- **<u>Objectives:</u>**

The site is to be based in Cambridge Bay, Nunavut with the Canadian High Arctic Research Station (CHARS). MOACC's monitoring strategy involves establishment of baseline Arctic datasets at the leading edge of current measurement capabilities, which may be generalized to the wider Arctic. Our monitoring strategy will be applied within the context of four research themes: TH1-Snow Remote Sensing and Ecological Applications; TH2-Snow Modeling and Hydrology; TH3-Atmosphere, and TH4-Permafrost. While each theme has its own motivation and objectives, they are inevitably linked together by climate change and impacts that transcend the Atmosphere-Snow-Ground interface (ASGint) system.

**THEME1:** The main objectives of this theme are: (1) to develop new techniques to derive snow water equivalent (SWE) and stratigraphy using passive and active microwave data; and (2) to quantify the processes governing snow spatial distribution using innovative photogrammetric approaches (Structure-for-Motion) at the in-situ and airborne scales. Snow retrievals approaches from (1) and (2) will be used (3) to map snow properties at various scales to assess ungulates foraging conditions. Finally, we will (4) continue our development of remote sensing algorithms capable of monitoring extreme events using satellite passive microwave data and in-situ Frequency Modulated Continuous Wave (FMCW) radars that will enable us, along with results from (3), (5) to develop an ungulate habitat quality index based on surface snow conditions and extreme event occurrence. The theme will also aim at developing a methodology to retrieve high-resolution snow information from unmanned aerial vehicle-UAVs (small scale).

**THEME 2:** The main objectives of the theme will be: (1) to pave the way towards improved model approaches by quantifying isotope values ($\delta^{18}O$, $\delta D$) of Arctic snow cover in order (2) to evaluate linkages between physical and geochemical measurements according to snow stratigraphy, weather factors and seasonal evolution providing a nice link to Theme 1. We will also (3) quantify the geochemical components of winter snow cover and spring snowmelt (4) to determine snow contributions to spring flow of the major river systems associated with the Greiner watershed at the MOACC site. These results will allow (5) the development of an isotope routine to be implemented in our snow simulation platform developed by the Université de Sherbrooke team [18] to better understand flow patterns in other important watersheds of the Arctic. Finally, this snow simulation platform will also (6) aim to predict the impact of future changes in snow cover to freshwater export into the marine system.

**THEME 3:** Within the context of lower Arctic region of the Canadian Arctic Archipelego, we seek: (1) To quantify the relative importance of regional sources and long-range transport on GHG concentrations and aerosols. (2) To better understand climate change impacts on the regional carbon cycle. (3) To determine what is driving changes in springtime tropospheric Arctic ozone depletion and Arctic Haze aerosols in the PBL (4) To investigate the near-surface microphysics and chemistry of aerosols (notably with respect to aerosol absorption) and relationships with snow/ice surface albedo (5) To characterize the surface to columnar transformation of aerosol microphysics and chemistry across the total PBL. (6) To employ CTMs in order to help understand the high- to low-Arctic transect from Alert to Eureka to Resolute Bay to CHARS. (7) To establish, in general the determinants of Arctic air quality and how they are changing with time.

**THEME 4:** The main objectives of this theme will be: 1) to develop a surface energy budget (SEB) to predict the ground surface temperature (GST) and energy fluxes with varying snow regimes and properties; 2) to evaluate the impact of weather events, in particular extremes events, on the thermal regime of permafrost; 3) to evaluate the movement of water in permafrost as a result of thawing and freezing cycles in a context of climate change; 4) to model the dynamics of ground ice in the transient layer to changing climatic conditions; 5) to evaluate the impact of changing climatic conditions and extreme events on surface stability and topographical changes; 6) to evaluate the thermal resistance of permafrost to warming using various ground ice scenarios and simulations of regional climate change; 7) to monitor long-term (beyond the duration of this project) climate change as recorded by deep permafrost temperature.

- **Rationale:**

The Arctic has warmed at twice the global average over recent decades [1] due to a number of processes and feedbacks [2; 3]. A direct consequence of this critical climate change tendency (Arctic amplification) is the increased occurrence of climate-change-induced extreme events such as rain-on-snow and blizzards [4; 5] and a longer melt season that have significant impacts on how the cryosphere responds to climate change [6]. Patterns in the spatial extent and mass balance of snow, and permafrost show a statistically significant trend towards negative anomalies [7]. These patterns impact the transport, health, safety and economic condition of Arctic communities. As such, communities across the cryosphere require accurate and timely information on the state of snow, atmosphere and permafrost for a range of needs, which are currently not available owing to a lack of observations networks. There is also a need for information on the potential paths of projected warming to generate climate scenarios.

There have been numerous calls for improved atmospheric and surface observing systems in the Arctic. Resolution 57 of the World Meteorological Organization's 16th World Meteorological Congress notes key gaps in observational capabilities and scientific understanding related to the Arctic atmosphere and "Requests Members: (1) To support efforts to address the key gaps in scientific understanding of the Earth system and environmental processes and interactions in polar regions; (2) To promote and/or establish national research programmes towards this endeavour" [8]. This proposal responds directly to this resolution and to this call from "Integrating Arctic Research - a Roadmap for the Future" [9]: "Focus should be given to … Establishing flagship observatories as part of this observing system of systems to provide comprehensive measurements over the entire Arctic region." Yet, large uncertainties remain with regard to the effect of climate change on climatological cooling and heating patterns [10]. Observed extreme events at southern latitudes during the current winter have been linked to the breakdown of the polar vortex:

a breakdown that is the consequence of changing stratospheric dynamics that are, in turn, linked to the warming Arctic troposphere. The direct and indirect (cloud nucleating) effects of aerosols represent the greatest source of short-term tropospheric radiative forcing uncertainty, while the longer-term greenhouse (GHG) trends represent the greatest source of concern in terms of the uncertainty generated by the precarious state of global mitigation efforts. Further, uncertainties in input information from the atmosphere-snow-ground interface (ASGint) within global circulation models (GCMs) lead to uncertainties in climate predictions [e.g., 11]. Uncertainties are larger for Arctic latitudes owing to a lack of in-situ temporal observations of the ASGint as a system used to drive the models and satellite retrieval algorithms. This was reported by Richardson et al. [2016, 12] who suggested that lack of historical data has led to an underestimation of global-mean warming. Mitigation strategies [13] related to reducing the Arctic warming effects of short-lived climate-forcing pollutants (SLCPs) such as black carbon and ozone (and the intricately linked cooling SLCPs such as particulate sulphate and nitrate) require carefully monitoring of SLCPs in addition to the long-term climate-forcing pollutants.

This proposal describes a new initiative, the Multidisciplinary Observatory for Arctic Climate Change and Extreme Events Monitoring (MOACC), which will be located at the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavut. MOACC will bring together a multidisciplinary team to make long-term measurements that will establish baseline data regarding the cryosphere, hydrology, the atmosphere, and permafrost. The requested infrastructure will enable new measurement capabilities in the Canadian Arctic for world-class research across a range of disciplines. It will address the infrastructure needs of several research programs whose common whole-system goal is to improve our empirical understanding of the ASGint and fundamentally to better understand current and future Arctic changes. Results from MOACC will thus be relevant for the ongoing development of climate and snow models that are not yet well adapted to Arctic conditions [14; 15] and for increased understanding of sources of uncertainty in climate scenario construction. Furthermore, in many Arctic regions, an increase in tourist activity and accessibility to natural resources is observed, which emphasizes the need for a better understanding of trends of the ASGint to provide decision-makers with essential information relevant to infrastructure development in the North, environmental protection and public safety. For example, mining and transportation industries will be interested in knowing when and how permafrost will thaw in order to adopt mitigative strategies in infrastructure development (e.g., elevating structures, isolating soil beneath, use helical piers, wind-induced cooling systems, etc.). Another example of a benefit would be better predictions of future extreme precipitation that could be used to avoid snow-related building collapse. Increased knowledge of these events will allow communities and industries to improve existing infrastructure (i.e., increase snow-load resistance). Hence, understanding the impact of extreme events on the ASGint conditions in Arctic regions is critical for indigenous peoples, traditional resource users, communities, scientists and other stakeholders in order to develop mitigative responses and adaptive strategies in a changing environment.

- **Progress to Date:**

Over the past 15 years, my participation in numerous projects has allowed me to develop significant expertise in remote sensing and cryospheric processes. I created and currently lead a polar research group at the Université de Sherbrooke, which includes 15 graduate students (14 of whom I supervise/co-supervise). The group has published 34 peer-reviewed papers since its creation in 2014, of which 23 were first-authored by students. In 2014, I also initiated a snow monitoring program in the Kitikmeot region (NU) and I now seek to expand this network to quantify the impacts of Winter Extreme Events (WEE) through two main themes: **1:** Monitoring changes across the Atmosphere-Snow-Ground interface (ASGint) in the Arctic using remote sensing and modelling. **2**: Measuring the impacts of ASGint changes on the Peary caribou population. The long-term objective of my program is thus to monitor WEE in the Arctic in order to better understand their impacts on snow cover that in turn will modify the Peary caribou population. Recent work from my group has highlighted that snow density is a significant driver for caribou foraging conditions and that winter storms and rain-on-snow events (ROS) can densify snow to a critical point for survival. Results from the development of snow state retrievals from space have shown that global remote sensing snow water equivalent (SWE) products are biased in wet snow conditions, however, snow models and radiative transfer models can improve the accuracy of retrievals when properly parameterized for vegetation, ice layer presence, soil roughness and snow microstructure. Lastly, work in snow model forcing uncertainties highlighted problems with precipitation phase parameterization in climate models that are exacerbated by the increased occurrence of ROS. Coupling state-of-the-art climate models with snow remote sensing observations will help the understanding of the various processes governing spatial and temporal changes in snow under WEE, which are the next intuitive steps motivating the objectives of this MOACC project, in conjunction with a NSERC Alliance project.

Our research design embraces EDI in that all 10 partner Indigenous Communities directly influenced the objectives and goals of this proposal. Indigenous partners will continue to provide guidance as Members of the Technical Committee to ensure their perspectives are represented in the research as the work progresses (i.e. co-development). Our project aims to find innovative solutions to climate change for arctic wildlife and people across the Canadian Arctic Archipelago. Our site in Cambridge Bay will be used as training and reference facility to train monitors in the various communities members of our NSERC alliance project. A primary consideration in our team composition is ensuring the research project's knowledges, opportunities, and benefits extend beyond academic and government organizations to be equitably inclusive of diversity among Inuit/Inuvialuit communities, households, and harvesters, as well as the regional organizations that represent them. Our team purposefully includes members from various Indigenous Organizations (HTOs/HTCs, WMAC-NWT, ITK) and gender diverse professionals from both the natural (geomatics, ecology, quantitative ecology) and social sciences (Indigenous peoples and food; policy). Our training plan is two-fold: 1) Training of highly-qualified personnel (HQP) and 2) training of Inuit research coordinators. **1)** The plan is to have HQP participating in all the field campaigns highlighted in this proposal. The participation of HQP in fieldwork will allow them to collect the core dataset for their theses while increasing their interest in the underlying science, which we believe is a great source of motivation for young researchers. They will also benefit from the multidisciplinary experience of the research team in the field and share their own experiences with other students at various seminars, conference presentations and classes. **2)** A training program will be developed for research coordinators in each Inuit community to run community workshops for the knowledge sharing sessions contributing to all themes of the partnership. The week-long training will be offered over zoom with a focus on developing the skills for conducting and documenting knowledge shared during Indigenous knowledge interviews, as well as leading and facilitating workshops using novel methods for documenting patterns of surface change. This training initiative is directly in line with the federal government's commitment to Reconciliation. It promotes the value of Indigenous perspectives on knowledge of conservation and wildlife management in support of the National Inuit Strategy on Research by enhancing Inuit and Inuvialuit governance of research; ethical conduct of research; ownership and control of data and information and capacity to conduct research. Research coordinators will be hired to run the workshops needed for the project once trained, organize conference calls for project updates and results, and coordinate community feedback.

- **Methodology:**

**THEME 1:** The field data from the proposed site will allow calibration and development of both the snow simulation and satellite retrievals for characterizing surface state variables. Meteorological station and radiometric measurements combined with stratigraphic measurements of snow (to be conducted inside a dedicated disturbed area periodically) will be used to develop satellite-based retrieval approaches for long-term operational monitoring. More specifically, we will use the rain-on-snow detection approach developed by Dolant et al. [2016, 16] and Montpetit [2015, 24] that use passive microwaves to detect rain-on-snow and icing event occurrence and implement measurements from visibility sensor that provides precipitation rate and phase information. This will address the main limitations identified in Dolant et al. [2017, 17] and is the last step in applying this method globally and operationally using satellite data. Furthermore, Langlois et al. [2017, 4] highlighted that more data are needed to improve the detection statistics, so this project will create a rain-on-snow/ice/wind slabs database extracted from the site, which will be used to improve and develop satellite retrievals. Finally, the method described in Kramer et al. [2019, 25] will be adapted to the needs of Arctic conditions to retrieve 3D snow depths from UAV flights. Our group will develop 24/7 flying capabilities for a UAV that will be able to map snow depth spatial variability at small scales in order to help resolved unanswered questions on the effect of surface roughness on snow distributions, which is of critical importance in parameterizing soil thermal characteristics required in climate and snow models.

**THEME 2:** This project will simulate snow conditions at 1-3 km spatial resolution using high-resolution topography from numerical elevation data Canada at 1:50,000 and soil occupation from Circa-2000 vector data produced using the classification of Landsat-5 and

Landsat-7 ortho-images. The site will be use as a calibration reference where continuous snow measurements will be made, allowing for a proper treatment of microstructure, which in turn will provide an improved understanding of the scattering processes observed in TH1. Meteorological data for the 2100 horizon will be extracted from the Canadian Regional Climate Model (CRCM; 39) generated in collaboration with the Ouranos consortium, Montréal. The simulations will be utilized to drive the SNOWPACK model using near-real time and continuous forcing data produced by the site. We will also undertake routine geochemical sampling from Freshwater Creek (Greiner Lake, near Cambridge Bay), from ice break-up to freeze-up, and snow observations will be carried out and related to observations of river geochemistry collected by community collaborators from CHARS. This will allow evaluating the "end-member" characteristics of snow melt contributions to river flow, including characterization of snow geochemical fingerprints, and incorporate these observations into a model (e.g., SNOWMOD after Ahluwalia et al., 2013, 40).

**THEME 3:** Four instruments, dedicated to the measurement of a suite of trace gases will be installed. Precise and accurate column-averaged dry-mole fractions of the GHGs $CO_2$ and $CH_4$ will be measured with a new Fourier transform infrared (FTIR) spectrometer that will be deployed as part of the international Total Carbon Column Observing Network (TCCON). Dual detectors will provide additional information on biomass burning tracers (HCN, $C_2H_6$) so that $C_2H_6$:$CH_4$ ratios can be used to distinguish sources of $CH_4$ to the Arctic atmosphere. The GHG measurements will be combined with other network data, satellite measurements, and atmospheric models (including the Environment and Climate Change Canada (ECCC) Carbon Assimilation System) to address the first two objectives. Two Pandora UV-visible Spectrometers will be bought for air quality measurements relevant to objectives 3 and 4, one for CHARS and one to complement ECCC's meteorological "super-site" at Iqaluit. These will be used to measure ozone, $NO_2$, HCHO, $H_2O$, and $SO_2$: both will join the new global Pandonia network. To enhance the measurement capabilities of the Pandoras, each instrument will have a mini micro-pulse lidar (MPL) co-located. The aerosol science objectives will be addressed with a unique combination of complementary measurements, as well as providing context and corrective capability for the Pandora measurements. The MPLs will continuously measure backscatter profiles of aerosols, clouds and PBL height. The MPL's capability to measure the polarization of the backscatter signal will facilitate aerosol and cloud classification and, with different levels of complementary information (including CTM simulations), a measure of aerosol sub-type classification. A CIMEL (AEROCAN/AERONET) sunphotometer/sky radiometer/ moonphotometer will enable the division of the aerosol optical depth (AOD) spectra into fine and coarse mode AODs (a separation that is strongly linked with estimates of lidar-derived aerosol and cloud optical depth determined using a threshold approach applied to the depolarization ratio channel). The MPL aerosol / cloud profiles are essentially calibrated by comparing their estimated optical depths with their fine and coarse mode CIMEL-derived analogues. This information, combined with surface extinction coefficients from an existing cavity ring-down spectrometer (Co-I Patrick Ayotte) will enable an optical characterization of the PBL (with the CIMEL in moonphotometer mode during the polar winter). We will also deploy a set of miniaturized aerosol instruments on a drone in order to measure particle size distributions and aerosol light absorption, including black carbon concentration across the lower PBL. The measurements will focus on characterizing the vertical profiles of these properties: they will be used for CTM evaluation, the analysis of surface to column transformations and investigations of correlative links with reflectances acquired by the CRem (Continuous Reflectance Monitor). The will also enable a better understanding of any local-pollution impact on regional aerosol trends

**THEME 4**: A 20-m long thermistor cable will be installed in the permafrost. This cable will be equipped with several thermistors, more closely spaced near the top to detect short-term temperature changes linked to weather and extreme events. A permafrost core-drill equipped with a cooling system to minimize thermal disturbance will be used to retrieve intact permafrost samples. The drilling operation will be conducted on rubber mats while the active layer is still completely frozen to avoid any surface disturbance such as damage to the vegetation, removal of organics or soil compaction. The permafrost samples will be kept frozen at CHARS facilities. At controlled temperature, they will be cleaned from drill-mud and photographed for cryostructure analysis. They will be weighted and scanned with a laser to precisely determine their volume and calculate the bulk density. Additional boreholes will be done in the near surface permafrost (0-3 m) to document the spatial variation of ground ice and especially the geometry of the transient layer. The permafrost cores from the different boreholes of the proposed site will allow a detailed characterization of the cryostratigraphy (active layer, transient layer, permafrost), which will form the base of the SEB-based numerical thermal model (obj. 1). Thermal conductivity needle probes, heat flux sensors, thermistors, time-domain reflectrometry sensors (volumetric water content above and below 0°C) and electrical conductivity sensors will be deployed in the active layer, above and below the transient layer, and in the permafrost to follow the changing thermal properties and ground temperature and to follow the movement of water in the ground leading to ice segregation (or ice loss) in the transient layer and in the permafrost (obj. 2, 3, 4). Repeated electrical resistivity tomography of the ground will image the phase changes in the near surface and coring will be conducted on a yearly basis to evaluate the impact on the transient layer. In collaboration with TH1, we will retrieve 3D snow depths (winter) and 3D ground surface topography (no snow period) from UAV flights, able to map snow depth/ground surface spatial variability at a small scale in order to feed the SEB (obj. 1), to evaluate the impact of extreme events on snow thermal properties and ultimately on permafrost temperatures (obj. 2), and to evaluate changes in topography due to the dynamics of ground ice (heave/subsidence related to ground ice formation/melt) (obj. 5), which is of critical importance in parameterizing the mechanical response of permafrost to weather events and climate change in permafrost models. These meteorological, nival and permafrost monitoring datasets will be used to calibrate a numerical model of permafrost and ground ice dynamics (obj. 1 and 4). More specifically, we will evaluate how meteorological events affect the thermal diffusivity, the moisture gradient and the thermal gradient in the active layer, the transient layer and the permafrost. These data are crucial to calibrate the numerical model of permafrost and ground ice dynamics. In a subsequent phase, the calibrated numerical SEB-based atmosphere-snow-permafrost model will be used to evaluate the thermal resistance and fate of permafrost to climate change using regional climate scenarios from the Ouranos Consortium (obj. 6). Well-maintained thermistor cables can last for decades and the deep thermistor cable will be used to monitor regional climate change on a longer perspective than the current project (obj. 7).

- **Data management:**

For the proposed research, PI Alex Langlois at the Université de Sherbrooke will take the lead and responsibility for coordinating and assuring data storage and access. Along with PI Alex Langlois, a Data manager will be hired to organize, store and disseminate the results of the project, particularly in regards of the metadata. The site manager will support field coordination in close collaboration with CHARS' operations manager, while supporting the data manager ensuring data quality, proper archive while establishing data sharing agreements. The site officer will also coordinate, with the UdeS engineer, field deployment of instruments. The HQP Committee will include existing and future students from MOACC and ensure the maximization of HQP training within the project. The data produced by the project will be hosted at the Université de Sherbrooke on existing data platforms managed by A. Langlois and D. Gravel and managed through the Site officer and a Data manager. Finally, outreach will be integrated through community meetings as well as HTO meetings to ensure the proper inclusion of traditional knowledge in the science objectives while contributing to training through snow/summer schools hosted at CHARS given the existing classrooms and laboratories availability. The project is also under an agreement between the partner institutions and the communities, where the data ownership of traditional knowledge is owned and managed by the communities themselves (memorandum of agreement).

- **Research outputs:**

The anticipated results from the MOACC research program are (1) new knowledge of the impact of climate change and extreme events on the ASGint of the Arctic, climate variability and change, (2) improved understanding of the ability of models and remote sensing retrievals to simulate key surface state and atmospheric variables affecting surface energy balance, ground thermal regime, melt dynamics and hydrological processes, and (3) new knowledge about the frequency of extreme events and the sensitivity of the local climate response to ASGint specification under such circumstances. These results will be relevant for the ongoing development of climate, atmospheric, permafrost and snow models and for increased understanding of sources of uncertainty in climate scenario construction. Furthermore, in many Arctic regions, an increase in tourist activity and accessibility to natural resources is underway, which stresses the need for a better understanding of trends within the ASGint in order to provide decision-makers with essential information relevant to infrastructure development in the North, existing infrastructure management and maintenance, environmental protection and public safety. For example, mining industries and the transportation sector will be interested in knowing when and how permafrost will thaw in order to adapt mitigative strategies in infrastructure development (e.g., elevating structures, isolating soil beneath, use helical piers, wind-induced air cooling techniques, etc.). Another example of a benefit would be better prediction of extreme precipitation to avoid snow-related building collapse. Increased knowledge on these events will allow communities and industries to improve existing infrastructure (e.g., to increase snow-load resistance). Understanding the impact of climate change on the ASGint conditions in Arctic regions is critical for indigenous peoples, traditional resource users, community leaders, scientists and other stakeholders in order to develop mitigative responses and adaptive strategies in a changing environment.

The proposed research program will aim at gaining a deeper understanding of the effect of climate change on the ASGint, climate in general and the associated feedbacks. The proposed infrastructure will address a resolution from the World Meteorological Organization that not only highlights the significant gaps in observation capacities but suggest supporting efforts enhancing our 'understanding of the Earth system and environmental processes and interactions in polar regions'. Given the recent changes in northern regions, in particular the significant trends toward negative anomalies in snow and permafrost spatial extent as well as an increased occurrence in extreme events, it is imperative for Canada to claim its sovereignty in the Arctic through scientific research activities and international recognition of its expertise in this region. Those opportunities must be identified and Arctic research can help develop new policies and co-management initiatives in order to adapt to currently observed changes.

MOACC results will also support ongoing development of global climate models while representing a reference dataset for numerous satellite missions (current and future). Of particular relevance, the operational perspective rendered possible with the proposed site will allow the delivery of near-real-time information crucial to supporting algorithm development and satellite observations (especially for new missions, such as the RADARSAT Constellation Mission – RCM and the Sentinel atmospheric missions of the European Copernicus program). The site will also support space missions for snow and permafrost studies: RCM, Sentinel, Snow Mass Mission project, MetOp-SG Sat B for multi-frequency active/passive synergy (WMO Polar Space Task Group). The measurements of GHGs and other trace gases along with aerosols and clouds will contribute to the validation of missions such as GOSAT-2, TROPOMI on Sentinel 5P, and potential missions such as AIM-North.