Paleoclimate models (transfer functions); Radiation models (calibration of satellites); Ecological and biogeochemical models; Extreme events models (frequency, intensity, duration); Models for end-users.

Funding Support

T-MOSAiC provides a wide range of benefits to participating researchers (see 'Why participate in T-MOSAiC?' below) and is supported through three tracks of funding and in-kind resources. Firstly, dedicated funding has been obtained for certain networking activities. The Government of Portugal has provided funding for the T-MOSAiC secretariat, and IASC has provided funds for workshops, specifically to support the participation of early career researchers.

Additional workshop support has been provided by centres and programs in Canada, notably the Centre for Northern Studies (CEN), the NCE program ArcticNet and the CFREF program Sentinel North. Secondly, new proposals and developing projects have included links to T-MOSAiC, as a way to foster international collaboration and to place specific studies in a broad circumpolar context. Finally, ongoing programs in the Arctic are providing data, expertise and other in-kind support to T-MOSAiC.

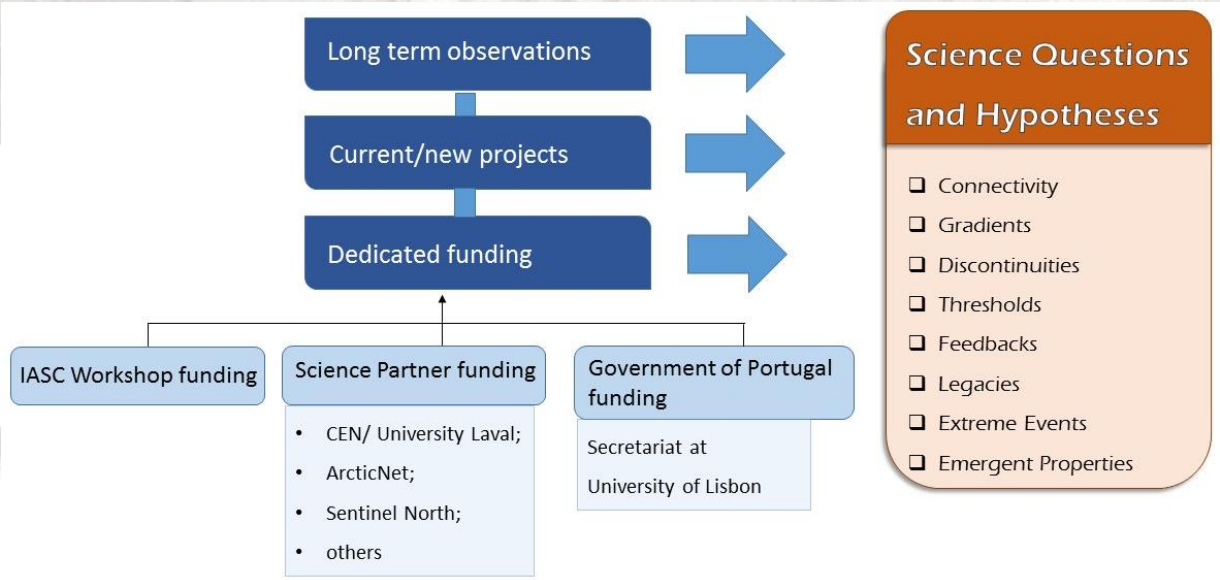

Figure 4. The three tracks of funding support for T-MOSAiC.

Data Management

The early career members of the Steering Committee of T-MOSAiC (Appendix 1) underscored at the first workshop the critical importance of data management. Open access to data (and its associated metadata) for sharing and collaboration will be a priority for T-MOSAiC. To the extent possible, data should be deposited in doi-referenced repositories and published as stand-alone products in data science journals to ensure a T-MOSAiC data legacy for the future, and in keeping with the Commitment Statement in the Earth, Space, and Environmental Sciences (*COPDESS 2014*). Attention will be given to the FAIR principles for data management: Findable, Accessible, Interoperable and Reusable (see *Wilkinson et al. 2016*). Efforts will be made towards producing merged, interoperable data sets, and there will be coordination with other data initiatives, such as the Canadian Consortium for Arctic Data Interoperability (CCADI).

Management and Coordination of T-MOSAiC

T-MOSAiC is managed through an Executive Committee, with scientific direction provided by a Steering Committee. Day-to-day operations are coordinated through the T-MOSAiC Science Coordinator, Mr. Diogo Folhas, who is based at the T-MOSAiC Secretariat at the University of Lisbon. T-MOSAiC welcomes participation from all nations and disciplines, and from Indigenous communities and organisations. For the endorsement of projects, the initial contact should be via the Coordinator. Requests for projects and networks to be officially endorsed by T-MOSAiC are considered by the Executive Committee (see above for criteria). News and updates on T-MOSAiC activities are provided regularly via the T-MOSAiC website: https://www.t-mosaic.com/

Why participate in T-MOSAiC?

• Join an international project across disciplines that targets key physical, ecological and societal issues affecting the Arctic and the world, at this critical time of rapid change and international decision-making;

• Contribute to fill key observational data in gaps identified by the T-MOSAiC science program;

• Assure laboratory and project visibility at the international level;

• Benefit from T-MOSAiC and IASC grants for early career researchers for networking;

• Link with large T-MOSAiC partners such as MOSAiC, INTERACT, Sentinel North, Nunataryuk, RATIC and others;

• Develop new collaborations, including across disciplines;

•Have research endorsed by T-MOSAiC and use this as a research priority stamp of support to apply for national/international funding.

Acknowledgements

We thank Ingibjörg Jónsdóttir for initiating discussions about land-based activities in parallel to MOSAiC, at the 2017 ASSW meeting of IASC; Markus Rex, overall lead of MOSAiC, for his encouragement, helpful advice and guidance, including for his co-formulation of Figure 1 with Taneil Uttal; and all members of the T-MOSAiC committees for their input to this document. We also are grateful to IASC, Sentinel North, ArcticNet, Centre d'études nordiques (CEN), Université Laval, Fundação para a Ciência e Tecnologia (Portugal) and University of Lisbon (IST and IGOT) for their funding and in-kind support to T-MOSAiC, and to all participants in the T-MOSAiC workshops past, present and future, for their stimulating ideas and ongoing input anad feedback.

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Appendix 1.

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